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Disaster Relief Inventory Management: Horizontal Cooperation between Humanitarian Organizations

Abstract

Cooperation among humanitarian organizations has attracted increasing attention to enhance effectiveness and efficiency of relief supply chains. Our research focuses on horizontal cooperation in inventory management which is currently implemented in the United Nations Humanitarian Response Depot (UNHRD) network. The present work follows a two-step research approach, which involves collection of empirical data and quantitative modeling to examine and overcome the coordination challenges of the network. Our interviews with members of the network identified several managerial issues for sustainable cooperative inventory management that the UNHRD network pursues. Using a newsvendor model in the context of non-cooperative game theory, our research has explored member humanitarian organizations' incentive of joining the network, a coordination mechanism which achieves system optimality, and impacts of members' decisions about stock rationing. Our results indicate that behaviors of member HOs do not necessarily align with the UNHRD's expectation. Our results suggest that for system optimality a system coordinator should carefully assess the circumstances, including demand coefficient and stock rationing. Our research also proposes a policy priority for the first-best system optimal inventory management.

Key Words: humanitarian operations, inventory sharing and rationing, pre-positioned stock management, newsvendor model, non-cooperative game theory

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1. Introduction

The increasing number and complexity of global disasters are calling for more efficient and effective logistics operations. Humanitarian and disaster operations rely heavily on logistics in uncertain, risky, and urgent contexts, which differ from commercial logistics (Gatignon et al., 2010; Kovács and Spens, 2007). In their attempt to mitigate these challenges to enhance the resilience of disaster relief operations, humanitarian organizations (HOs) are forming structures such as coordination bodies (Zhao et al., 2008). Most humanitarian logistics coordination mechanisms observed in reality take a horizontal cooperation style, which involves an umbrella agency acting as a logistics infrastructure provider on a non-profit basis (Balcik et al., 2010). Horizontal cooperation among HOs can be observed in fundraising, procurement, transportation, and stock storage. Current research on humanitarian and disaster logistics also acknowledges that horizontal cooperation among HOs could help enhance performances of relief supply chains (Van Wassenhove, 2006; Thomas and Kopczak, 2005; Schulz, 2009; Feng and Shanthinkumar, 2016).

However, research on horizontal cooperation in the disaster relief context is still in its infancy (Schulz and Blecken, 2010). This paper intends to address this research gap by focusing on horizontal logistics cooperation among HOs in inventory management, including lateral stock transshipment between HOs. This paper focuses on inventory management which is implemented in the United Nations Humanitarian Response Depot (UNHRD) network. The UNHRD managed by World Food Program (WFP) is a network of depots in strategic locations around the world which stores, manages and transports emergency relief items on behalf of HOs that are members of this network mainly free of charge. Unlike private sectors' horizontal cooperation in their stock management, humanitarian sectors' lateral stock transshipment is performed on a borrowing and loaning scheme without generating additional monetary transfer between HOs, that is, non-profitable stock transshipment. Little attention has been paid to explore lateral stock transshipment on a non-profit basis although many studies about the counterpart on a for-profit basis have been conducted. To gain insights regarding practical issues and empirical data, we conducted interviews with the UNHRD and seven member HOs as well as several non-member HOs before we develop analytical models.

Our interviews disclose perception gaps about the network operations between the UNHRD and HOs. Responding to the tight budget constraint, the UNHRD is seeking to minimize system-wide costs, which is referred to as *system optimality* in our paper. Currently, the UNHRD expects further growth of stock transshipment between member HOs. Although interviewed member HOs value services provided by the UNHRD network, the degrees of their involvement into the UNHRD network differ depending on member HOs because of several impediments, including long lead times and tendering processes as well as lack of traceability of the UNHRD. Some member HOs are considering leaving the network or significantly reducing stocks stored in warehouses of the UNHRD while exploiting benefits from the network. In our paper, a member HO which stores its stocks in a warehouse of the UNHRD and thus can loan them is referred to as a *fully-participating* member HO; and a member HO which does not store its stocks in a warehouse of the UNHRD and thus cannot loan them is referred to as a *partially-participating* member HO. To identify key factors that achieve system optimality of the UNHRD network, our research proposes introducing a *premium fee* for member HOs' usage of backups stocks. Our second interviews with the UNHRD also confirm potential applicability of the premium in the system. Based on results of our interviews, we develop quantitative models to answer the following research questions:

- What are the members' incentives to join the network?
- What are the effects of introducing the premium fee on member HOs? Can the premium be used as a coordination mechanism which achieves system optimality?
- What are the impacts of members' decisions about the ratio of stocks allocated between UNHRD's warehouses and members' own warehouses?

To answer these research questions, we have developed models under newsvendor settings with backup stocks and stock transshipment among UNHRD members in the context of non-cooperative game theory. Following insights of a series of interviews, our models cover three options that member HOs face for managing their decentralized inventory systems: (1) being fully in the UNHRD network; (2) staying partially in the network; and (3) staying completely out of the network. As a benchmark setting, a model of a centrally coordinated system which achieves system optimality is also developed in this paper. Then, numerical simulations have been conducted to estimate the optimal expected inventory cost. Our analytical and numerical results indicate that a premium on usage of the UNHRD's backup stocks would allow the network to achieve system optimality. However, our results also suggest that prior to implementing the premium charge the UNHRD should resolve impediments which induce member HOs' partially-participating behavior if it pursues the first-best system optimality. Otherwise, partially-participating member HOs would enjoy a lower expected inventory cost than loaning member HOs after the premium charge is being implemented, which could increase the number of partially-participating member HOs and eventually may compromise the functioning of the stock transshipment. Developing an extended model with more than two member HOs, we have also confirmed that the general trend of the results are robust with respect to the number of HOs.

Following the introduction, section 2 describes a brief literature review related to our research. In section 3, the structure and services of the UNHRD network as well as major findings from our interviews are presented. Assuming that two HOs are in the network, section 4 describes our inventory models and analytical results. Following a setting with two HOs in the network, section 5 explains the results of our numerical simulations as well as data used. To verify the robustness of results in the previous sections with respect to the number of member HOs, section 6 explains results of numerical simulations based on an extended model with more than two member HOs. Section 7 presents conclusions which focus on managerial recommendations and future research avenues of this research.

2. Literature review

The research presented in this paper considers horizontal cooperation and inventory management of HOs. This section reviews the previous literature in these two areas and highlights novelties of our models. The terms cooperation and coordination have many definitions in the literature in the area of logistics (Cruijssen et al., 2007; Schulz and Blecken, 2010; Ergun et al., 2014). In previous literature (Minear, 2002; Stephenson Jr, 2005; Coles et al., 2012), the terms coordination, collaboration, and partnerships are often used interchangeably. In our paper, we use the term *horizontal cooperation* to specify the interactive and interdependent activities between member HOs of the UNHRD network, including stock transshipment. However, interdependent activities (e.g. stock transshipment) between member HOs may not always align with the UNHRD's goals, including system optimality, because these goals are not always member HOs' primary interests. In our paper, we use the word "coordination" as UNHRD's management activities to facilitate members' horizontal cooperation and to match individual member HO's cooperation activities with system optimality. In this light, the meaning of "coordination" in our paper is similar to the meaning of *coordination mechanism* defined by Xu and Beamon (2006, p.4) as " a set of methods to manage interdependence between organization."

Much of the work in horizontal cooperation between HOs is descriptive and highlights types of organizations which coordinate actions in practice (Minear, 2002; Stephenson Jr, 2005; Schulz, 2009; Schulz and Blecken, 2010). Although this area attracts strong interests from academics and practitioners, the related quantitative analysis is rare, including partnership formation (Coles and Zhuang, 2011), information sharing (Wakolbinger et al., 2013), cooperative fundraising activities (Toyasaki and Wakolbinger, 2014) and cost allocation of information technology (Ergun et al., 2014). The present work analyzes horizontal cooperation in inventory management, which is observed in the UNHRD network, applying non-cooperative game theory.

