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ORIGINAL ARTICLE

Investigating the impact of postponement and stock-sharing strategies on prepositioned relief stocks

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Abstract

Prepositioning is a critical disaster preparedness mechanism for humanitarian organizations (HOs) but requires significant investment. Improving the efficiency of prepositioned stocks is a primary concern within the humanitarian community. This study, conducted in collaboration with the Emergency Supply Prepositioning Strategy (ESUPS) Working Group, examines the impact of implementing postponement and stock-sharing strategies in a regional humanitarian warehouse. We focus on a setting where multiple HOs preposition supplies within the same warehouse to serve disaster-affected countries. Traditionally, these prepositioned supplies are branded with the respective HOs' logos, hindering the sharing of surplus stock during disaster response. Our system defers the branding process for a portion of the stockpile until after a disaster, facilitating the sharing of unbranded stock among HOs. To evaluate the benefits of postponement in this humanitarian context, we develop a two-phase inventory allocation framework for distributing branded and unbranded stocks to disaster-affected countries and for sharing unbranded stocks among HOs. We then incorporate our inventory allocation models into a Monte Carlo simulation algorithm that accounts for uncertainties regarding the occurrence and impact of disasters. Using a case study based on data from ESUPS members in the Caribbean region, we demonstrate that the proposed strategy can significantly enhance the efficiency and effectiveness of prepositioning. Remarkably, we observe a U-shaped relationship in response time as the postponement rate increases, while the fill rate and inventory utilization consistently improve. Our numerical study provides valuable insights for decision making in humanitarian logistics.

KEYWORDS
collaboration, inventory allocation, Monte-Carlo simulation, postponement, prepositioning

1 | INTRODUCTION

Prepositioning is a widely implemented disaster preparedness strategy among humanitarian organizations (HOs), involving the storage of relief supplies in warehouses to ensure rapid response during disasters (Balcik & Beamon, 2008; Sabbaghtorkan et al., 2020). However, maintaining large stockpiles in warehouses for extended periods represents dormant investments. Recent studies suggest that collaborative practices could help HOs reduce prepositioning costs while enabling timely responses (Balcik et al., 2010; Jahre, 2017; Van Wassenhove & Pedraza Martinez, 2012; Ye et al., 2020). Notably, the United Nations Humanitarian Response Depot (UNHRD) network serves as a platform for collaborative prepositioning strategies (UNHRD, 2023), bringing together different HOs physically and fostering collaborative logistics efforts. Inventory in UNHRD warehouses is categorized into authorized users' (i.e., HOs') stock and suppliers' stock (i.e., white stock) (UNHRD, 2022). Our focus is on enhancing the efficiency of HOs' stocks. While HOs may engage in stock sharing within regional warehouses, these collaborations often occur ad hoc after disasters. We aim to

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present practical methods to facilitate improved collaboration among HOs for more effective and efficient prepositioning.

HOs that preposition supplies in the same regional warehouse often have distinct focus areas, selectively responding to disasters in specific countries. This offers stock-sharing opportunities, allowing HOs to lend and borrow excess stocks for disaster response. However, stock-sharing practices are not widely implemented for several reasons. One major hindrance is that HOs tend to keep their relief stocks branded rather than unbranded (i.e., blank, standard) for visibility and quick dispatch after disasters (ICRC, 2013). Sharing branded stocks, which is rarely practiced, would require a rebranding (repackaging) process, increasing resource requirements and packaging waste. Alternatively, maintaining a portion of prepositioned stocks unbranded can facilitate effective stock sharing and improved response. In partnership with the Emergency Supply Prepositioning Strategy (ESUPS) Working Group, dedicated to enhancing prepositioning practices through improved coordination and collaboration among HOs (ESUPS, 2022), our study provides empirical evidence supporting the benefits of a collaborative approach involving postponement. We offer data-driven recommendations for positive transformations in the humanitarian sector.

This study emerged from extensive collaborations with HOs, primarily through a long-term partnership between researchers from Özyeğin University and ESUPS. This partnership, spanning several years, provided the foundation for our research and ensured its practical relevance. Our collaboration began in May 2019, when the ESUPS project manager (who later became the third author) attended an academic conference presentation by the second author on designing collaborative prepositioning networks in the Caribbean (Balcik et al., 2019). Informal discourse during the conference revealed a potential application of the postponement concept to regional humanitarian depots, promising to enhance the efficiency of existing prepositioning practices. Following initial discussions, our research team collaborated with ESUPS executives to create a comprehensive terms of reference document, which clearly defined the project's scope and outlined specific data requirements. Throughout the project's duration, we actively engaged with numerous HOs partnered with ESUPS. These interactions allowed us to gain a deeper understanding of the operational context, collect relevant data, verify our modeling assumptions, present research findings, and gather critical feedback from practitioners. This iterative process of collaboration ensured that our research remained grounded in practical realities while advancing theoretical concepts in humanitarian logistics.

Our collaborative research introduces an analytical framework to assess the impact of keeping unbranded prepositioned stocks and sharing them among HOs after a disaster. Specifically, we examine the impact of postponement coupled with a stock-sharing policy on key performance indicators (KPIs) such as demand fulfillment, response time, and inventory utilization. We address the following questions: (1) *Should HOs keep unbranded stock and apply stock sharing to improve disaster response performance?* (2) *If so, what should be the proportion of unbranded stock kept by HOs?* (3) *Should the decisions from questions 1 and 2 be uniformly applied across all HOs, or is there variation in decision making among different HOs with different sizes and response regions?*

Assessing the effects of stock-sharing and postponement strategies is challenging due to complexities related to modeling a realistic stock-sharing system among HOs with different response regions. Specifically, we need to model the allocation of unbranded stocks in regional depots owned by different HOs after a disaster, accounting for simultaneous disaster impacts across multiple countries. Drawing on expert knowledge and practitioner insights, we develop a two-phase inventory allocation framework for sharing stocks in a regional warehouse. In each phase, optimization models are solved to determine the distribution of different stock types (i.e., branded, unbranded, and shared) to affected areas. We also develop a Monte Carlo simulation algorithm that integrates the proposed inventory allocation framework and evaluates the expected performance of the regional depot under various disaster scenarios, considering uncertainties related to disaster occurrences and effects.

We apply our approach in a case study focusing on hurricane preparedness and response in the Caribbean region, using data from ESUPS, its partner HOs, and UNHRD Panama warehouse. While our analysis centers on a specific case, our analytical framework is adaptable to assess the impact of proposed strategies in diverse settings. Our numerical analysis investigates: (1) *how different rates of unbranded stock and stock-sharing policies influence the efficiency and effectiveness of prepositioning at both warehouse and country levels*, and (2) *factors affecting the extent of benefits from postponement in this humanitarian setting*. Our results demonstrate significant positive effects of postponement and stock-sharing policies on KPIs based on fill rate, response time, and inventory utilization. Specifically, as the unbranded stock rate increases, response time follows a U-shaped trend while the fill rate improves. We offer insights to explain these patterns and provide valuable managerial guidance for the effective implementation of the proposed strategies.

Our research findings have been systematically disseminated to practitioners through multiple channels. We presented versions of our model and insights at several ESUPS Working Group meetings and at ESUPS' Humanitarian Networks and Partnerships Week in 2020 and 2022. The project's outcomes were synthesized in an executive report, published by ESUPS and presented at The Annual Global Preparedness Workshop in November 2023, jointly organized by Logistics Cluster, Welthungerhilfe, and ESUPS (Fortier et al., 2023). ESUPS publicly endorsed this report on their website, emphasizing its pioneering nature and potential to transform collaborative practices among HOs. The announcement highlighted the broader implications of our findings, urging HOs to adopt and replicate our model to refine their strategies, ultimately benefiting both the humanitarian community and those affected by crises (ESUPS, 2023). This positive reception from ESUPS

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validates the practical relevance of our research and its potential to enhance humanitarian logistics operations.

We structure the remainder of the article as follows. In Section 2, we position our article within the existing literature. In Section 3, we describe current branding practices in the humanitarian landscape and explain our proposed system and approach. In Section 4, we describe the system and present our models. In Section 5, we describe our case study and the results of analyses. In Section 6, we discuss our findings and conclude the article.

2 | LITERATURE REVIEW

While prepositioning is extensively studied in humanitarian logistics literature, existing research primarily focuses on optimizing the location and quantity of prepositioned inventory. Some studies emphasize exploring innovative strategies to enhance prepositioning practices, including collaboration, standardization, postponement, and localization (Jahre, 2017; Jahre et al., 2009; Van Wassenhove & Pedraza Martinez, 2012; Ye et al., 2020). Our study, which investigates the potential impact of implementing a postponement strategy combined with stock sharing within a regional humanitarian depot, aligns with two key streams of literature: collaborative inventory management and postponement.

2.1 | Collaborative inventory management

Collaboration in humanitarian supply chains can be categorized into vertical and horizontal types. Vertical collaboration involves interactions between an HO and other actors in the upstream or downstream supply chain, whereas horizontal collaboration occurs among different HOs at the same level (Adsanver et al., 2024; Balcik et al., 2010). Our study focuses on horizontal collaboration to improve the efficiency and effectiveness of prepositioning.

While prior work has emphasized enhancing horizontal collaboration in prepositioning networks (e.g., Acimovic & Goentzel, 2016; Balcik et al., 2019; Rodríguez-Pereira et al., 2021), our study specifically investigates stock-sharing practices among HOs that preposition supplies within the same warehouse. Research on collaborative inventory planning within single warehouses, like UNHRD facilities, typically distinguishes between authorized HOs' stocks (both unbranded and branded) and suppliers' unbranded white stocks (UNHRD, 2022). Through UNHRD's inventory portal, HOs can monitor stocks owned by others (UNHRD, 2024). White stock, managed by suppliers under Long-Term Agreements with UNHRD, is available to member HOs. On one hand, centralized systems like white stocks can have certain advantages for HOs such as lower information costs or reduced inventory holding costs. On the other hand, white stock's postdisaster availability, especially for smaller organizations, remains uncertain (Schulz, 2009). Furthermore, white stock may not be present in all humanitarian warehouses. Our article aims to enhance the efficiency of HOs' stocks through a combination of postponement and stock-sharing strategies.