Several papers in operations management literature (Anupindi et al., 2001; Rudi et al., 2001; Hu et al., 2007; Özen et al., 2008; Huang and Sošić, 2010) focus on systems similar to the UNHRD network where inventory sharing or lateral transshipments are possible. However, a few studies investigate inventory management in the context of humanitarian operations (Beamon and Kotleba, 2006a,b; Davis et al., 2013; Londree and Taskin, 2008; Manoj et al., 2016). Furthermore, to the best of our knowledge, no research quantitatively analyzes HOs' horizontal cooperation for inventory management, including lateral stock transshipment. Unlike existing models from commercial settings, our models take into account the following three aspects: (1) stock transshipment based on borrowing and loaning (2) inventory rationing decisions; and (3) a logistics service provider on a non-profit basis. The previous models from the commercial settings assume that stock transshipment is conducted based on players' profit motivation through transfer of a transshipment price. In our model stock transshipment is performed on a borrowing and loaning scheme which does not aim to generate additional monetary transfer. Here, penalty costs of leftover stocks are driving forces behind their stock transshipment. Our models also assume that member HOs loan their stocks whenever they are requested. This assumption can actually take into account HOs' altruistic reasons for loaning stocks, which are confirmed in our interviews. Some of the previous models (Anupindi et al., 2001; Granot and Sošič, 2003; Brandenburger and Stuart, 2007) assume allocation mechanism of profits and/or costs resulting from cooperation. They explore co-opetition circumstances of private companies' pooling inventory management. Their models describe excess profits resulting from players' cooperation applying cooperative game theory, in which players' cooperation is considered as a premise by assuming players' binding commitment through, for example, a legal system. In contrast, our models apply non-cooperative game theory to analyze players' cooperation behavior focusing on individual player's self-enforcing motivations. Furthermore, the previous models assume that all players fully participate in the system. Our models capture not only all players' full involvement, but also some players' partial involvement in the system, reflecting member HOs' inventory rationing decision observed in the UNHRD network.

Lastly, the relevant previous models (Anupindi et al., 2001; Rudi et al., 2001; Hu et al., 2007; Özen et al., 2008; Huang and Sošić, 2010), which explore lateral transshipment in decentralized systems, assume single echelon systems (Paterson et al., 2011). Our models consider a two-echelon system prepared by a logistics infrastructure provider, the UNHRD, on a non-profit basis: lateral transshipment between member HOs and backup stocks (i.e. emergency shipments from a different echelon) of the UNHRD. Stock management in two-echelon supply chains was discussed in the context of competition between suppliers and retailers (Cachon and Zipkin, 1999; Lee and Whang, 1999; Cachon, 2001; Chen et al., 2001) for profits. In this setting, no player behaves considering system optimality. In our setting, the upper stage (the UNHRD) acts as the logistics service provider for the humanitarian community on a non-profit basis (Schulz and Blecken, 2010). Our models intend to examine interactions between the UNHRD, which seeks to pursue system optimality, and member HOs which consider their own costs. Here, no competition caused by conflict of interests between the UNHRD and member HOs occurs. To our best knowledge, few models consider impacts of a non-profitable logistics service provider on lateral transshipment in decentralized systems. Like Rudi et al. (2001) and Hu et al. (2007), our models assumes that only residual inventory is transshipped, which is called pooling of residual (Özen et al., 2008). Unlike theirs, our models explore a premium for usage of backup stocks as a mechanism for system optimality.

3. Background information about the UNHRD network

This section explains information relevant to our research about the UNHRD network. First, the structure of the network and services that the UNHRD provides are explained. The explanation focuses on information relevant to our models although the services that the UNHRD provides cover many areas, including transportation, and provision of training facilities. Then, interview results which are directly related to assumptions of our models and numerical analysis are highlighted.

3.1 Structure and services of the UNHRD network

Table 1: The UNHRD's services relevant to stock management

Services	**Descriptions**
Storage	Member HOs can store as many items as they want for free of charge. There is no minimum required amount of storage.
Procurement	Member HOs bear procurement costs plus a management recovery cost of an additional 7%.
Stock transshipment (Stock swaps)	The UNHRD promotes the option of exchanging stocks between member HOs. Member HOs have the right to sell, only borrow or loan stocks. Real-time stock visibility is offered to all member HOs.
Backup stocks (White Stocks and Virtual Stocks)	"White Stocks" are suppliers' stocks stored, within the network premises, but not marked with a member's logo. "Virtual Stocks" refer to items which are positioned within suppliers' premises based on Long Term Agreements that the WFP has with suppliers. For backup stocks, payment does not become due until a member HO buys them.

The UNHRD network intends to deliver humanitarian relief items worldwide to point of entry within 24-48 hours after a disaster occurs. Currently, the UNHRD provides logistics services and comprehensive supply chain solutions for 78 partners including United Nations agencies, government and non-governmental organizations. The network has six depots which are strategically located in Accra (Ghana), Brindisi (Italy), Dubai (UAE), Kuala Lumpur (Malaysia), Panama City (Panama) and Las Palmas de Gran Canaria (Spain, operational from 2014). The network facilities and services enable partners to coordinate their efforts, prioritize dispatches to emergencies, loan and borrow stocks, and benefit from immediate access to relief items. Logistics solutions are shared among partners; therefore, they could minimize emergency response costs and ensure faster delivery of items (UNHRD, 2015).

Within the UNHRD network, the World Food Programme (WFP) acts as the service provider for the humanitarian community on a non-profit basis (Schulz and Blecken, 2010). Other humanitarian organizations can register as "authorized users" (hereafter members). Table 1 summarizes the services directly relevant to this paper. The UNHRD provides its members with "standard services" free of charge, including storage, offloading, receipt, warehousing, stock management and administration, preparation for unbranded backup stocks (white stocks and virtual stocks) and consolidated procurement and transportation services. Real-time stock visibility is offered to all members and helps them to transship stocks in case of stockouts. If HOs are not members of the UNHRD, then they are not allowed to enjoy services of stock transshipment and backup stocks that the UNHRD provides. The UNHRD also provides its member with "specific services" upon request and on the basis of full cost recovery, i.e. the cost of the service plus a management recovery fee which is currently 7%. The specific services include major repairs, extraordinary maintenance of equipment, offloading of un-palletized cargo, procurement of non-food items and services, transport of those items, technical missions to the field, insurance, stock disposal and any other service required from the members (UNHRD, 2015). The UNHRD is responsible for delivering relief supplies at airports of the affected areas (point of entry) and not directly to the beneficiaries. Local government, local or international HOs are responsible for the last-mile distribution.

The typical flow of transactions for a depot can be simplified and shown as in Figure 1. During the disaster preparedness phase (dotted arrows of Figure 1), member HOs preposition their own stocks via the UNHRD or directly from suppliers and the UNHRD prepares backup stocks. During the disaster response phase (solid arrows of Figure 1), member HOs can exchange stocks via transshipment in case of shortages during their disaster response operations. The UNHRD also provides backup stocks that member HOs could use in case of running out of stocks. However, as Figure 1 (b) describes, if HO i behaves as an *partially-participating* HO, which does not have its stock in UNHRD's warehouses to loan, then HO j cannot borrow or buy stocks from HO i. In that case, HO j needs to rely on backup stocks only. A member HO which borrows relief items from other member HOs is responsible to replenish them either by its own procurement or procurement through the UNHRD as Table 1 describes.

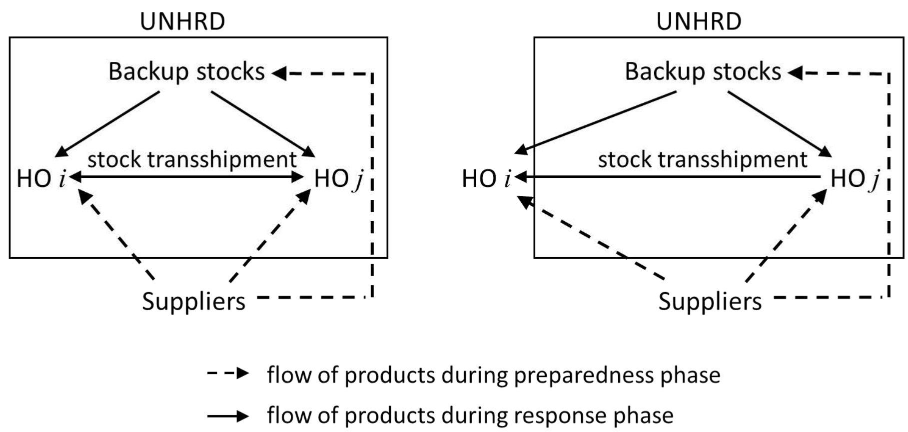


Figure 1: (a) Model FP and (b) Model PP

3.2 Main findings from interviews

We have conducted interviews with the UNHRD, six non-governmental organizations (CARE, NCA, LWR, MercyCorps, ShelterBox and World Vision) and one governmental organization (JICA). We also conducted informal discussions with organizations which are not members of the network (for confidentially reasons we do not mention their names).