Existing studies on collaborative inventory planning within warehouses involving HOs' stocks or white stock typically address scenarios with two (e.g., Coskun et al., 2019; Mochizuki et al., 2015) or more HOs (e.g., Toyasaki et al., 2017; Wang et al., 2021). In these systems, HOs can access additional supplies when faced with inadequate stock for disaster response. For instance, Mochizuki et al. (2015) investigate two HOs sharing prepositioned stocks over multiple periods, categorizing stocks based on ownership and location, including HOs' own stocks stored at UNHRD facilities, swapped stocks, and UNHRD's white stocks. They employ a multiagent simulation model to analyze HOs' decisions on stock placement. In a different context, Coskun et al. (2019) focus on a relief network where each HO manages its own disaster region, without overlapping response areas, within a single-period setting. They propose a stock-sharing policy considering independent disaster risks in various regions and identify scenarios where horizontal collaboration benefits arise. Similarly, Wang et al. (2021) examine a single-period scenario within a humanitarian network where prepositioned stocks from different warehouses can be transported directly to disaster areas or through other facilities (transshipment), incorporating stock sharing among warehouses. Finally, Toyasaki et al. (2017) analyze the impact of different levels of stock sharing (partial and full-sharing) on incentivizing HOs within a single-period system. They determine membership fees for HOs maintaining stocks in shared warehouses and propose a proportional sharing policy for allocating excess stock among collaborating organizations.

While previous research has explored collaborative inventory management systems in humanitarian depots, our study is the first to investigate the effects of postponement in this context. Unlike previous models that focus on surplus stock sharing and overlook the branding process, our approach categorizes prepositioned stocks as either shareable (unbranded) or nonshareable (branded), enabling us to model and analyze the impact of postponement on prepositioning performance. This necessitates the development of new inventory allocation models to accurately represent current stock-sharing practices in humanitarian operations.

2.2 | Postponement in supply chain management

Numerous studies have explored the application of postponement strategies in supply chains. These strategies are commonly classified into three main categories: *time*, *place*, and *form* postponement (Bowersox & Closs, 1996; van Hoek, 1997; Zinn & Bowersox, 1988). Time postponement involves delaying the shipment of goods until customer orders arrive. Place postponement entails delaying the shipment of goods, often focusing on storing goods centrally to facilitate inventory pooling. Form postponement refers to delaying final manufacturing or processing activities. Prataviera et al.

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(2020) further develop this framework by considering the geographical aspect of postponement, identifying three options for postponement: the home region (i.e., the main production facility), a third-country region (i.e., a region separate from both the factory and customer locations), and the destination region (i.e., the customers' locations).

Time postponement involves delaying centralized manufacturing, impacting the positioning of finished goods within the supply chain. Finished product distribution postponement has been studied in retail (e.g., Appelqvist & Gubi, 2005), specialty retail (e.g., Fernandes et al., 2015), and electronics (e.g., Luo et al., 2017) industries. *Place postponement* is linked to inventory pooling strategies, where it facilitates the aggregation of demand variability across products or locations, resulting in smoother demand profiles that enhance supply chain flexibility and efficiency. Numerous studies have explored the implications of inventory pooling in supply chains, particularly in contexts with significant commercial urgency, such as spare parts management (e.g., Alptekinoğlu et al., 2013; Wang & Yue, 2015), online retailing (e.g., Govindarajan et al., 2021; Qin et al., 2022), and fast fashion (e.g., Aftab et al., 2017). The purpose of *form postponement* is to push the product's differentiation point as downstream as possible by reconfiguring the process, standardizing or modularizing the components (Prataviera et al., 2020). Studies investigating form postponement include research on labeling (e.g., Varas et al., 2018), packaging (e.g., Graman & Magazine, 2006), assembly (e.g., Van Kampen & Van Donk, 2014), or manufacturing (e.g., Fu et al., 2012).

In our humanitarian context, we focus on a regional warehouse storing relief items of multiple HOs. In this setting, "labeling process," "finished products," and "customer order arrivals" correspond to branding process, branded items, and disaster occurrences, respectively. The current system already utilizes time and place postponement strategies. Specifically, branded items are stored in regional warehouses, separate from supplier manufacturing and disaster locations (place postponement). In addition, these items are dispatched post-disaster (time postponement). We add an extra layer of postponement by delaying the branding process to a third country until disasters occur, categorizing our article under third-country postponement of the labeling process, a type of form postponement.

Labeling postponement has been studied within wine (e.g., Ferreira & Alcântara, 2015; Gualberto et al., 2021; Varas et al., 2018), telecommunications (e.g., Reiner, 2005), and IT (e.g., Chiou et al., 2002) industries. Among these studies, the first four focus on home-region postponement, while the last study explores destination-region postponement. Third-country postponement has been explored for assembly postponement (e.g., Lee & Silvermann, 2008; Saiz & Uribetxebarria, 2012) and finished product distribution postponement (e.g., Fernandes et al., 2015). Our study is the first to explore the impact of third-country postponement of the labeling process, addressing a gap in the literature highlighted by Prataviera et al. (2020) as still underrepresented and deserving further consideration.

Investigating postponement within a humanitarian context presents unique challenges compared to its applications in supply chain settings. We outline two key distinctions. First, humanitarian supply chains prioritize alleviating human suffering, unlike profit-driven commercial chains (see, e.g., Fu et al., 2012; Reiner, 2005; Varas et al., 2018; Wong et al., 2009). Our models aim to reduce unsatisfied demand (weighted by the severity of disasters) rather than maximize profits. Second, the inventory allocation rules utilized in commercial contexts for distributing pooled inventory among customers do not directly apply to our humanitarian setting. Unlike typical allocation policies in commercial contexts, which are often based on fixed or randomized lists due to predictable demand structures and/or single-period considerations (e.g., Alptekinoğlu et al., 2013), our setting involves distinct sharing rules affected by the complexities of humanitarian operations, such as overlapping response regions (countries served), the management of both branded (nonshareable) and unbranded (shareable) items, interdependencies in sharing decisions over time, and highly unpredictable demands. Our inventory allocation models incorporate these aspects, significantly complicating our problem. Therefore, designing an implementable postponement and stock-sharing strategy in the humanitarian context requires the development of new models tailored to these challenges.

Finally, in addition to its research contributions in presenting new models and insights, our study advocates for positive changes in the humanitarian sector by empirically showcasing the benefits of stock-sharing and postponement strategies, ultimately leading to enhanced outcomes for disaster-affected populations.

3 | BACKGROUND AND APPROACH

Given the significant costs of supply chains for HOs (Stumpf et al., 2022), exploring strategies to enhance efficiency is crucial. Our study investigates combining postponement (keeping a proportion of stocks unbranded) with a stock-sharing (lending and borrowing) strategy in a humanitarian depot to improve prepositioned stock performance.

Collaborative strategies are generally expected to yield positive results through resource pooling, but it remains uncertain whether these enhancements are significant enough to motivate HOs to change practices. We present an analytical framework for HOs to assess the impact of postponement and stock-sharing strategies within a regional depot, developed in collaboration with humanitarian practitioners. Below, we describe current practices and outline our proposed system and research approach.

3.1 | Current branding practices

HOs commonly brand relief items with logos to enhance visibility and public relations (ICRC, 2013). Research

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underscores the correlation between brand visibility and donations (do Paço et al., 2014), highlighting the significance of international media exposure for HOs. Logos also serve to credit HOs and donors' efforts (Loy, 2023). They help governments in demonstrating aid origin and taxpayer money utilization, as well as improving their global image (DG_ECHO, 2023; Pew Research Center, 2005; USAID, 2024). Branding facilitates tracking of stocks and ensures ownership during storage and distribution (Gharib, 2018; Schulz, 2009). We refer the reader to Online Appendix A.1 for an expanded discussion on rationale for branding in humanitarian systems.

In the current system, HOs employ two primary methods of branding their stocks. Branding involves either printing the HO's logo directly onto the item or its packaging, or applying stickers with the HO's logo to the item or its package (see Online Appendix A.2 for visual examples of branding practices). The choice between these methods depends on the type of item and is determined by the HO.

Printing logos directly onto items or packaging is irreversible. In contrast, applying stickers, while potentially reversible, can still be time-consuming and costly to remove. Consequently, sharing branded stocks—whether permanently printed or sticker-applied—is rarely practiced due to the challenges of rebranding. Even with sticker-applied branding, the rebranding process can substantially increase expenses because it involves not only applying new brand stickers, but also the labor-intensive task of removing existing ones. As a result, this process not only generates packaging waste but also requires significantly more resources compared to branding standard items.

In current practice, HOs often utilize supplier-managed branding, either through printed logos or logo stickers, for its convenience and to streamline efforts during crises. Given the current reality and practices, branding remains essential in the humanitarian sector, and our proposed model acknowledges this reality. Instead of advocating for the elimination of branding, we propose more efficient approaches that involve minor compromises on visibility. Specifically, we investigate the performance implications of postponing branding until a disaster occurs for a portion of the stocks. This approach allows HOs to retain branding benefits while facilitating collaborative practices like stock sharing.

3.2 | Research approach

We focus on a humanitarian setting with a single regional warehouse, like UNHRD, where multiple HOs preposition stocks to respond to multiple countries. Each HO starts with a base stock (initial inventory) at the beginning of the planning horizon (e.g., a year) involving multiple periods (e.g., weeks), during which various countries may be affected by disasters. In our approach, HOs postpone branding process on a proportion (0–100%) of stocks, keeping them in an unbranded form in the regional warehouse. This facilitates HOs to quickly share these unbranded (i.e., shareable) stocks when needed. While such quick sharing after a disaster would require an effective information-sharing system, the existing UNHRD portal that provides visibility of available stocks (UNHRD, 2024) can be adapted for managing stock sharing among HOs.

We evaluate how varying unbranded stock rates (i.e., postponement rates), defined as the ratio of each HO's unbranded stocks to total stocks, impact system performance, focusing on KPIs: response time, fill rate, and inventory leftover ratio. Response time is critical for saving lives and gaining visibility among donors. The fill rate measures how sharing unbranded stocks affects demand satisfaction in the network, while the inventory leftover ratio serves as a proxy for prepositioning costs.

To compute the proposed KPIs, modeling the inventory management system at a regional depot after a disaster is essential but challenging. The decision-making process involves determining which HOs should deploy stocks to specific countries, how to distribute branded and unbranded stocks, and how to manage shareable resources in a network with multiple HOs having overlapping response regions and countries. To facilitate comparisons across different postponement rates in this complex setting, we develop inventory allocation models that capture key trade-offs and provide an "optimal" allocation within a centralized system. While real-world decisions may differ from optimal outcomes, our approach enables objective comparisons among various strategies and sets a benchmark for HOs, guiding them in coordinating prepositioned inventory management at regional depots.

In our proposed inventory management system with postponement, HOs respond to disasters by mobilizing their branded, unbranded, and borrowed stocks to meet the demand. To determine the stock quantities for shipment and sharing, we formulate a two-phase inventory allocation system, which initially deploys each HO's branded and unbranded stocks and then allows sharing excess stocks if demand remains unmet. We solve two inventory allocation models in these phases: *Model 1* allocates HOs' own stocks to disaster-affected countries, and *Model 2* addresses the allocation of shareable stocks. These models are developed based on insights from consultations with our partner organization ESUPS and its member HOs, capturing typical business objectives and constraints within this network rather than those specific to each HO. Our objective is to understand and demonstrate the effects of postponement and stock-sharing practices on KPIs on average, without prescribing specific inventory allocation decisions for individual HOs.