Our interview with the chief of the UNHRD reveals many managerial issues of the network from the perspective of a system coordinator, including its budget situation and capacity of backup stocks. The UNHRD plans to improve the "sustainability" of the network based on four aspects: development of new services offered from the UNHRD at the field level on the basis of full recovery costs, promotion of relief item standardization, increase of the number of members as well as the number of donors, and the capability of the network to respond to two-three simultaneous disasters worldwide. The UNHRD is under pressure to run cost efficient system. It has been facing 25% shortfall of operational funding. Thus, the cost efficient network operation is a current crucial issue for the UNHRD. Regarding backup stocks that the UNHRD prepares, the current capacity of backup stocks can cover unexpected demand of three disasters. The UNHRD has never faced stockout of backup stocks except in two occasions. The chief of the UNHRD explained in detail that these two occasions were caused by suppliers' failures. After the incidents, the UNHRD does not accept any agreement without seeing items physically. No stockout has occurred after this remediation. We also recognize that no interviewed member HO is concerned about backup stock shortages. UNHRD's sufficient backup stocks does not necessarily mean that relief items arrive to beneficiaries because UNHRD's involvement finishes at entry points. Indeed, the chief pointed out that distribution problems often occur after entry points (i.e., last-mile distribution); however, last-mile distribution is currently out of scope of the UNHRD work.

All of the interviewed member HOs elaborate on benefits and challenges of services that the UNHRD network provides. They stated that free warehousing, stock transshipment, and UNHRD's backup stocks provide significant reduction of facilities and administrative cost of running and maintaining own warehouses. For some of the interviewed member HOs, the cost reduction from free warehousing and stock transshipment is the single reason to join the network. The majority of interviewed member HOs utilize stock transshipment. They agree that stock transshipment contributes to resolving stockouts and excess stocks. They also agree that real-time stock visibility through IT systems that the UNHRD prepares facilitates stock transshipment. Although interviewed member HOs value the services provided by the UNHRD network, some member HOs reduce their participation in the network while exploiting only benefits from the network due to its somewhat ineffective services. Some member HOs store the majority of their stocks in UNHRD's warehouses whereas some are reducing stocks stored at the UNHRD system because of setting up their own new warehouses or several impediments to efficient and effective HOs' response operations. They are planning only to borrow from other member HOs in case that there is a need and not to loan stocks in the stock transshipment system. As described in the introduction section, we call them *partially-participating* HOs. They explained that they significantly reduce their stocks in UNHRD's warehouse because of lack of delivered product traceability, long tendering processes until transportation processes start, and long lead times of restocking via the UNHRD (on average three months, sometimes six or twelve months). They mentioned that they would increase their stocks if these impediments were resolved.

4. Model

Following a series of interviews, we have developed stylized models under newsvendor settings with backup stocks and stock transshipment among UNHRD members in the context of non-cooperative game theory. Our models cover three options that member HOs face for managing their decentralized inventory systems: (1) being fully in the UNHRD network (fully-participating model, Model FP); (2) staying partially in the network (partially-participating model, model PP); and (3) staying completely out of the network (stand-alone model, Model NV). Model FP assumes that each member HO stores its stocks in warehouses of the UNHRD, so that it can loan its stocks. In contrast, model PP assumes that some member HOs have no stocks to loan in warehouses of the UNHRD. We call this type of member HOs *partially-participating* HOs. Model NV assumes that HOs are not members of the UNHRD network, which corresponds to the standard newsvendor model. As a benchmark, models of centrally coordinated systems (Models CFP and CPP) are also developed in this paper. A centrally coordinated system assumes that a system coordinator, the UNHRD in our models, determines each member HO's order quantities to minimize system-wide costs. The resulting outcomes indicate *system optimality.*

Reflecting facts about the UNHRD network from public information and our interviews, our models make three major assumptions: newsvendor setting, unlimited backup stocks and leftover penalty, and non-cooperative complete information game setting. The following is a brief explanation for each assumption from the perspective of the findings from the interviews presented in section 3.2.

Newsvendor setting

The demand for relief items during the response phase of a disaster is highly unpredictable and member HOs cannot expect to replenish their products from suppliers within an acceptable response time as our interviews found. Thus, when a disaster occurs demand has to be satisfied through pre-positioned stocks. The findings from our interviews also support the assumption that cost efficiency is a major reason for all of the interviewed HOs (the single reason for some of them) to join the network. Due to this fact, our models assume that member HOs seek to minimize their expected inventory costs.

Unlimited backup stocks and leftover penalty cost

As discussed in section 3.1, the UNHRD is not currently concerned about the shortage of its backup stocks. In light of this fact, our models assume that member HOs can access backup stocks whenever they need (i.e., unlimited backup stocks). Furthermore, member HOs are required to discard their expired stocks or to "take back any stocks for which no movement has been recorded after 24 months" at stock owner's expense (UNHRD, 2011). Following this fact, our models assume leftover penalty costs.

Non-cooperative complete information game

Each member HO determines its procurement level independently. As described in section 3.2, the UNHRD provides member HOs with real time reports about their stocks in warehouses of the UNHRD. The information includes which members are storing which items and where within the network. Member HOs with stock deficits know for sure that they can borrow stocks from member HOs with excess stocks. Following the fact, our models apply non-cooperative complete information game theory to the decentralized inventory model.

We consider a stylized model which consists of two humanitarian organizations indexed by i and j. The notation is summarized in Table 2. The demand that HO i faces is assumed to be a positive random variable X_i with a strictly increasing distribution function $F_{X_i}(x)$. Before demand is realized, HO i orders Q_i units from external suppliers at the cost of c_i per unit. The transshipments in our model are operated in terms of borrowing or loaning items. If demand during the period turns out to be larger than Q_i, HO i tries to satisfy the shortage by transshipment from HO j, $i \neq j$. If HO i borrows items, it replenishes them at their usual cost c_i and returns them to HO j after the period is over. The lending HO avoids the leftover penalty cost which is only applicable to items without turnover. A unit stock transshipment cost incurred by borrower i is defined as $c_i + \tau_{ji}$. Because of the *transaction* cost τ_{ji} (e.g., cost related to relabeling, repacking, and searching), it is not optimal for either of the two HOs to rely solely on stock transshipment.

If shortages cannot be fully satisfied by transshipment, backup stocks can be used. Backup stock cost c_w consists of three components (the UNHRD, www.unhrd.org): (1) the price that the UNHRD pays to a supplier of backup stock, (2) the management recovery cost of 7% of the procurement, and (3) the administration and handling costs incurred by member HOs that use backup stocks. The management recovery cost as well as administration and handling costs are standard fees that the UNHRD charges. Hence, c_w is typically larger than the unit procurement cost c_i that the HOs pay for their own stocks and it is larger than the cost of a unit transshipment $c_i + \tau_{ji}$. Therefore, we assume that using backup stocks is more costly than using transshipments, i.e. $c_w \geq c_i + \tau_{ji}$. In addition, we assume that $s_i + \tau_{ji} \geq s_j$ which ensures that excess stock from HO j is only transshipped to HO i if i is facing a shortage. These are the standard complete pooling assumptions which are required for the model to make "sense" (Pasternack and Drezner, 1991).

Table 2: Notation

Notation	Description
Q_i	procurement (ordering) quantity by HO i
Q_i^k	equilibrium or optimal procurement (ordering) quantity by HO i under model $k \in \{FP, PP, NV, CFP, CPP\}$
C_i^k	expected inventory costs of HO i under model $k \in \{FP, PP, NV, CFP, CPP\}$
X_i	demand faced by HO i (random variable)
$F_{X_i}(x_i)$	cumulative distribution function of X_i
$f_{X_i}(x_i)$	probability density function of X_i
c_i	unit procurement cost that HO i bears
s_i	penalty cost per unit of leftover stock that HO i bears
τ_{ij}	transaction cost per unit of stock transferred from HO i to HO j
c_w	unit backup stock cost charged by the UNHRD
τ_{wi}	premium on backup stock that HO i pays to UNHRD
p_i	unit stockout penalty cost that HO i bears

4.1 Full participation in the network (FP)

Model FP describes a case where member HO i and HO j keep all their prepositioned stocks in warehouses of the UNHRD; thus, they can loan their stocks to each other. In this case, each member HO determines its order quantity which minimizes its own inventory costs.

The expected inventory cost incurred by HO i is given by

$$\begin{aligned} C_i^{FP}(Q_i, Q_j) = & E[c_i Q_i + s_i(Q_i - X_i^e)^+ \\ & + (c_i + \tau_{ji})((X_i - Q_i)^+ - (X_i^n - Q_i)^+) \\ & + (c_w + \tau_{wi})(X_i^n - Q_i)^+]. \end{aligned} \tag{1}$$

HO i's expected inventory cost function consists of its procurement cost, leftover penalty, cost incurred by stock transshipment from HO j to i, and cost incurred in backup stock from the UNHRD. Following Huang et al. (2011), we define $X_i^e \doteq X_i + (X_j - Q_j)^+$ as the effective demand for HO i. It includes the demand which directly comes to HO i plus the part of HO j's demand that can not be satisfied by HO j. Similarly, $X_i^n \doteq X_i - (Q_j - X_j)^+$ is the net demand for HO i, which is the demand that comes directly to HO i minus the part that can be satisfied by HO j.