To compare system performance with and without the proposed strategies, we employ a Monte Carlo simulation algorithm, which calculates relevant KPIs based on numerous disaster scenarios. By integrating our inventory allocation models, we assess how different unbranded stock rates impact performance under varying disaster conditions and quantify the benefits of postponement and stock-sharing strategies.

Next, we provide a detailed system description and present our models.

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4 | SYSTEM DESCRIPTION AND MODELING

In this section, we detail the humanitarian prepositioning system components (Section 4.1), introduce our two-phase inventory allocation framework and models (Section 4.2), and present the Monte Carlo simulation algorithm (Section 4.3) along with KPIs (Section 4.4). The article's notation is summarized in Online Appendix F.

4.1 | System description

We describe the important elements of the prepositioning system and modeling framework.

4.1.1 | Network

We consider a humanitarian relief network with multiple HOs, each maintaining prepositioned stocks in a regional warehouse serving multiple countries. Each HO has a designated disaster response region covering specific countries. Let $\mathcal{A}$ denote the set of HOs, and $\mathcal{C}$ represent the set of countries. The HOs' response regions are represented by an HO-country level response matrix (see Online Appendix D, Table D2), which includes binary parameters $\overline{\delta}_{ac}$, where $\overline{\delta}_{ac} = 1$ if country $c \in \mathcal{C}$ is in the response region of HO $a \in \mathcal{A}$, and 0 otherwise.

4.1.2 | Planning horizon and disaster scenarios

We focus on preparedness and response for hurricanes, which occur multiple times during a season, affecting multiple countries with varying severity levels. To address uncertainties in hurricane occurrence, we use a discrete representation of disaster scenarios based on historical data, as in Balcik et al. (2019) (see Figure 2). Each scenario $s \in \mathcal{S}$ represents a disaster season with periods $t \in \mathcal{T}$ (e.g., weeks). In each period, there may be zero, one, or multiple disaster events with different severity levels (λ), resulting in different severity levels and demands per affected country denoted by $\overline{\lambda}_{stc}$ and $\overline{d}_{stc}$. We define Γ_s and Υ_{sc} as subsets of $\mathcal{T}$ representing periods with disasters, and periods where country c is affected in scenario s, respectively. In addition, ζ_c indicates the scenarios in which a disaster affects country c.

At the start of the planning horizon, each HO maintains an initial prepositioned inventory, which is used and replenished throughout the horizon as the HO responds to disasters in its own region or shares stocks with other responding HOs (see Online Appendix B, Figure B1 for an illustration of different types of stock movements). Assumptions regarding delivery times and stock replenishment will be discussed next.

4.1.3 | Delivery times

The response time for each disaster in each scenario depends on the *delivery times* of branded, unbranded, and shared/borrowed stocks from the regional warehouse to the disaster-affected countries, as well as the delivery time for unmet demand directly from the suppliers. We approximate shipment times without considering variations in in-land transportation, assuming they are uniform across branded, unbranded, and shared supplies.

Delivery time for branded stocks ($\overline{\tau}^b$) includes loading onto vehicles and transportation to affected countries. The delivery time of unbranded stocks ($\overline{\tau}^u$) encompass branding, loading, and transportation times. Delivery time for borrowed stocks ($\overline{\tau}^s$) adds extra time for the sharing process. If demand remains unmet, suppliers deliver directly within $\overline{\tau}^p$ units. Based on practitioner consultations, we assume $\overline{\tau}^b < \overline{\tau}^u < \overline{\tau}^s < \overline{\tau}^p$ (see Online Appendix B for an illustrative example).

4.1.4 | Replenishment of the regional warehouse

Each HO's inventory decreases at the end of a period due to usage, if any, and increases at the beginning of a period upon replenishment from the supplier. While we assume a single supplier for simplicity, the model can accommodate multiple suppliers with varying delivery times. HOs place replenishment orders with the supplier at each disaster period, matching the amount used for branded, unbranded, and borrowed stocks. Replenishment orders arrive at the regional warehouse in unbranded form at the start of the first period after a replenishment lead time $\overline{\tau}^r$, which is typically longer than the supplier lead time during the response phase $\overline{\tau}^p$.

Upon receiving unbranded stocks at the warehouse, the responding HO (i) labels a portion of the stocks that is equal to the branded stock usage amount with its own brand to replenish its branded stock, (ii) replenishes its unbranded stock, and (iii) replenishes the unbranded borrowed stock of each sharing HO (see Online Appendix B for an example).

As explained before, to evaluate the performance of the current and proposed systems, we simulate HOs' decisions on inventory allocation to meet demands in each disaster scenario. We define and model the inventory allocation problem with postponement and stock-sharing features in two phases, presented next.

4.2 | Two-phase inventory allocation framework

To formulate the inventory allocation problem with postponement and stock sharing, without loss of generality, we consider a single relief item prepositioned by several HOs in a regional warehouse (e.g., blankets, tarpaulins, and fam-

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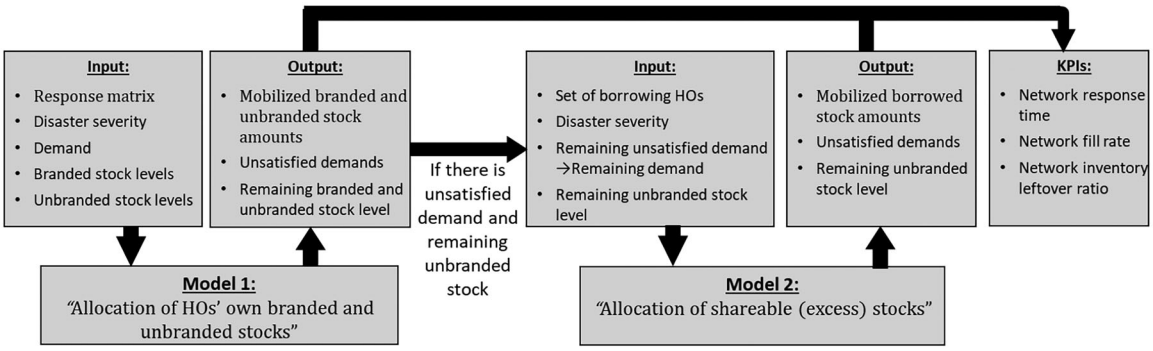


FIGURE 1 The illustration of the two-phase decision-making framework for inventory allocation. HOs, humanitarian organizations; KPIs, key performance indicators.

ily kits). HOs maintain a proportion (R) of the prepositioned stocks in unbranded form to facilitate sharing when needed. At the beginning of each planning horizon (e.g., hurricane season), HOs start with an initial total stock level equal to an order-up-to level ($\bar{q}_a^T$). This total includes branded stocks ($\bar{q}_{sta}^b = (1-R)\bar{q}_a^T$) and unbranded stocks ($\bar{q}_{sta}^u = R\bar{q}_a^T$). Each HO owns and manages its own *branded* and *unbranded* stock. In each period, the available branded and unbranded stock of each HO depends on the usage and replenishment from the supplier over previous periods.

During each period when a disaster affects one or multiple countries, we face the critical decision of *determining how each HO will address the demand for relief supplies using branded, unbranded, and shared stocks*. This complex problem involves simultaneous relief delivery and stock-sharing decisions across multiple HOs, further complicated by the need to prioritize countries. To address this challenge, we model the inventory allocation problem in two phases, as illustrated in Figure 1. This approach not only offers a practical solution for stock sharing among organizations but also ensures efficient computation in each period. By integrating this framework into our Monte Carlo simulation algorithm (Section 4.3), we can compute relevant KPIs for a large number of scenarios quickly, enabling comprehensive numerical analysis within reasonable times. We also developed a single optimization model that integrates both phases (see Online Appendix E.7), which yields similar results. However, we proceed with the two-phase model because the integrated model requires more computational resources and has led to out-of-memory errors during our analysis.

Figure 1 illustrates our two-phase optimization approach. We solve two optimization models sequentially in each period with a disaster throughout the planning horizon. In the first phase (Model 1), we allocate HOs' own stocks, followed by the allocation of shareable stocks in the second phase (Model 2). Next, we provide a detailed explanation of these inventory allocation problems and models.

In the first phase, HOs mobilize their own branded and unbranded stocks to meet the demand in disaster-affected countries within their response region. When multiple countries are affected, each HO prioritizes those affected more severely and allocates stocks accordingly. Specifically, if HOs have excess stocks after fulfilling severe demands, they respond to less severely affected countries.

4.2.1 | Phase 1: Allocation of HOs' own stocks (Model 1)

Model 1 parameters include disaster demands, severities, HO response regions, and stock levels for branded and unbranded items. Key decisions involve determining the amount of unbranded (X_{stac}^u) and branded (X_{stac}^b) stocks mobilized by each HO to affected countries. Consequently, this phase identifies *responding* (i.e., $\delta_{stac} = 1$ if $X_{stac}^u + X_{stac}^b > 0$) and *nonresponding* ($\delta_{stac} = 0$ if $X_{stac}^u + X_{stac}^b = 0$) HOs for disasters occurring in different countries. In addition, U_{stc} denotes unsatisfied demand in affected countries. Furthermore, I_{sta}^b and I_{sta}^u variables keep remaining branded and unbranded stock levels, respectively.

We present Model 1, which is solved in every period $t \in \mathcal{T}$ of each scenario $s \in \mathcal{S}$ below.

$$\text{minimize} \quad \sum_c \bar{\lambda}_{stc} U_{stc} \tag{1}$$

$$\text{subject to} \quad U_{stc} = \bar{d}_{stc} - \sum_{a \in \mathcal{A}} \left(X_{stac}^b + X_{stac}^u\right) \qquad \forall c \in \mathcal{C}, \tag{2}$$

$$X_{stac}^b + X_{stac}^u \le M\bar{\delta}_{ac} \qquad \forall a \in \mathcal{A}, c \in \mathcal{C}, \tag{3}$$

$$\sum_{c \in \mathcal{C}} X_{stac}^u + I_{sta}^u = q_{sta}^u \qquad \forall a \in \mathcal{A}, \tag{4}$$

$$\sum_{c \in \mathcal{C}} X_{stac}^b + I_{sta}^b = q_{sta}^b \qquad \forall a \in \mathcal{A}, \tag{5}$$

$$I_{sta}^b \le M(1 - Z_{sta}) \qquad \forall a \in \mathcal{A}, \tag{6}$$

$$\sum_{c \in \mathcal{C}} X_{stac}^u \le MZ_{sta} \qquad \forall a \in \mathcal{A}, \tag{7}$$

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$$X^b_{stac}, X^u_{stac} \geq 0 \text{ and integer} \quad \forall a \in \mathcal{A}, c \in \mathcal{C}, \tag{8}$$

$$I^b_{sta}, I^u_{sta} \geq 0 \text{ and integer} \quad \forall a \in \mathcal{A}, \tag{9}$$

$$U_{stc} \geq 0 \text{ and integer} \quad \forall c \in \mathcal{C}, \tag{10}$$

$$Z_{sta} \in \{0, 1\} \quad \forall a \in \mathcal{A}. \tag{11}$$

The objective function (1) of Model 1 minimizes the total unsatisfied demand in each country, weighted disaster severity levels. This approach, common in the literature (see, e.g., Balcik & Beamon, 2008; Rawls & Turnquist, 2010), aligns with our practitioner collaborators' preferences. In our case study, we explore alternative objective functions, like minimizing the maximum unsatisfied demand ratio per country weighted by disaster severity, detailed in Online Appendix E.5. This analysis confirms that our primary study insights on postponement effects (Section 5.2.1) remain unchanged.

Constraint (2) defines the unsatisfied demand based on total mobilized stocks from HOs to an affected country and its demand. Constraint (3) restricts HOs to responding only within their designated regions. Constraints (4) and (5) limit the mobilized amounts of unbranded and branded stocks to not exceed each HO's respective stock levels, respectively. Constraints (6) and (7) ensure that HOs use unbranded stocks only after depleting their branded stocks, controlled by decision variable Z_{sta}, where $Z_{sta} = 1$ if an HO mobilizes unbranded stock, and 0 otherwise. Finally, constraints (8)–(11) define variable domains.

As shown in Figure 1, the outputs of Model 1 become inputs for Model 2 if stock sharing is necessary; otherwise, only the outputs from Phase 1 suffice to compute the relevant KPIs in our simulation algorithm.

4.2.2 | Phase 2: Allocation of shareable stocks (Model 2)

If responding HOs' own stocks are insufficient to meet the demand in Phase 1, Model 2 is employed in Phase 2 to distribute *shareable* (i.e., excess unbranded) stocks among the responding HOs to satisfy the *remaining demand*. The outputs of the remaining demand (U_{stc}) and shareable stock ($I^u_{st\acute{a}}$) variables from Model 1 serve as parameters of Model 2.

In Phase 2, we establish rules for identifying HOs eligible to share and borrow shareable stocks through consultations with practitioners. Model 2 incorporates these rules to determine the amount of stocks to be shared and delivered. Accordingly, if a responding HO borrows shareable stock from either a nonresponding HO or another responding HO with excess unbranded stock, the responding HO becomes a *borrowing HO*, while the lending HO becomes a *sharing HO* (see Online Appendix B for an illustrative example).

The rules for implementing a sharing policy in the second phase are as follows:

1. An HO that responds to a disaster-affected country in Model 1 (i.e., a responding HO) can borrow stocks for responding to that country if it has already deployed its own branded and/or unbranded stocks in Model 1. If there is no responding HO for the country in Model 1 (e.g., because all HOs that include the country within their response regions mobilized their own stocks to other countries in Model 1), then nonresponding HOs that include the country within their response regions can borrow unbranded stock to respond to the country. This mechanism prioritizes HOs that already mobilized stocks (i.e., responding HOs) over those that did not (i.e., nonresponding HOs) for borrowing stocks, ensuring that response resources are effectively utilized.
2. HOs responding to the same country do not exchange stocks among themselves, except when a responding HO can share its excess unbranded stock after fulfilling the demands of disaster-affected countries within its response region.
3. No specific prioritization rules dictate a specific lending and borrowing sequence among multiple sharing and borrowing HOs. Allocation is determined based on the remaining demand of countries, weighted by the severity of the situation.

To formulate Model 2, we specify *candidate-sharing HOs* and *candidate-borrowing HOs for country c* using binary parameters $\gamma_{sta} = 1$ and $\Pi_{stac} = 1$, respectively. Specifically, $\gamma_{sta} = 1$ if $I^u_{sta} > 0$, and $\Pi_{stac} = 1$ if $\delta_{stac} = 1$ and $U_{stc} > 0$ or if $\bar{\delta}_{ac} = 1$, $\sum_{a \in \mathcal{A}} \delta_{stac} = 0$ and $U_{stc} > 0$. Furthermore, decision variables of Model 2 include the amount of stocks HO a borrows from HO $\acute{a}$ and mobilizes to the disaster-affected country c ($Y_{st a\acute{a} c}$). The unsatisfied demand of countries and the remaining unbranded stock levels of HOs are represented by V_{stc} and W^u_{sta}, respectively. We present Model 2 below.

$$\text{minimize} \quad \sum_{c} \bar{\lambda}_{stc} V_{stc} \tag{12}$$

$$\text{subject to} \quad V_{stc} = U_{stc} - \sum_{a \in \mathcal{A}} \sum_{\substack{\acute{a} \in \mathcal{A} \\ \acute{a} \neq a}} \Pi_{stac} \gamma_{st\acute{a}} Y_{st a\acute{a} c} \quad \forall c \in \mathcal{C}, \tag{13}$$

$$I^u_{st\acute{a}} - \sum_{\substack{a \in \mathcal{A} \\ a \neq \acute{a}}} \sum_{c \in \mathcal{C}} \Pi_{stac} \gamma_{st\acute{a}} Y_{st a\acute{a} c} = W^u_{st\acute{a}} \quad \forall \acute{a} \in \mathcal{A}, \tag{14}$$

$$Y_{st a\acute{a} c} \geq 0 \text{ and integer} \quad \forall a \in \mathcal{A}, \acute{a} \in \mathcal{A}, c \in \mathcal{C}, \tag{15}$$

$$V_{stc} \geq 0 \text{ and integer} \quad \forall c \in \mathcal{C}, \tag{16}$$

$$W^u_{sta} \geq 0 \text{ and integer} \quad \forall a \in \mathcal{A}. \tag{17}$$

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Similar to Model 1, the objective function (12) of Model 2 minimizes the total severity-weighted unsatisfied demand. Constraints (13) ensure that the total mobilized borrowed stocks from HOs to an affected country does not exceed the demand of that country, thereby defining the unsatisfied demands. Constraints (14) guarantee that the total mobilized borrowed stocks from HOs to affected countries do not exceed the shareable amount held by HOs, while also specifying the remaining unbranded stocks of HOs after sharing. Finally, Constraints (16 and 17) define the domains of variables.

Given the solutions of Model 2, if the sum of responding HOs' branded, unbranded, and borrowed stocks is insufficient to meet the demand at the end of Phase 2, the unmet demand is satisfied by the supplier.

4.3 | Monte Carlo simulation

For a specific unbranded rate $R \in [0\%, 100\%]$, we run our simulation algorithm for each scenario and compute the relevant KPIs (Section 4.4). Our main goal is to compare these KPI values across different R values with a *base case*, which represents the current situation where all stocks are kept in branded form (i.e., $R = 0\%$).

We present the pseudocode of our simulation algorithm (Algorithm 4.3), where $s = 1, 2, \ldots, \mathcal{S}$ and $t = 1, 2, \ldots, \mathcal{T}$ represent disaster scenarios and time periods, respectively. A detailed flowchart of the simulation algorithm is available in Online Appendix C. Next, we briefly explain the algorithm's steps, referring to the lines in Algorithm 4.3 as needed.

At the beginning of each time period in each scenario, we first update inventory levels by checking the arriving replenishments from the supplier (*Line 5*). We then initiate a response if a disaster occurs during the period (*Line 7*). If a disaster occurs, we determine the amount to allocate and ship to the affected countries by using Models 1 and 2 (*Lines 8–12*).

At the end of each disaster-affected time period (*Line 13*), we calculate the network response time, the network fill rate, the response time of each country, and the fill rate of each country (respectively, (18) and (19), (26) and (27)) to use them to calculate their corresponding KPIs (*Line 16*). Then, HOs place orders to the supplier in the amount they mobilize from branded, unbranded, and borrowed stocks (*Line 14*). Finally, at the end of each scenario (*Line 15*), we calculate the network inventory leftover ratio (see (20)) to calculate its corresponding KPI (*Line 16*). We provide the detailed formula for each KPI in the next subsection.

We use Eclipse Integrated Development Environment (IDE) for Java Developers to run our simulation algorithm. The algorithm utilizes CPLEX libraries in Java to solve two inventory allocation models optimally within the simulation. On a standard laptop equipped with an i7-1065G7 CPU and 16.0 GB RAM, the simulation algorithm completes within a minute for each instance in our case study.

4.4 | Key performance indicators

The impact of different unbranded rates is evaluated based on several KPIs, computed based on the outputs of the proposed two-phase inventory allocation framework. The KPIs are based on three primary concerns of the prepositioning network: *response time*, *fill rate*, and *inventory leftover ratio*, which serves as a proxy for inventory holding costs.

The response time performance of the prepositioning network in a period depends on the mix of mobilized stock types, which include branded ($\overline{X}^b_{stc} = \sum_{a\in\mathcal{A}} X^b_{stac}$), unbranded ($\overline{X}^u_{stc} = \sum_{a\in\mathcal{A}} X^u_{stac}$), shared/borrowed ($\overline{Y}_{stc} = \sum_{a\in\mathcal{A}} \sum_{\acute{a}\in\mathcal{A}, \acute{a}\neq a} Y_{staác}$), or supplier sourced ($\overline{U}_{stc} = U_{stc}$ if sharing is not needed; otherwise $\overline{U}_{stc} = V_{stc}$) items, and their delivery times ($\overline{\tau}^b$, $\overline{\tau}^u$, $\overline{\tau}^s$, and $\overline{\tau}^p$ days, respectively). The network response time, represented by ψ_{stR} for each $t \in \mathcal{T}$ in each $s \in \mathcal{S}$ and $R = [0\%, 100\%]$, is equal to the total weighted average of the response times for the four types of stocks, where weights are the ratio of the amount of each stock type to the demand ($\overline{d}_{stc}$), calculated as follows:

$$\psi_{stR} = \sum_{c\in C} \left(\overline{\tau}^u \overline{X}^u_{stc} + \overline{\tau}^b \overline{X}^b_{stc} + \overline{\tau}^s \overline{Y}_{stc} + \overline{\tau}^p \overline{U}_{stc} \right) \Big/ \sum_{c\in C} \overline{d}_{stc} \quad \forall R \geq 0\%, s \in \mathcal{S}, t \in \mathcal{T}. \tag{18}$$