Notice that the unit cost incurred in the backup stock consists of two parts: backup stock cost, c_w, and premium incurred by HO i, τ_{wi}. Backup stock cost c_w is a standard fee that the UNHRD currently charges to member HOs which use backup stocks of the UNHRD. Our model introduces τ_{wi} as a premium for backup stocks of the UNHRD when HO i uses them. Currently, the UNHRD does not charge the premium. As the later sections of this paper discuss, our research has verified analytically as well as numerically that system optimality can be achieved by charging the premium on member HOs. There are two reasons why the premium for backup stock is considered in our models. One reason is that introducing the premium in our models allows us to identify key factors that achieve system optimality of the UNHRD network. Secondly, following our interviews with the UNHRD, we recognize that measures for system optimality need to satisfy three conditions: 1) direct controllability by the UNHRD; 2) no financial burden to the UNHRD; and 3) potential revenue source for the UNHRD. Introducing the premium for the backup stock satisfies these three conditions. To our best knowledge, other measures theoretically considered cannot meet these conditions.

Notice that the expected cost function of HO i, $C_i^{FP}(Q_i, Q_j)$, depends not only on its own stocking level Q_i but also on Q_j. The partial derivative of (1) with respect to Q_i obtains the first-order condition,

$$(c_i + \tau_{ji})F_{X_i}(Q_i) + s_i F_{X_i^e}(Q_i) + (c_w + \tau_{wi} - \tau_{ji} - c_i)F_{X_i^n}(Q_i) - (c_w + \tau_{wi} - c_i) = 0. \tag{2}$$

HO j's first-order condition can be obtained in a similar way.

From the assumption $c_w \geq c_i + \tau_{ji}$, the expected cost function is convex in Q_i, which guarantees the existence of Nash equilibrium (Cachon and Netessine, 2006). The Nash equilibrium, (Q_i^{FP}, Q_j^{FP}), can be obtained by solving the first-order conditions for i and j simultaneously.

Proposition 4.1. *Under full participation (FP) in the network, there exists a unique Nash equilibrium,* (Q_i^{FP}, Q_j^{FP}).

Proof. The proof follows along the lines of the proof of Proposition 1 in Rudi et al. (2001). The implicit differentiation of (2) derives

$$\frac{\partial Q_i}{\partial Q_j} = -\frac{s_i g_{X_i^e}(Q_i) + (c_w + \tau_{wi} - c_i - \tau_{ji}) g_{X_i^n}(Q_i)}{(c_i + \tau_{ji}) f_{X_i}(Q_i) + s_i f_{X_i^e}(Q_i) + (c_w + \tau_{wi} - c_i - \tau_{ji}) f_{X_i^n}(Q_i)}. \tag{3}$$

For X_i^e, define $f_{X_i^e}(Q_i) \doteq \partial F_{X_i^e}(Q_i)/\partial Q_i$ and $g_{X_i^e}(Q_i) \doteq \partial F_{X_i^e}(Q_i)/\partial Q_j$, and similarly for X_i^n. From the definitions of the effective demand and the net demand, one can derive $F_{X_i^e}(Q_i) \leq F_{X_i}(Q_i) \leq F_{X_i^n}(Q_i)$, which leads to $f_{X_i^e}(Q_i) \geq g_{X_i^e}(Q_i)$ and $f_{X_i^n}(Q_i) \geq g_{X_i^n}(Q_i)$, respectively. Combining these properties and our assumption $c_w \geq c_i + \tau_{ji}$, one can conclude that $-1 \leq \frac{\partial Q_i}{\partial Q_j} \leq 0$. That is, the slopes of the best response functions are less than one, which is the sufficient condition for the uniqueness of the Nash equilibrium (Cachon and Netessine, 2006). □

Corollary 4.2. *The optimal procurement quantity Q_i^{FP} and Q_j^{FP} is increasing in the premium τ_{wi} and τ_{wj}, respectively.*

Corollary 4.2 implies that raising the unit backup stock cost would lead member HOs to increase their inventory levels.

The interview with the chief of the UNHRD indicates necessity for cost efficient operations of the network due to its 25% shortfall of operational funding (see section 3.2). Informal discussions with some non-member HOs also imply the importance of accountability to donors about efficient operations of the network. To analyze how the UNHRD network can achieve system optimality, we develop a centrally coordinated model denoted as CFP. The centrally controlled system achieves system optimality. In this setting, a system coordinator, the UNHRD, determines HO i and HO j's order quantities to minimize the total costs incurred by the system.

The expected total cost of the centralized system under full participation is

$$\begin{aligned} C^{CFP}(Q_i, Q_j) =& E[\sum_{i,j,i \neq j} (c_i Q_i + s_i (Q_i - X_i^e)^+ \\ & + \tau_{ji}((X_i - Q_i)^+ - (X_i^n - Q_i)^+) \\ & + c_w (X_i^n - Q_i)^+)] \end{aligned} \tag{4}$$

Notice that in the centrally coordinated system the items are not borrowed or sold but they are shared without asking for a replacement when stock transshipment occurs. The transaction cost is still incurred because it reflects handling and administration costs that the system coordinator bears.

Since we assume $c_w \geq c_i + \tau_{ji}$ and $s_i + \tau_{ji} \geq s_j$, $C^{CFP}(Q_i, Q_j)$ is convex in (Q_i, Q_j) (see online appendix for the proof of convexity in the centralized systems). The optimal procurement quantities Q_i^{CFP} satisfy the following first-order condition:

$$(\tau_{ij}+\tau_{ji}-c_w-s_j)F_{X_i}(Q_i)+(s_i-\tau_{ij}+c_w)F_{X_i^e}(Q_i)+(c_w-\tau_{ji}+s_j)F_{X_i^n}(Q_i)-(c_w-c_i)=0. \tag{5}$$

From this the following result can be derived.

Proposition 4.3. *The premium* τ_{wi}^* *which leads to the optimal centralized policy is given by*

$$\tau_{wi}^*=\frac{(c_w-\tau_{ij})(F_{X_i}(Q_i^{CFP})-F_{X_i^e}(Q_i^{CFP}))-(c_i+s_j)(F_{X_i^n}(Q_i^{CFP})-F_{X_i}(Q_i^{CFP}))}{(1-F_{X_i^n}(Q_i^{CFP}))}, \tag{6}$$

where Q_i^{CFP} *is the optimal order quantity under centralized control.*

Proof. The coordinating premium induces the HOs to choose the same order quantities under decentralized and centralized settings. Therefore τ_{wi}^* in (6) is found by equating the left-hand sides of equations (2) and (5) at $Q_i=Q_i^{CFP}$. □

Proposition 4.3 allows us to provide two implications about network coordination mechanisms. First, charging the premium allows the network to achieve system optimality. Second, τ_{wi}^* can be different for the two HOs depending on their cost and demand parameters. This implies that UNHRD might need to charge different fees for different member HOs, which may ignite an additional conflict between member HOs.

4.2 Partial participation in the network (PP)

Following our interview results, this section describes the partial participation scenario PP_i, in which one of the two organizations, member HO i, does not store its stocks in warehouses of the UNHRD and keeps all its inventory in its own warehouses whereas member HO j stores all its stocks in warehouses of the UNHRD (see Figure 1(b)). Member HO i does not loan its stocks to HO j because HO i's stocks are not recognized by HO j and the UNHRD, but member HO i still can borrow stocks through stock transshipment from HO j and/or use the backup stock from the UNHRD. This means that member HO j can only rely on backup stocks from the UNHRD when it faces a stockout.

The expected inventory cost of HO i, which stores all its stocks in its own warehouse, is:

$$
\begin{aligned}
C_i^{PP_i}(Q_i, Q_j) =& E[c_i Q_i + s_i (Q_i - X_i)^+ \\
& + (c_i + \tau_{ji})((X_i - Q_i)^+ - (X_i^n - Q_i)^+) \\
& + (c_w + \tau_{wi})(X_i^n - Q_i)^+]. \qquad (7)
\end{aligned}
$$

Notice that s_i is a penalty cost per unit of leftover stocks in HO i's own warehouse.

The expected inventory cost of member HO j, which can not borrow items through transshipment, is:

$$
C_j^{PP_i}(Q_i, Q_j) = E[c_j Q_j + s_j (Q_j - X_j^e)^+ + (c_w + \tau_{wj})(X_j - Q_j)^+]. \qquad (8)
$$

Notice that, unlike $C_i^{PP_i}$, $C_j^{PP_i}$ does not include the cost of stock transshipment from i because i does not have its stocks in the UNHRD network and j cannot rely on it.