The fill rate in a disaster period is equal to the ratio of the total mobilized amount from the regional warehouse to disaster-affected countries ($\overline{X}^u_{stc} + \overline{X}^b_{stc} + \overline{Y}_{stc}$) to the total demand of these countries ($\overline{d}_{stc}$). We calculate a network-level average across all disasters, time periods, and countries. The network fill rate for each $t \in \mathcal{T}$ in each $s \in \mathcal{S}$ for each $R = [0\%, 100\%]$, which is represented by ϕ_{stR}, is calculated as follows:

$$\phi_{stR} = \sum_{c\in C} \left(\overline{X}^u_{stc} + \overline{X}^b_{stc} + \overline{Y}_{stc} \right) \Big/ \sum_{c\in C} \overline{d}_{stc} \quad \forall R \geq 0\%, s \in \mathcal{S}, t \in \mathcal{T}. \tag{19}$$

For each scenario, we calculate the inventory leftover ratio at the network level, ι_{sR}, by dividing the total remaining stock level in the regional warehouse at the end of the last disaster period $\bar{t}$ ($\overline{Q}_{\bar{s}ta}$) by the total beginning inventory in the regional warehouse ($\overline{q}^T_a$) as below.

$$\iota_{sR} = \sum_{a\in\mathcal{A}} \left(\overline{Q}_{\bar{s}ta} \right) \Big/ \sum_{a\in\mathcal{A}} \overline{q}^T_a \qquad \forall R \geq 0\%, s \in \mathcal{S}. \tag{20}$$

While one can calculate the expected values of these three metrics at the end of Algorithm 1, our main goal is to compare these metric values with all HOs keep some proportion of unbranded stocks ($R > 0\%$) versus those obtained from the base case where all HOs keep only branded stocks ($R = 0\%$), and gain insights about the differences. Therefore, we

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ALGORITHM 1 Simulation Algorithm.

1 Initialization;
2 **for** $R \in [0\%, 100\%]$ **do**
  Input: Scenario data, Network data
3 **for** *scenario* $s = 1, 2, \ldots, S$ **do**
4 **for** *time period* $t = 1, 2, \ldots, T$ **do**
5 **if** $\exists$ *a shipment from the supplier* **then**
6 Update inventory levels based on the shipment;
7 **if** $\exists$ *a disaster in time period* t **then**
8 Solve the "Model 1–Allocation of HOs' own stocks";
  Output: $X^b_{stac}, X^u_{stac}, I^b_{sta}, I^u_{sta}, U_{stc}, \delta_{stac}$;
9 Update HOs' inventory levels depending on output;
10 **if** $\exists$ *at least one country with unsatisfied demand and at least one HO with excess unbranded stock* **then**
11 Solve the "Model 2–Allocation of shareable stocks";
  Output: $Y_{staác}, W^u_{sta}, V_{stc}$;
12 Update HOs' inventory levels depending on output;
13 Calculate network response time, network fill rate, response time for each country, and fill rate for each country;
14 Open an order from the supplier, which arrives after $\overline{\tau}^r$;
15 Calculate the inventory leftover ratio at the regional warehouse (network) and for each HO ;
16 Calculate KPIs based on the aforementioned metrics in *Lines 13 and 15* for each $R > 0\%$

calculate the expected relative differences for the aforementioned three metrics between each unbranded stock ratio ($R > 0\%$) and the base case ($R = 0\%$), denoted as $\mathbf{E}(\Delta\overline{\psi}_{R\to 0\%})$, $\mathbf{E}(\Delta\overline{\phi}_{R\to 0\%})$-, $\mathbf{E}(\Delta\bar{\iota}_{R\to 0\%})$, which are referred to as KPI_1, KPI_2, and KPI_3, respectively. Given the occurrence probability of each scenario ($\overline{p}_s$), we calculate KPI_1, KPI_2, and KPI_3 as follows:

$$\text{KPI}_1: \quad \mathbf{E}(\Delta\overline{\psi}_{R\to 0\%}) = \sum_{s\in\mathcal{S}} \overline{p}_s \left(\sum_{t\in\Gamma_s} (\psi_{stR} - \psi_{st0\%})/\psi_{st0\%} \right) /|\Gamma_s| \qquad \forall R > 0\%, \tag{21}$$

$$\text{KPI}_2: \quad \mathbf{E}(\Delta\overline{\phi}_{R\to 0\%}) = \sum_{s\in\mathcal{S}} \overline{p}_s \left(\sum_{t\in\Gamma_s} (\phi_{stR} - \phi_{st0\%})/\phi_{st0\%} \right) /|\Gamma_s| \qquad \forall R > 0\%, \tag{22}$$

$$\text{KPI}_3: \quad \mathbf{E}(\Delta\bar{\iota}_{R\to 0\%}) = \sum_{s\in\mathcal{S}} \overline{p}_s \left(\iota_{sR} - \iota_{s0\%} \right)/\iota_{s0\%} \qquad \forall R > 0\%. \tag{23}$$

When comparing results across different R values to the base case ($R = 0$), we calculate the nominal difference for events where the metric value in the base case solution is zero, instead of computing the relative difference. This approach is essential to avoid division by zero, which could lead to undefined values and inaccurately suggest infinite savings. As a

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result, our approach may underestimate the observed savings in our numerical results.

5 | CASE STUDY

We implement the proposed approach on a case study using real data. We describe our data set in Section 5.1 and present our analysis and results in Section 5.2.

5.1 | Data set

We have compiled a detailed data set on disaster relief operations in the Caribbean by processing information from ESUPS, HO websites, and the UNHRD portal. Table D1 in Online Appendix D summarizes our data sources and main assumptions. Below, we outline the data set's key features.

Disaster region and scenarios: We focus on hurricane preparedness in the Caribbean region, encompassing 18 vulnerable countries during the Atlantic hurricane season from June 1 to November 30 (NOAA, 2023): Anguilla (AIA), Antigua and Barbuda (ATG), Bahamas (BHS), Belize (BLZ), Bermuda (BMU), Barbados (BRB), British Virgin Islands (BVI), Cayman Islands (CYM), Dominica (DMA), Grenada (GRD), Haiti (HTI), Jamaica (JAM), Saint Kitts and Nevis (KNA), Saint Lucia (LCA), Montserrat (MST), Turks and Caicos Islands (TCA), Trinidad and Tobago (TTO), and Saint Vincent and the Grenadines (VCT).

We adopted hurricane scenarios from Balcik et al. (2019), representing each hurricane season divided into 16 two-week periods. An example scenario is shown in Figure 2. Furthermore, while Balcik et al. (2019) categorize hurricanes into three levels (*mild* for H2 or lower, *strong* for H3, and *very strong* for H4 and H5), our study focuses on H3, H4, and H5 hurricanes, as milder disasters often have localized relief needs.

Our data set comprises 268 hurricane seasons, 494 disaster periods, and 852 disaster-country combinations after excluding mild disasters. Of these, 280 were single-country events, while 214 affected two or more countries. In Online Appendix D Figure D1, we illustrate our region of focus and the distribution of events across countries.

Relief items. Our study focuses on tarpaulins as a representative relief item, aligning with ESUPS's guidance and historical dispatch data from HOs at UNHRD Panama and The International Federation of Red Cross and Red Crescent Societies (IFRC). Tarpaulins are among the frequently dispatched items, including hygiene kits, blankets, jerrycans, and so forth, which have high inventory levels. To adapt the demand values from Balcik et al. (2019) to our setting, we double the demand values for family kits because each kit contains two tarpaulins. In addition, we adjust the demand values from the Balcik et al. (2019) data set by assuming that 20% of the demand after a severe disaster is supplied by the regional warehouse, with the remaining sourced locally.

HOs and inventory levels. We consider 19 HOs with prepositioned stocks in a regional warehouse, such as UNHRD's regional warehouse in Panama serving the Caribbean region. The response regions of the HOs are specified based on their country office availability in the Caribbean countries obtained from ESUPS and the web pages of each HO. We categorize HOs into *large* and *medium* sizes, with seven large HOs and 12 medium HOs in our data set. This categorization enables us to analyze the effects of different settings, such as various unbranded stock rates, across different HO sizes. Similar-size HOs have the same initial inventory levels. The average number of countries that a large HO can respond to (about 14 countries) is significantly greater than that of a medium HO (three countries). The response matrix, along with HOs' sizes, is presented in Online Appendix D, Table D2.

The specific inventory levels of HOs are not directly available. To determine the initial inventory level of each HO, we allocate a total initial inventory of 10,000 units for the warehouse, corresponding to the 60th quantile of demands during disaster periods in the Caribbean region. Based on UNHRD data on dispatched stocks, we computed a scale factor representing the comparative size between large and medium HOs, set at three. This results in initial inventory levels of 904 units for large HOs and 308 units for medium HOs. Additional analyses for different inventory levels are presented by modifying the base scale factor (see Online Appendix E.6).

Unbranded stock rate (R). In our case analysis, we consider five unbranded stock rates: $R \in \{0\%, 25\%, 50\%, 75\%, 100\%\}$ to facilitate easy communication of the results with HOs. We also explore our setting with

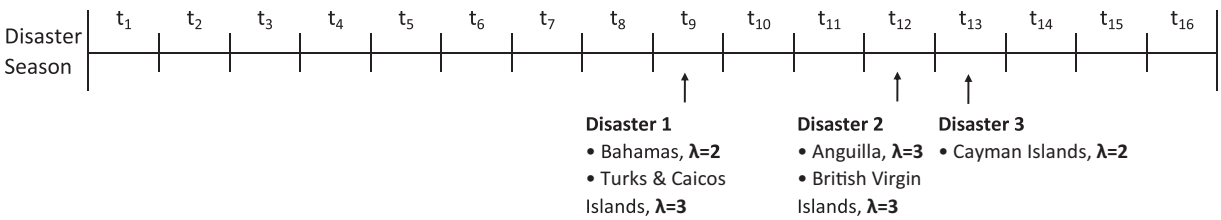


FIGURE 2 An example of planning horizon and scenario adapted from Balcik et al. (2019).

Note: An example scenario is shown with disasters occurring at $t = 9$, $t = 12$, and $t = 13$. For instance, at $t = 9$, a hurricane affects Bahamas (BH) and Turks and Caicos Islands (TCA) with severity levels $\lambda = 2$ and $\lambda = 3$, respectively.

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increased granularity in R values (increments of 5% between 0% and 100%) in Online Appendix E.9, where our insights remain consistent. As explained before, $R = 0\%$ represents the base case where HOs keep all their stocks in branded form, while $R > 0\%$ represents varying degrees of postponement. For example, $R = 25\%$ implies that the HOs keep 25% of the initial inventory level in unbranded form. As suggested by ESUPS, in our *base setting*, we assume each HO keeps the same proportion of unbranded stock (R) at the beginning of each scenario, simplifying the implementation and analysis.

Delivery and replenishment lead times. Delivery time estimates are obtained from different HOs affiliated with ESUPS (see Online Appendix D, Table D1). We set delivery times of branded ($\bar{\tau}^b$), unbranded ($\bar{\tau}^u$), and shared ($\bar{\tau}^s$) stocks from the regional warehouse to countries via air to three, four (including an extra day for branding), and five (including an extra day for sharing process) days, respectively. Unsatisfied demand met by the supplier has a delivery time ($\bar{\tau}^p$) of 14 days. Replenishment lead times from suppliers ($\bar{\tau}^r$) range from 4 to 12 weeks in the data, so we set it as 28 days in our model (equivalent to two time periods). In our analysis, we test for the effects of varying branding times (see Online Appendix E.2).

Next, we present our results illustrating the performance effects of the proposed strategies, along with in-depth analyses explaining the effects of various factors on performance.

5.2 | Case analysis and results

In this section, we present the results of our numerical analysis on a case study. While our analyses demonstrate the effectiveness of the proposed approach within a single case study, we provide generalizable insights regarding the potential savings and limitations of these strategies on system performance across different scenarios and sensitivity analyses.

Our results are based on the Monte Carlo simulation algorithm explained in Section 4.3, which incorporates the two-phase inventory allocation models in Section 4.2. As outlined in Section 4.2, we conducted tests on the variants our inventory allocation model, exploring different objective functions and an integrated framework as part of our preliminary analysis (see Online Appendices E.5 and E.7, respectively). While the results from alternatives are similar, we opted for the proposed version due to its computational efficiency.

In Section 5.2.1, we compare different unbranded stock rates ($R > 0\%$) with the base case ($R = 0\%$), evaluating the effects of postponement and stock sharing on network performance. In Section 5.2.2, we explain the observed postponement effects on KPIs and country-level performance. In Section 5.2.3, we compare the base setting where all HOs have identical R values with a modified setting where only medium HOs keep unbranded stocks and large HOs keep only branded stocks.

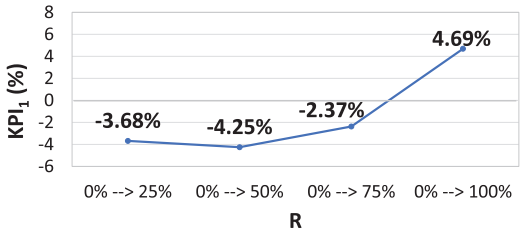


FIGURE 3 KPI_1 values for the base setting.

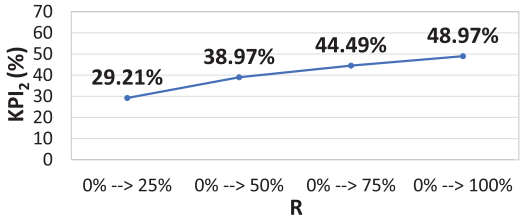


FIGURE 4 KPI_2 values for the base setting.

5.2.1 | Effects of postponement on KPIs

In this section, we compare network-related KPIs, which are based on fill rate, response time, and inventory leftover ratio, across different unbranded rates R.

(a) Response time and fill rate. Figure 3 shows the expected relative differences in network response time between four unbranded rates and the base case (KPI_1). Overall, the proposed strategy leads to lower network response times, with an exception observed at $R = 100\%$.

Figure 4 shows the impact of the proposed strategy on the expected relative differences in network fill rate between four unbranded rates and the base case (KPI_2). The network fill rate shows improvement for all R values compared to the base case, with KPI_2 increasing as the R value rises. Evaluating KPI_1 and KPI_2 together can guide the selection of a suitable R value that enhances fill rate without compromising response time. For instance, $R = 75$ appears favorable in our case. In Section 5.2.2, we provide an explanation for the behavior observed in KPI_1 and KPI_2 values with increasing R.

In addition, in Online Appendix E.8, we investigate the effects of postponement and stock-sharing strategies on another KPI based on unsatisfied demand ratio (i.e., 1-fill rate) for each disaster severity level, referred to as KPI_2^λ. This analysis is conducted separately for severity levels ($\lambda = 2$ and $\lambda = 3$), showing that KPI_2^λ declines as R increases, with a more pronounced decline rate for severe disasters compared to very severe ones (see Online Appendix E.8 for the details of this analysis).

(b) Inventory leftover ratio. Figure 5 displays the relative differences in network inventory leftover ratio between four unbranded rates and the base case (KPI_3). Higher R values lead to improved inventory utilization for the regional warehouse. Figure 5 also shows KPI_3 values for large (KPI_3^L) and medium HOs (KPI_3^M), indicating a greater improvement in

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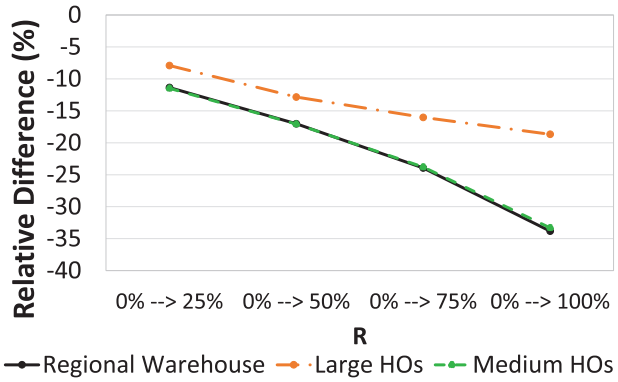


FIGURE 5 KPI_3 and $KPI_3^{L,M}$ values for the base setting.

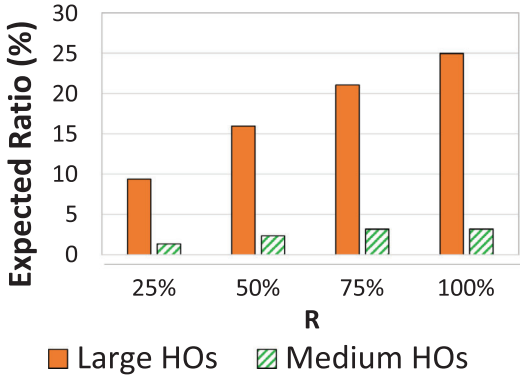


FIGURE 6 Expected ratio of the humanitarian organizations (HOs)' borrowed stock to total delivered stock for each R value.

inventory utilization for medium HOs compared to large HOs with increasing R.

Figure 6 presents the expected ratios of borrowed stock to total delivered stock for large and medium HOs separately. Large HOs exhibit a significantly higher expected borrowed stock ratio than medium HOs under all R values, reflecting different borrowing/sharing behaviors. Specifically, large HOs tend to borrow more due to their larger response region, while medium HOs share their stocks more often.

Our results highlight the important impact of the R value on system performance across all KPIs. Motivated by our observations regarding response time deterioration with high R values and different sharing behaviors among organizations of different sizes, we analyze a new setting in Section 5.2.3 where all large HOs keep only branded stock and medium HOs keep some unbranded stock. While our practitioner collaborators advocate for equal R values across all HOs initially, they also express interest in considering varied R values among HOs in later stages.

(c) Sensitivity analysis. We analyze how R's effects are influenced by various parameters and modeling assumptions, testing different lead times, objective functions, and initial inventory levels of HOs.

First, we examine the impact of varying lead times for branded stock (i.e., different branding times) on response time, and find that each additional day of branding time worsens KPI_1 (see Online Appendix E.2). The proposed strategy decreases the network response time, on average, up to a specific R value between $R = 75\%$ and $R = 100\%$—referred to as the *break-even* point. Our analyses in Online Appendix E.2 show that increasing branding time reduces this break-even point. For instance, a one-day increase in branding time shifts the worsening of KPI_1 to an R value between $R = 50\%$ and $R = 75\%$.

Second, in our inventory allocation models, we explore an alternative objective function that minimizes the maximum of each country's unsatisfied demand ratio (i.e., 1–fill rate) weighted by disaster severity, rather than minimizing the total weighted unsatisfied demand. This objective function ensures each disaster-affected country receives a proportion of the total stock from responding HOs, promoting equitable inventory allocation among affected areas. This alternative objective function, commonly used in humanitarian logistics literature (e.g., Tofighi et al., 2016), shows minimal differences in network-related KPIs compared to the main objective (see Online Appendix E.5). Similarly, country-specific KPI patterns remain consistent, with only slight variations observed as we increase R values.

Finally, we analyze the system's performance considering different inventory levels for HOs (see Online Appendix E.6). Specifically, we explore scenarios where large HOs maintain larger inventories while medium HOs retain smaller amounts, while the total inventory remains constant. Notably, this approach reduces collaboration benefits, as medium HOs, with fewer countries in their response region, tend to share more. However, irrespective of inventory levels, strategies involving postponement and stock sharing consistently yield favorable impacts on all KPIs compared to the base case ($R = 0\%$). In summary, our analysis underscores the value of increasing shareable stocks by efficiently leveraging inventories from HOs with narrower response regions.

Our results consistently demonstrate expected relative savings from implementing the proposed strategies, emphasizing the benefits regardless of potential variations in magnitude. Next, we conduct a detailed examination of the solutions to provide insights into the underlying reasons for the observed savings.

5.2.2 | Insights on savings in fill rate and response time

Postponement and stock-sharing strategies, as demonstrated in Section 5.2.1, consistently yield savings across all KPIs. However, specific trends and patterns emerge. While one might anticipate increased benefits with higher R values due to enhanced sharing, results show that beyond a certain threshold, KPI_1 values increase, indicating response times. Simultaneously, the rate of improvement in KPI_2 diminishes, suggesting reduced improvements in fill rate (see Figures 3 and 4). These trends are observed across different settings, including varied lead times, alternative objective

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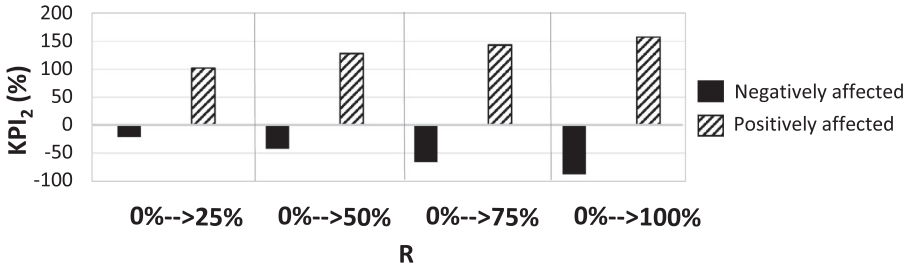


FIGURE 7 KPI_2 values for negatively and positively affected periods.

functions, and diverse initial HO inventory levels (see Online Appendices E.2, E.5, and E.6).