The first-order conditions of (7) and (8) are

$$
(c_i + s_i + \tau_{ji}) F_{X_i}(Q_i) + (c_w + \tau_{wi} - c_i - \tau_{ji}) F_{X_i^n}(Q_i) - (c_w + \tau_{wi} - c_i) = 0 \qquad (9)
$$

$$
(c_w + \tau_{wj}) F_{X_j}(Q_j) + s_j F_{X_j^e}(Q_j) - (c_w + \tau_{wj} - c_j) = 0, \qquad (10)
$$

respectively.

$C_i^{PP_i}(Q_i, Q_j)$ is convex in Q_i and $C_j^{PP_i}(Q_i, Q_j)$ is convex in Q_j, which guarantee the existence of the Nash equilibrium. The Nash equilibrium, $(Q_i^{PP_i}, Q_j^{PP_i})$, can be obtained by solving equations (9) and (10) simultaneously.

Proposition 4.4. *Under partial participation (PP) in the network, there exists a unique Nash equilibrium,* $(Q_i^{PP_i}, Q_j^{PP_i})$.

Proof. Similar to the proof of Proposition 4.1 we can derive that $-1 \leq \frac{\partial Q_i}{\partial Q_j} \leq 0$ and $-1 \leq \frac{\partial Q_j}{\partial Q_i} \leq 0$, which is the sufficient condition for the uniqueness of the Nash equilibrium. □

Corollary 4.5. *The optimal procurement quantity Q_i^{PP} and Q_j^{PP} is increasing in the backup charge τ_{wi} and τ_{wj}, respectively.*

Next we introduce a centralized model under HO i's partial participation in the network, denoted as model CPP_i. The expected total cost of this system is:

$$\begin{aligned} C^{CPP_i}(Q_i, Q_j) =& E[c_iQ_i + c_jQ_j + s_i(Q_i - X_i)^+ + s_j(Q_j - X_j^e)^+ \\ & + \tau_{ji}((X_i - Q_i)^+ - (X_i^n - Q_i)^+) \\ & + c_w((X_i^n - Q_i)^+ + (X_j - Q_j)^+)] \end{aligned} \quad (11)$$

since $c_w \geq c_i + \tau_{ji}$ and $s_i + \tau_{ji} \geq s_j$, $C^{CPP_i}(Q_i, Q_j)$ is convex in (Q_i, Q_j). The optimal procurement quantities $Q_i^{CPP_i}$ and $Q_j^{CPP_i}$ satisfy the first-order conditions:

$$(s_i - s_j + \tau_{ji})F_{X_i}(Q_i) + (c_w + s_j - \tau_{ji})F_{X_i^n}(Q_i) - (c_w - c_i) = 0, \quad (12)$$

$$\tau_{ji}F_{X_j}(Q_j) + (c_w + s_j - \tau_{ji})F_{X_j^e}(Q_j) - (c_w - c_j) = 0. \quad (13)$$

Proposition 4.6. *Under partial participation, the decentralized system cannot be coordinated using the premiums τ_{wi} and τ_{wj} as a coordination mechanism.*

Proof. In order to coordinate the system under partial participation, the pair of backup charges $(\tau_{wi}^{**}, \tau_{wj}^{**})$ should be set as

$$\tau_{wi}^{**} = \frac{(s_j + c_i)(F_{X_i}(Q_i^{CPP_i}) - F_{X_i^n}(Q_i^{CPP_i}))}{1 - F_{X_i^n}(Q_i^{CPP_i})}, \quad (14)$$

$$\tau_{wj}^{**} = \frac{(c_w - \tau_{ji})(F_{X_j}(Q_j^{CPP_i}) - F_{X_j^e}(Q_j^{CPP_i}))}{1 - F_{X_j}(Q_j^{CPP_i})}. \quad (15)$$

Notice that τ_{wi}^{**} is always negative. Namely, there is no premium such that $\tau_{wi} \geq 0$. □

Proposition 4.6 implies that a premium for backup stocks cannot work as a feasible mechanism for system optimality under the circumstance of partial participation. This is similar to the result of Hu et al. (2007). In the commercial setting, Hu et al. (2007) also prove that if two retailers have certain asymmetries in their problem parameters a coordinating transshipment price might not exist. Proposition 4.6 implies that allowing transshipment in only one direction induces a strong asymmetric effect on the premiums, even if the two HOs are symmetric in their demand and cost parameters. Hence, in our model PP the UNHRD should employ some other contract mechanism. We leave this issue for future research.

Comparing the first order conditions under full and partial participation, one can derive the following corollary.

Corollary 4.7. *The following hold for the Nash equilibria under full and partial participation:*

(i) $Q_i^{FP} \geq Q_i^{PP_i}$ *and* $Q_j^{FP} \leq Q_j^{PP_i}$;

(ii) $Q_i^{CFP} \geq Q_i^{CPP_i}$ *and* $Q_j^{CFP} \leq Q_j^{CPP_i}$.

Corollary 4.7 indicates that the borrower HO i's equilibrium order quantity would be smaller under partial participation compared to the full participation and the opposite applies to the loaner HO j. This holds true for both the decentralized and centralized systems. Further, for the symmetric setting, we can derive the following.

Corollary 4.8. *If the cost and demand parameters are equal for both HOs, then* $Q_i^{PP_i} \leq Q_j^{PP_i}$.

Corollary 4.8 indicates that, under partial participation with symmetric parameters, HO i (partially-participating HO) orders less than HO j (fully-participating HO) in the equilibrium.

4.3 No participation in the network (NV)

To analyze incentives that make HOs join the UNHRD network, this section describes a stand-alone setting, in which HOs are not members of the network. They run their own warehouses and cannot access the stock transshipment and/or backup stocks. If HO i faces a larger demand than its procurement, it incurs a penalty cost of $p_i > c_i$ per unsatisfied demand. The penalty cost covers the additional costs incurred for quick replenishment, for example, via air shipment from its central warehouses, and the loss of reputation which may cause the reduction of future funding.

This setting corresponds to the standard newsvendor model and the expected cost can be written as

$$C_i^{NV}(Q_i) = E[c_iQ_i + s_i(Q_i - X_i)^+ + p_i(X_i - Q_i)^+], \tag{16}$$

which is a convex function of Q_i (Khouja, 1999) and the order quantity which minimizes (16) is $Q_i^{NV} = F_{X_i}^{-1}\left(\frac{p_i - c_i}{p_i + s_i}\right)$.

From HOs' perspective, there would be no cost advantage by joining the network if the stockout penalty cost (i.e., p_i) is less than the cost of using stock transshipment and/or backup stock options. Therefore, model NV assumes that the unit penalty cost is higher than the cost incurred by the stock transshipment and/or the backup stock that the UNHRD network offers. That is, $p_i \geq c_w \geq c_i + \tau_{ji}$.

Regarding the total system costs under different scenarios, one can derive the following.

Corollary 4.9. *For* $p_i \geq c_w$, $C^{CFP} \leq C^{CPP_i} \leq C_i^{NV} + C_j^{NV}$.

Corollary 4.9 indicates that the centralized system under member HOs' full participation can achieve the lowest system optimal cost. Following the result of Corollary 4.9, one can also conclude: for τ_{wi}^*, τ_{wj}^*, τ_{wi}^{**} and τ_{wj}^{**}, $C_i^{FP} + C_j^{FP} \leq C_i^{PP_i} + C_j^{PP_i} \leq C_i^{NV} + C_j^{NV}$. These results suggest that the UNHRD should change its policy priority for its sustainable network operations. Specifically, the UNHRD should prepare a circumstance where member HOs fully participate in the network before implementing the premium fee for system optimality if it seeks the first-best outcome.

The analytical results in this section do not answer the ordering of the expected inventory costs for arbitrary backup stock premiums. Hence, we leave this analysis to our numerical simulations in section 5.

5. Numerical analysis

In this section, we shed light on how different demand patterns impact order quantities and expected costs using numerical simulations. The convexity of the cost functions with respect to Q_i and Q_j and the uniqueness of the Nash-equilibrium proven in section 4 allow us to use a line search to find the intersection of the response function and, hence, the Nash equilibrium procurement quantities.

5.1 Data

Our numerical simulations have been conducted under the assumption that the HOs are symmetric in their cost parameters. From our interviews and UNHRD's real time stock levels (http://www.unhrd.org), we assume that transferable items among HOs are products such as blankets, of which unit procurement costs are relatively similar among HOs, but they are not always perfectly substitutable. The assumption of symmetric costs also allows us to focus on impacts of discrepancies of demand patterns between member HOs on network coordination mechanisms.

Specifically, we explore the impacts of coefficient of variation of demand, cv, and correlation of demands, ρ. A negative correlation can happen if the HOs are competing for supplying items to the same group of beneficiaries. On the other hand, the size of total demand depends on external factors, mainly on the size of the disaster, which implies a positive correlation of demands across HOs.