Next, we explain the underlying reasons behind these trends under the base case and examine the conditions in which savings are positive or negative. We then analyze which countries benefit more from the proposed strategies in terms of fill rate and response time.

(a) What are the factors affecting values of KPI_1 and KPI_2? We investigate why the rate of increase in KPI_2 decreases as R increases, and explore the shift in KPI_1's trend from decreasing to increasing after a certain point (the U-shaped relationship observed in Figure 3).

As discussed in Section 5.2.1, while KPI_2 improves with increasing R, the rate of improvement in KPI_2 diminishes (see Figure 4). To understand this effect, we categorize disaster-affected time periods into *negatively affected*, *positively affected*, and *unaffected* periods. These represent disaster-affected time periods where fill rate (i.e., KPI_2) decreases, increases, or remains unchanged when $R > 0\%$, compared to when $R = 0\%$. The frequencies of these categories average 5.61%, 41.60%, and 52.78% across $R > 0\%$ values (see Online Appendix E.1). We focus on negatively and positively affected periods separately by computing KPI_2 values, depicted in Figure 7. As R increases, the change in KPI_2 values is more pronounced for negatively affected periods compared to positively affected periods. This observation indicates diminishing returns of the R value, as a higher R is more likely to result in significantly lower KPI_2 values in certain periods.

We next explore why KPI_2 is affected adversely by increasing R in *some* periods. When total demand in a disaster period mobilizes all warehouse stocks, increased unbranded stocks prompt more extensive sharing among HOs to meet this demand. This increased sharing can significantly improve KPI_2 for that period but may deplete inventory for subsequent periods until restocking occurs. If another disaster occurs before inventories are replenished, HOs may be unable to ship necessary amounts, resulting in significant decreases in KPI_2.

Next, we analyze the setback in KPI_1 under high R values, despite the consistent improvement in KPI_2. We observe that the effect of varying R values on KPI_1 depends on changes in KPI_2. We observe that, as R increases, (i) if KPI_2 also increases, then KPI_1 decreases; however, (ii) if KPI_2 decreases or does not change, then KPI_1 increases. Next, we elaborate on these two effects. First, in 41.60% (on average) of time periods, KPI_2 increases when R increases, resulting in less stock from the supplier, which decreases KPI_1 in these periods. This arises because the supplier's delivery time is significantly longer than that of borrowed stock. Second, in over half of the time periods, the fill rate does not change (i.e., KPI_2 is zero) because the HOs do not need sharing to meet the demand in these periods. That is, they solely mobilize their own branded and unbranded stocks. The increased R value leads to shipping more of their own unbranded stock *after branding*, which increases delivery time of unbranded stock compared to branded stock and, consequently, KPI_1 in these periods. In the remaining time periods, KPI_2 decreases when R increases. Decreasing values of KPI_2 imply larger amounts of stocks shipped from the supplier, increasing KPI_1 in these periods. However, this impact is relatively minor due to the rare occurrence of such time periods.

Combining the above two opposing effects of increasing R on KPI_1, we explain the U-shaped relationship in Figure 3 as follows. Initially, as R increases from 0 to small levels (up to 50%), the factors diminishing KPI_1 outweigh those increasing it, resulting in an overall decline in KPI_1. However, as R surpasses 50%, the factors increasing KPI_1 outweigh the opposing factors, leading to an overall increase in KPI_1.

These observations suggest that reserving some unbranded stocks or limiting stock sharing among certain HOs could be beneficial. In addition, faster stock replenishment from suppliers may significantly improve KPI_2 performance, safeguarding against low values that can occur after severe disasters before inventories are replenished. Implementing strategies where only specific HOs retain unbranded stocks can also eliminate additional branding times associated with mobilizing unbranded stocks, potentially improving KPI_1. We explore the effects of such strategies in Section 5.2.3 using our framework.

(b) Which countries benefit more? The countries in the Caribbean region exhibit varying characteristics, including the number of responding HOs, severity of disasters, and demand profiles. To understand how the benefits of proposed strategies vary across different affected countries, we calculate the expected values of response time and expected fill rate of each country denoted by $\mathbf{E}(\overline{\Omega}_{cR})$ and $\mathbf{E}(\overline{\kappa}_{cR})$, and referred to as KPI_4 and KPI_5, respectively.

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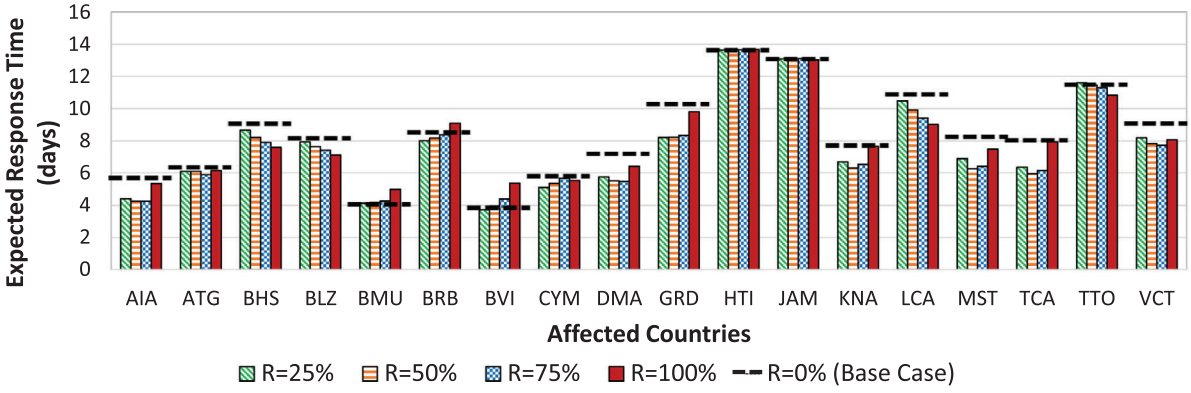


FIGURE 8 KPI_4 values.

The response time (respectively, fill rate) of a country c for each $t \in \mathcal{T}$ in each $s \in \mathcal{S}$ for each $R = [0\%, 100\%]$ is represented by Ω_{stcR} (respectively, κ_{stcR}). Given the average response time and fill rate of each country in each scenario, calculated by Equations (26) and (27), respectively, $\mathbf{E}(\overline{\Omega}_{cR})$ and $\mathbf{E}(\overline{\kappa}_{cR})$ are computed as follows:

$$\text{KPI}_4: \quad \mathbf{E}(\overline{\Omega}_{cR}) = \sum_{s\in\mathcal{S}} \left(\overline{p}_s \sum_{t\in\mathcal{T}} \Omega_{stcR} / |\mathrm{Y}_{sc}| \right) \Big/ \sum_{s\in\zeta_c} \overline{p}_s \qquad \forall R \geq 0\%, c \in \mathcal{C}, \tag{24}$$

$$\text{KPI}_5: \quad \mathbf{E}(\overline{\kappa}_{cR}) = \sum_{s\in\mathcal{S}} \left(\overline{p}_s \sum_{t\in\mathcal{T}} \kappa_{stcR} / |\mathrm{Y}_{sc}| \right) \Big/ \sum_{s\in\zeta_c} \overline{p}_s \qquad \forall R \geq 0\%, c \in \mathcal{C}, x \tag{25}$$

$$\Omega_{stcR} = \left(\overline{\tau}^u \overline{X}^u_{stc} + \overline{\tau}^b \overline{X}^b_{stc} + \overline{\tau}^s \overline{Y}_{stc} + \overline{\tau}^p \overline{U}_{stc} \right) \Big/ \overline{d}_{stc} \qquad \forall R \geq 0\%, s \in \mathcal{S}, t \in \mathcal{T}, c \in \mathcal{C}, \tag{26}$$

$$\kappa_{stcR} = \left(\overline{X}^u_{stc} + \overline{X}^b_{stc} + \overline{Y}_{stc} \right) \Big/ \overline{d}_{stc} \qquad \forall R \geq 0\%, s \in \mathcal{S}, t \in \mathcal{T}, c \in \mathcal{C}. \tag{27}$$

Figures 8 and 9 show the expected response times (KPI_4) and fill rates (KPI_5) for each country under different R values. Among the 18 countries analyzed, three consistently show improvements in KPI_4 (response time) and five in KPI_5 (fill rate) across all $R > 0\%$ values compared to the base case. Furthermore, 13 (respectively, 15) countries benefit from the postponement strategy for R values up to 75%. Overall, most countries experience substantial benefits from these strategies.

Two key factors influencing the impact of postponement on KPI_4 and KPI_5 are the number of responding HOs and the severity of disasters in each country (see Table E1 in Online Appendix E.4 for a summary of these characteristics). Specifically, countries with relatively few responding HOs and high disaster severity typically benefit from postponement due to limited ability to satisfy demand without stock sharing.

For countries with lower disaster severity, the impact of postponement and stock-sharing strategies can be mixed. If other countries' disasters consume most available stocks, there can be a negative impact. However, if some unbranded stocks remain in responding HOs from other countries, the focal country can benefit from stock-sharing opportunities.

If both the number of responding HOs and the severity of disasters are relatively high in a country, that country is susceptible to the negative impacts of postponement and stock sharing. This occurs because the responding HOs in such a country may share their unbranded stock with HOs that responded to previous disasters in other countries, leading to reduced stock levels for potential disasters in the current period. Without stock sharing, a country with many responding HOs and high disaster severity has an advantage over others.

These findings, along with those in Section 5.2.1 regarding inventory utilization, motivate us to analyze a new setting where some HOs retain all stocks in branded form, preventing their complete depletion through sharing, presented next.

5.2.3 | Analysis of the modified setting: Different $R\%$ across HOs

Motivated by our observations on postponement effects, we consider a modified setting where only medium HOs keep unbranded stocks for sharing when needed. Here, large HOs keep only branded stocks and do not share, but can borrow unbranded stocks from medium HOs if necessary. This alternative policy is based on three observations: (i) depleting all stocks in a period can harm performance if subsequent disasters occur soon after, (ii) borrowing tendencies are more common among large HOs, while sharing tendencies are more common among medium HOs, and (iii) increasing unbranded stocks for large HOs can negatively impact network response time due to longer branding times.

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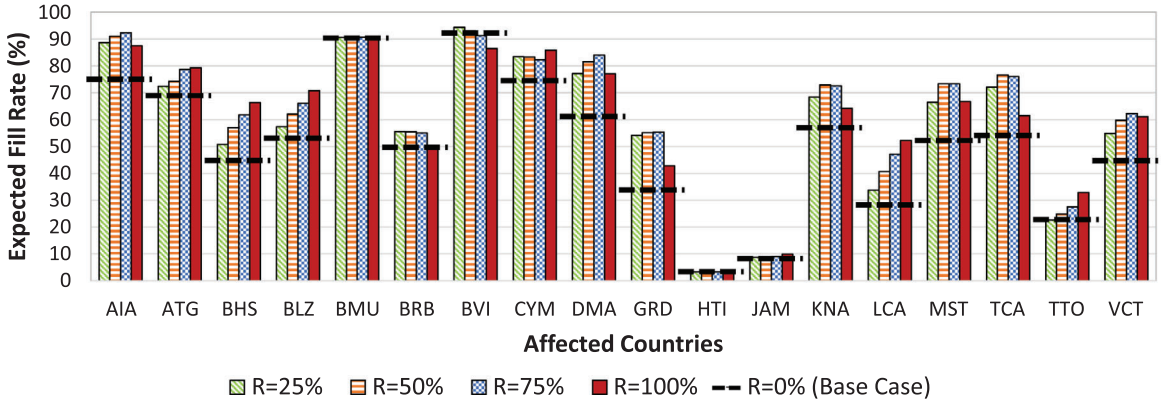


FIGURE 9 KPI_5 values.

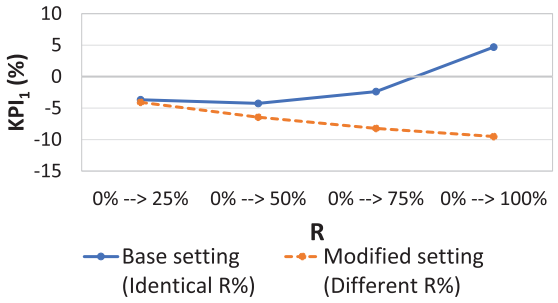


FIGURE 10 KPI_1 values for base and modified settings.

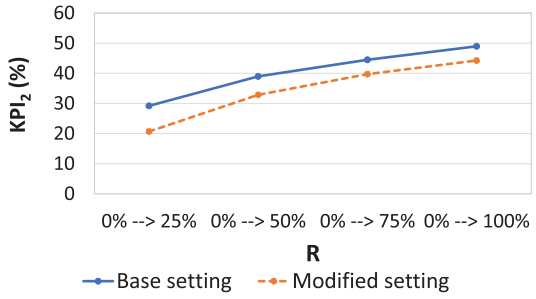


FIGURE 11 KPI_2 values for base and modified settings.

We compare the relative difference in network response time (KPI_1) under the base and modified settings in Figure 10. Under the modified setting with $R = \{25\%, 50\%, 75\%, 100\%\}$, KPI_1 values are 4.08%, 6.44%, 8.22%, 9.51%, respectively. This shows an improvement in response time for all $R\%$ values compared to the base setting. We can explain this decrease with the help of Figure 12a, which illustrates that the ratio of HOs' own unbranded delivered stocks to total delivered stocks is smaller in the modified setting, with large HOs keeping all stocks branded. Consequently, the time spent on branding decreases on average.

Recall that in the base setting where postponement applies to all HO sizes, the network fill rate (KPI_2) improves under all $R\%$. Figure 11 compares the expected relative difference in the network fill rate (KPI_2) between the base and modified settings. Although the magnitude of improvements in KPI_2 slightly decreases when only medium HOs can share stocks due to reduced total shareable stocks, Figure 12b demonstrates the relationship between total borrowed stock and KPI_2. Nevertheless, the benefits obtained under the modified setting justify the implementation of the postponement practice.

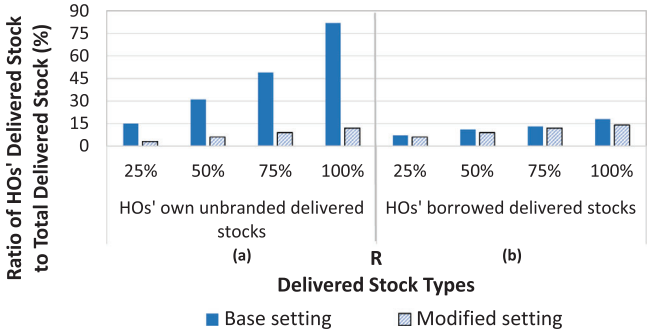


FIGURE 12 Ratio of humanitarian organizations (HOs)' (*own unbranded* in the left panel/*borrowed* in the right panel) delivered stocks to total delivered stocks for base and modified settings.

In the modified setting, when KPI_1 and KPI_2 are jointly considered, adopting a 100% postponement policy for medium HOs is favorable. This policy performs similarly to maintaining 75% unbranded stocks for all HOs in terms of KPI_2, but significantly surpasses the "75% postponement for all HOs" policy in improvements in KPI_1 (9.51% vs. 2.37%).

In addition, we compare the results of the base and the modified settings in terms of inventory leftover ratio (KPI_3) (see Online Appendix E.3) and find that large HOs exhibit lower inventory utilization while medium HOs show higher utilization, with overall network-level utilization remaining consistent. Finally, our analysis of the modified setting on country-level response time and fill rate (KPI_4 and KPI_5) indicates improved performance across most countries (see Online Appendix E.4).

In summary, customizing the postponement rate for different types of HOs can enhance the impact of proposed

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strategies. However, our partner ESUPS prefers delaying this customized policy implementation to later stages, focusing initially on presenting postponement benefits to the humanitarian community with a simple approach. Nonetheless, our insights and results exploring different settings can guide practitioners in deploying these strategies effectively.

6 | DISCUSSION AND CONCLUSION

This article investigates the impact of postponement and stock sharing on prepositioning efficiency in a regional humanitarian warehouse where multiple HOs keep stock for relief supplies. Although postponement is well-studied in supply chain management, its application in humanitarian operations remains underexplored. We develop an inventory management system integrating postponement and stock-sharing strategies to assess improvements in important performance metrics such as fill rate, response time, and inventory utilization. Our simulation algorithm, which incorporates this inventory management system, is used to evaluate the effects of different unbranded stock levels on system performance. Through extensive numerical analysis, we develop important managerial insights for informed decision making (such as choosing the right level of unbranded stock rate based on the demonstrated implications of each level on KPIs) and effective implementation of the postponement and stock-sharing strategies.

Our efficient simulation-based framework provides effective and intuitive solutions, which are shared with the humanitarian community. Results from practitioner workshops with ESUPS and partner HOs have received significant interest, highlighting the potential value of our findings for broader dissemination within the practitioner community.

Key findings and remarks from this study are summarized below:

- Postponement combined with stock sharing significantly enhances all relevant KPIs across various scenarios, which indicates that a shift in prepositioning practices within the humanitarian community can substantially improve the effectiveness and efficiency of prepositioning. Specifically, we propose discontinuing the practice of permanently branding items before disasters. Instead, we recommend procuring standard (unbranded) items and applying stickers after a disaster if necessary, or sharing them with other HOs.
- While our study focuses on a specific case study, it yields generalizable insights for implementation and policy development. For instance, we discover a U-shaped relationship between response time and unbranded stock rate, where fill rate and inventory utilization consistently improve as the unbranded stock rate increases. This pattern emerges when HOs' own unbranded stocks is sufficient to fully satisfy the demand from a disaster event, eliminating the need for stock sharing and thus increasing response time due to branding. Moreover, we show that in scenarios with consecutive disasters, maintaining high unbranded stock rates may deplete available stocks in the first disaster, making countries more vulnerable to subsequent impacts. This effect leads to diminishing fill rate improvements and increase response time. We show that a modified setting where large HOs exclusively retain branded stocks can be a remedy to this occurrence, preventing complete depletion during initial disasters and improve response time. Finally, our results highlight the importance of establishing a supplier base that can provide quick replenishment of stocks during and after response, elevating the benefits of the proposed strategies on expected response time.
- Our analysis show that benefits of the postponement strategy may vary based on disaster scenarios (e.g., timing and demands in each country), HOs' response regions, and inventory levels. Therefore, careful analysis is crucial for each unique humanitarian setting. Our proposed algorithm facilitates efficient testing of various scenarios and parameters, allowing decision makers (e.g., HOs, umbrella organizations) to tailor unbranded stock rates to their specific context and perform relevant analyses. For example, in our case, ESUPS advocates a solution with uniform (i.e., 75%) unbranded stock rate across all HOs for ease of communication and transition to the proposed system at the UNHRD warehouse.

Implementing our proposed system requires an information-sharing infrastructure among HOs to identify members with unbranded stocks and facilitate loaning and borrowing processes. Enhancing the existing UNHRD portal, which currently provides visibility of available stocks, can support the implementation of this system. In addition, the development of information systems to support coordination and collaboration mechanisms is a current priority within the humanitarian sector. For instance, initiatives like the STOCKHOLM platform developed by ESUPS and supported by USAID (ESUPS, 2024) demonstrate the feasibility of establishing the necessary information infrastructure.

Currently, HOs may lack strong incentives to keep unbranded stocks individually and share them when necessary, which contributes to a limited culture of stock sharing. Our discussions with ESUPS executives underscore the need for increased awareness about coordination and research demonstrating the added value of collaboration among HOs. Our article highlights the benefits of postponing branding and engaging in collaborative unbranded stock sharing on efficiency and effectiveness of prepositioning. Through empirical evidence, we aim to influence HOs, donors, and umbrella organizations such as UNHRD to adopt these strategies. Once these stakeholders recognize the merits of our approach, they can establish incentive structures to promote broader adoption among HOs. Institutional donors (including governments), leveraging their influence through donation conditions, can encourage participation by linking funding to collaborative system involvement. Similarly, UNHRD can incentivize participation by conditioning its free warehouse storage services on joining the collaborative network. These

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measures can also mitigate the risk of past free-riding behavior observed in the UNHRD system (see, e.g., Toyasaki et al., 2017).

Given that postponement is an underexplored area in humanitarian systems, several future research directions exist. First, our approach can be adopted to examine the impact of postponement and stock-sharing strategies in other regional humanitarian warehouses, exploring various settings with different disaster susceptibility and considering alternative inventory management systems. For example, in our case study, we generated disaster scenarios based on seasonal Atlantic hurricanes affecting the Caribbean region from June 1 to November 30 (NOAA, 2023). Although this seasonality enables HOs to replenish their prepositioned inventory each season, strategies and methods for nonseasonal or sudden-onset disasters like earthquakes require further exploration. Second, given the increased attention on stock-sharing practices and the use of white stocks in UNHRD warehouses with growing member HOs (e.g., Schulz, 2009), exploring systems and method that address managing both types of stocks would be valuable. Finally, while our simulation approach can efficiently determine promising unbranded stock rates experimentally, studying optimization models to determine the optimal unbranded rates can establish benchmark values.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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