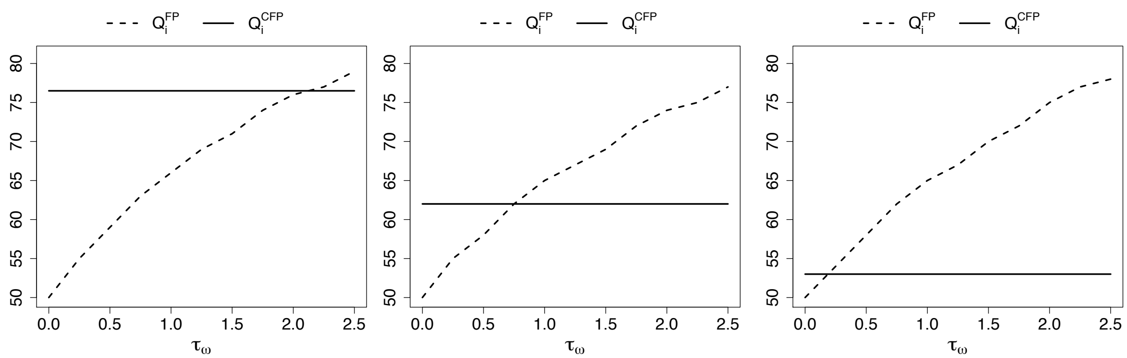
In order to identify the range of demand cv, we evaluated the disaster and emergency relief data of JICA (http://www.jica.go.jp) from 2006 to 2014. For many items cv is around 1, and if demand is disaggregated to specific geographical regions, it increases up to 1.5-2. We also observed that the demand distribution is skewed rather than symmetric. Based on this observations, we assume a gamma distribution for demands, which allows us to consider higher levels of coefficients of variation than other distributions, such as the normal distribution.

The parameters presented in Table 3 have been used for our simulations. As Table 3 shows, numerous combinations of demand parameters (i.e., μ_i, cv_i and ρ) between the two HOs have been used for the simulations. Indexes of HOs in the cost parameters are dropped due to the symmetric cost parameter assumption between the two HOs.

For the procurement cost, c, we refer to the unit price of a blanket shown in the UNICEF Supply Catalogue (https://supply.unicef.org). Backup stock cost, c_w, consists of three components (www.unhrd.org): (1) price that the UNHRD pays to a supplier of backup stock, c_b , (2) the management recovery cost of 7% of the procurement (a standard fee that the UNHRD charges), and (3) transaction costs τ incurred by member HOs that use backup stocks. Hence,

Table 3: Demand and cost parameters

Demand parameters	
Mean demand of HO i and j μ_i, μ_j	{50, 100}
Coefficient of variation of demand of HO i and j cv_i, cv_j	{0.5, 1, 1.5, 2}
Correlation coefficient of demand of the two HOs ρ	{-0.7, -0.3, 0, 0.3, 0.7}
Cost parameters	
Unit procurement cost that a HO bears c	5
Unit procurement cost that the UNHRD bears for backup stock c_b	{5,7,9.3}
Leftover penalty s	{0.1,0.5,2.5}
Transaction cost τ	{0.3,0.5,0.8,1.0,1.3,1.5,1.8,2.0,2.3,2.5}
Premium for usage of the UNHRD's backup stock τ_w	{0.0,0.5,1.0,1.5,2.0,2.5}



(a) $\rho = -0.7$ (b) $\rho = 0$ (c) $\rho = 0.7$

Figure 2: Optimal order quantities in the centralized Q_i^{CFP} and decentralized systems Q_i^{FP} with respect to the premium τ_w

we define the backup stock cost as $c_w \doteq 1.07 \cdot c_b + \tau$. Reflecting comments in our interviews, base case values of the parameters are set as $\mu_i = \mu_j = 100$, $c = c_b = 5$, $s = 0.1$, $cv_i = cv_j = 0.5$ and $\tau = 0.5$.

5.2 Coordination mechanism

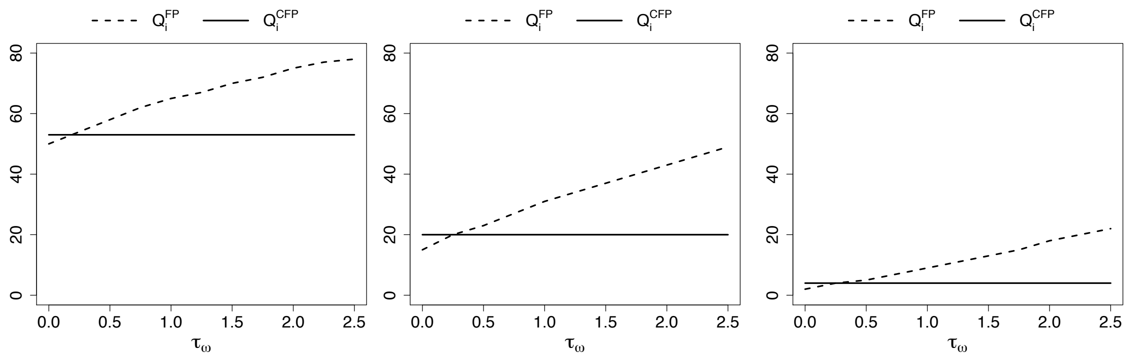
Currently, the UNHRD does not charge a premium for its backup stock service (i.e., $\tau_w = 0$). Due to the current low backup stock cost, there is a concern that member HOs may depend too much on backup stocks (Schulz, 2009). From the results of Proposition 4.6, we learn that no applicable premium exists under member HO i's partial participation. In this subsection, we focus on identifying key factors for implementation of the premium provided that member HO i and j both fully participate in the network.

Observation 5.1. *The levels of the premium, τ_w^*, for backup stocks where system optimality is achieved are sensitive to demand correlation, ρ. For a positive (negative) ρ, τ_w^* tends to become lower (higher) (see Figure 2).*

Figure 2 illustrates the optimal order quantity for HO i under case FP and CFP. As shown in Corollary 4.2, the decentralized optimal procurement quantity Q_i^{FP} is increasing in τ_w. Let τ_w^* denote the levels of τ_w where the minimum total network cost is achieved (i.e., system optimality), that is, the intersection of the curves of Q_i^{FP} and Q_i^{CFP} in the figures. Figure 2 indicates that under the current setting of the UNHRD (i.e. $\tau_w = 0$) system optimality can not be attained.

As Figure 2 shows, ρ has a major impact on τ_w^*. Figure 2 (c) indicates that for $\rho = 0.7$ system optimality can be achieved at $\tau_w^* = 0.19$, which is around 4.75% of c. When the demand correlation between the two HOs is positive (i.e., $\rho = 0.7$), the risk pooling effect from stock transshipment becomes smaller, in which case advantages of the network come from the availability of the UNHRD's backup stock. Thus, from the perspective of system optimality, a relatively low τ_w^* should be set up in such a way that member HOs can use the backup stock option to a large extent. Whereas, as Figure 2 (a) shows, system optimality has been achieved at a level of τ_w around 2.2 when $\rho = -0.7$. If the demand correlation between the two HOs is negative (i.e., $\rho = -0.7$), the risk pooling effect from the transshipments is large. A relatively high τ_w^* should be set up so that the HOs increase order quantities and use stock transshipments rather than the backup stock option. We have also confirmed that this general trend of τ_w^* in ρ holds for the different levels of s and c_w.

As Figure 2 indicates, the trend of τ_w^* in ρ stems from sensitivity differences to ρ between Q_i^{FP} and Q_i^{CFP}. In other words, Q_i^{CFP} shifts more substantially than Q_i^{FP} for the different levels of ρ. Under the current low c_w, the HOs can secure themselves with the backup stock option in a costless manner, rather than relying on the stock transshipment option. They tend to ignore benefits of risk pooling via stock transshipment and behave (almost) independently of each other. When the HOs tend to behave independently, demand correlation, ρ, cannot affect their procurement decisions. In contrast, the centralized case (i.e., model C) can adapt the system to the change of ρ more effectively than model FP, which enables member HOs to fully enjoy benefits of risk pooling. This is why Q_i^{CFP} is more sensitive than Q_i^{FP} to the changes of ρ. The impact of correlation on centralized optimal order quantities has been proven by Dong and Rudi (2004) for normally distributed demands. The simulation results indicate that this



(a) $cv = 0.5$ (b) $cv = 1$ (c) $cv = 1.5$

Figure 3: Optimal order quantities in the centralized Q_i^C and decentralized systems Q_i^{FP} with respect to the premium τ_w, when $\rho = 0.7$

trend holds for demands following a gamma distribution as Figure 2 shows. That is, Q_i^{CFP} decreases as ρ increases. We have also confirmed that the optimal order quantities decrease more significantly when c_w is low and/or s is high. This result is also consistent with Dong and Rudi (2004).

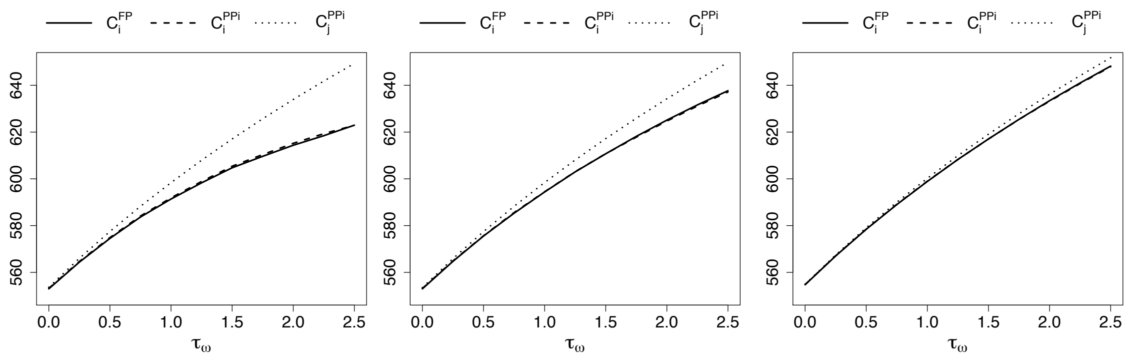
Observation 5.2. *The levels of the premium, τ_w^*, for backup stocks where system optimality is achieved is relatively insensitive to demand coefficient of variation, cv, compared to demand correlation, ρ (see Figure 3).*

Figure 3 shows, the levels of τ_w^* are relatively consistent regardless of the *cv* levels. This result is caused by the fact that Q_i^{FP} and Q_i^{CFP} shift downward in similar magnitude as *cv* increases, which implies that the decentralized system (i.e., model FP) reacts to demand variability as effectively as the centralized system (i.e., model C). Our simulation has confirmed that this trend also holds for different levels of τ, s and ρ.

5.3 Impacts of members' rationing decision

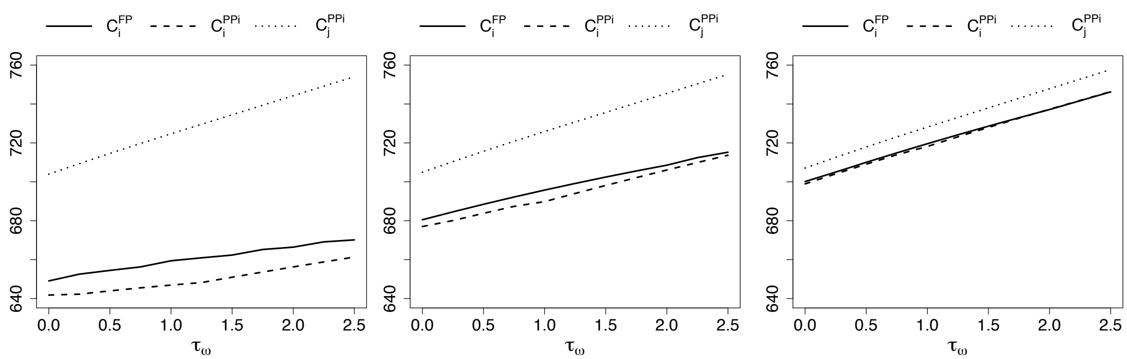
Our interviews reveal that cost efficiency does not always motivate member HOs to fully participate in the UNHRD network. Some member HOs are substantially reducing the ratio of their stocks in warehouses of the UNHRD due to several impediments that the network has, for examples, long lead times for restocking and lack of traceability.

As Proposition 4.6 indicates, under a member HO's partial involvement in the network, there is no applicable premium that achieves system optimality. However, considering the current situation where member HOs have different levels of involvement to the network, a question would arise: what if the premium is implemented under the circumstance of member HOs' partial involvement? The numerical experiments in this section would answer this question.



(a) $\rho = -0.7$ (b) $\rho = 0$ (c) $\rho = 0.7$

Figure 4: Expected cost C_i^{FP}, $C_i^{PP_i}$, $C_j^{PP_i}$ with respect to the premium τ_w



(a) $\rho = -0.7$ (b) $\rho = 0$ (c) $\rho = 0.7$

Figure 5: Expected optimal cost C_i^{FP}, C_i^{PPi}, C_j^{PPi} with respect to the premium τ_w: high procurement cost for backup stock, that is, $c_w = 10.5$.

The impacts of member HOs' rationing decision (i.e., either storing at UNHRD's or storing at members' own warehouses and just using the network for borrowing) on member HOs' expected total inventory costs are shown in Figure 4. It presents the expected optimal cost of HO i and j with respect to the backup stock premium τ_w under model FP and PP. Figures 4 indicates that fully participating HO j enjoys lower expected inventory cost under FP than PP_i; that is,

$C_j^{PP_i} \geq C_j^{FP}$ for any τ_w and ρ. However, this trend is not true for partially participating HO i. HO i's cost under model PP_i, $C_i^{PP_i}$, can be higher (Figure 4 (a)) or lower (Figure 5) than its cost under model FP, C_i^{FP}.

Observation 5.3. *Member HO i, which does not store stocks in warehouses of the UNHRD but just uses the network for borrowing, tends to enjoy lower expected inventory costs than member HO j, which stores all its stocks at warehouses of the UNHRD (i.e., $C_i^{PPi} < C_j^{PPi}$). The cost discrepancy between the two member HOs tend to: (1) be smaller as demand correlation, ρ, increases; and (2) be enlarged as the premium for backup stocks, τ_w, increases (see Figures 4 and 5).*

Interestingly, HO i could enjoy a larger cost-saving benefit than HO j under the model PP_i if the UNHRD implements a premium fee (i.e., $\tau_w > 0$). We call this advantage of HO i *free-rider benefits.* Comparing Figure 4 with Figure 5, one can recognize that a higher backup stock cost in Figure 5 would increase HO i's free-rider benefit. The free-rider benefit decreases as ρ increases. This is because the risk pooling effect associated with the UNHRD network decreases when both of the HOs' demands have a similar trend (i.e., $\rho > 0$). If additional fixed costs (e.g., administrative costs for running HO i's own warehouse) are included into our model, then the free-rider benefit might become a minor issue. Nonetheless, the results indicate that the network has an intrinsic risk that would encourage member HOs' partially-participating behavior. This intrinsic weakness of the system is considered to somewhat explain why currently some HOs are reducing the ratio of stocks in the UNHRD and are relying on borrowing stocks from other member HOs.

Our simulation also has revealed that a high left-over penalty (e.g., s is more than 50% of c) would prevent HO i from being a free-rider, effect of which, however, is canceled out if a system coordinator sets up a high backup stock cost, (c_w is more than 100% of c). This is because a higher backup stock cost drives the HOs to increase their procurement rather than rely on the UNHRD's backup stocks. In the meanwhile, only HO i can enjoy benefits of stock transshipment from HO j.

Lastly, we compare C^{FP} with the expected cost of a stand-alone HO under model NV (i.e., C^{NV}).

Observation 5.4. *A member HO's expected inventory cost under the full participation setting, C_i^{FP}, is lower than the cost under the stand-alone setting, C_i^{NV}.*

We have confirmed from our simulations that the result of Observation 5.4 holds even if penalty costs of stockout are rather low (e.g. $p = 10$). This result is also consistent with comments of interviewee HOs, in which they explained that the cost efficiency is a major reason for joining the network.

6. Extension to multiple HOs

In previous sections, analysis has been conducted based on a setting with two HOs. The question still has remained unanswered whether the general trend of the results is robust with respect to the number of member HOs. To answer this question, this section presents a brief extension to a setting with more than two HOs in the system, where some member HOs are fully participating in the system and the rest of them are partially participating. Let N denote the total number of member HOs in the system. Let $i, j = 1, ..., n, ..., N$ where $i \neq j$ as indexes of member HOs, assuming that the first n HOs store their stocks in warehouses of the UNHRD (i.e., $i = 1, ..., n$) and the last $N - n$ HOs do not store their stocks there. That is, stocks can be transshipped only from HOs $i = 1, ..., n$ to HOs $i = 1, ..., N$. When all N HOs store their stocks in warehouses of the UNHRD (i.e. $n = N$), we denote it as FP^N since this case corresponds to the full participation model. If at least one member HO does not store its stocks in warehouses of the UNHRD, (i.e. $n \neq N$), then we denote this case as $PP^{N,n}$ since this falls into the partial participation model.

Analyzing such a system with more than two decentralized agents is known to be a nontrivial task (Rudi et al., 2001; Huang and Sošić, 2010; Shao et al., 2011). First, an allocation rule for stock transshipment between member HOs has to be defined for assigning the leftovers to HOs with shortages. Referring to Huang and Sošić (2010), the following proportional allocation rule is applied to our models. Under this allocation rule, the amount that HO i receives via transshipments is $TI_i = \min(TL, TS)(X_i - Q_i)^+/TS$, where $TS = \sum_{i=1}^{N}(X_i - Q_i)^+$ is the total stock deficits which may be covered by transshipment and $TL = \sum_{i=1}^{n}(Q_i - X_i)^+$ is the total excess stocks which can be used for transshipment. The first term, $\min(TL, TS)$, is the total amount of stocks which can be transshipped. This term is multiplied by the proportion of HO i's stock deficits to the total deficits. Similarly, the quantity that HO i transships out is $TO_i = \min(TL, TS)(Q_i - X_i)^+/TL$ for $i = 1, ..., n$ and $TO_i = 0$ for $i = n + 1, ..., N$.

After realizing the amount of stock transshipment, HO i might either have leftovers $L_i =$

$(Q_i - X_i - TO_i)^+$ or need to purchase backup stocks as many as $S_i = (X_i - Q_i - TI_i)^+$. The total expected cost incurred by HO i for model $k \in \{FP^N, PP^{N,n}\}$ is

$$C_i^k = E[c_i Q_i + s_i L_i + (c_i + \tau_{ji}) TI_i + (c_w + \tau_{wi}) S_i], \tag{17}$$

where $i \neq j$.

For the simplicity of analysis, our numerical experiments in this section assume that member HOs are symmetric in their cost and demand parameters. Under the proportional allocation rule and symmetric setting, the HOs that store their stocks in the UNHRD have the same equilibrium order quantities i.e., $Q_i^{PP^{N,n}} = Q_j^{PP^{N,n}}$ for $i, j = 1..., n$, and consequently the same expected costs. Similarly, all HOs that do not store their stocks in the UNHRD have the same equilibrium values where $Q_i^{PP^{N,n}} = Q_j^{PP^{N,n}}$ for $i, j = n+1..., N$.

Our numerical experiments for the N-HOs setting confirm that the general trend of our results holds. In particular, the optimal procurement quantities $Q_i^{FP^N}, Q_i^{PP^{N,n}}, i = 1...N$ are increasing in the premium τ_{wi} (Corollary 4.2 and 4.5) for $N \geq 2$. Additionally, for model FP^N the optimal levels of premiums for backup stocks which achieve system optimality, τ_w^*, are sensitive to demand correlation ρ (Observation 5.1) and insensitive to demand coefficient of variation cv (Observation 5.2).

In addition, the numerical experiments in this section reveal impacts of the number of member HOs on the UNHRD's coordination mechanism as follows:

Observation 6.1. *The optimal premium charge τ_w^* increases as N increases (see Figure 6).*

In other words, increasing number of member HOs tends to lower their stocks whereas system optimal stock levels increase. The result implies public good characteristics of inventories, in which each member HO would benefit from more stocks in the system, but each wants others to invest them. The public good characteristics of inventories are also observed in a vertical cooperation setting (Cachon and Zipkin, 1999). We also confirm that the expected inventory costs (i.e., $C_i^{FP^N}$ and C^{CFP^N}/N) decrease as N increases.

Our numerical analysis confirms that for model $PP^{N,n}$ the equilibrium order quantities and costs are sensitive to the total number of HOs N as well as to the proportion of HOs storing in the UNHRD, n/N. Specifically, as a result that transshipment opportunities increase in n/N, the following is observed in our numerical analysis:

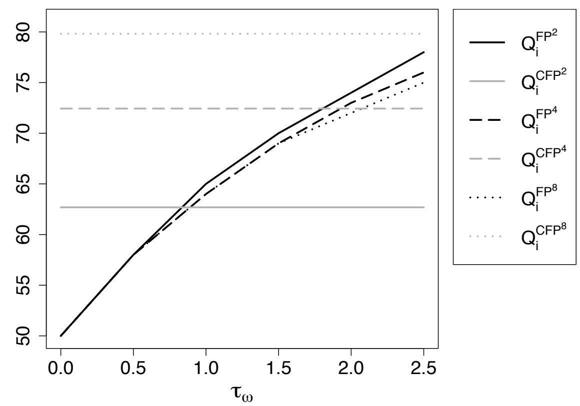


Figure 6: Optimal order quantities $Q_i^{CFP^N}$ and $Q_i^{FP^N}$ with respect to τ_w with correlation $\rho = \rho_{ij} = 0, i, j = 1...N, i \neq j$ for $N = 2, 4, 8$.

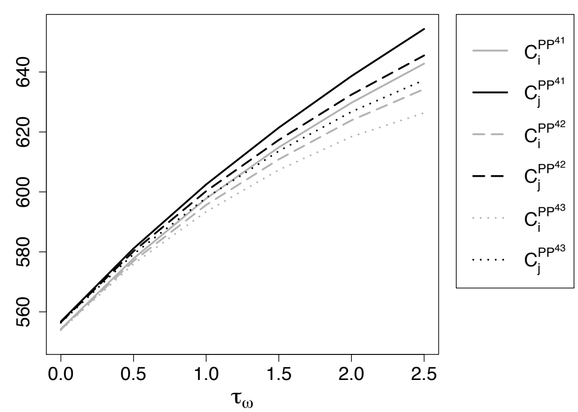


Figure 7: Expected cost of HO $i > n$, $C_i^{PP^{N,n}}$ compared to HO $j \leq n$, $C_j^{PP^{N,n}}$ with respect to τ_w, $\rho = 0$ and $N = 4$.

Observation 6.2. *The equilibrium order quantities decrease as n/N increases.*

Figure 7 shows impacts of n on the expected inventory costs of the HOs for a fixed N. As shown in the figure, expected costs of the HOs decrease in n. Figure 7 also displays that the free-rider benefits of HOs $i = n + 1, .., N$ increase in τ_w and decrease in ρ, which are consistent with the results in section 5.3.

7. Summary and Discussion

The present work makes a unique contribution to the studies of not-for-profit operations management in that it sheds light on a governance mechanism to control a lateral stock transshipment system in humanitarian sectors. We have presented an analytical framework to explore horizontal cooperation between HOs for their inventory management. This type of cooperation is observed in the UNHRD, International Federation of Red Cross and Red Crescent Societies (IFRC) and European Community Humanitarian Aid Department (ECHO). We have especially focused on the UNHRD network because the network specializes in disaster response operations, is growing rapidly in terms of number of member HOs and has a more holistic horizontal cooperation in inventory management, including stock transshipment and backup stocks. Currently, the UNHRD does not take any measures for system optimality although they are subject to a tight budget constraint. Our analytical and numerical results indicate that behaviors of member HOs do not necessarily align with the UNHRD's expectation, which is consistent with our interview results. To identify key factors that achieve system optimality, we have proposed the premium fee for backup stocks, which satisfies the three conditions (i.e., direct controllability, no financial burden, and potential revenue source).

Our results suggest several managerial recommendations for the UNHRD. As long as every member HO has stocks to loan in warehouses of the UNHRD, charging the premium would achieve the first-best system optimality. The result implies that the UNHRD should resolve current impediments which induce some member HOs' partial-participating behaviors before implementing the premium if it seeks to achieve the first-best system optimality. Otherwise, implementing the premium would lead partially-participating HOs to enjoy a free-rider benefit. This partially-participating HOs' advantage would accelerate member HOs' reduction of their stock ratio in UNHRD's warehouses, which may eventually compromise the functioning of stock transshipment between member HOs. The UNHRD is currently considering transferring the authority of restocking decisions from member HOs to the UNHRD for more efficient and effective network operations. This new restocking policy is somewhat similar to our centralized models. Compared with this new restocking policy, charging the premium fee that we propose appeals more to individual member HO's self-enforcing motivation. The UNHRD should consider which measure is more appropriate from the perspective of efficiency, effectiveness and equity between member HOs and the UNHRD. Our research also reveals a key indicator for levels of the premium for system optimality. The UNHRD should select an appropriate premium level before disasters occur based on information about demand correlations between member HOs. In this respect, the UNHRD should also collect detailed and sufficient data on demand for relief items that individual member HOs store in warehouses of the UNHRD.

Our research also proposes several managerial recommendations for the HOs. HOs would enjoy cost-saving benefits by participating in the UNHRD network as long as they adjust their order quantities depending on levels of the premium. For a higher (lower) premium, member HOs should increase (decrease) their order quantities. From an individual member HO's viewpoint, behaving as a partial participant is economically rationalized especially if they have own warehouses and/or partnerships with private logistics companies (sometimes on a pro-bono basis), which is common among large HOs. Partial participants could enjoy a lower expected inventory cost than full participants. However, member HOs should keep in mind that the advantage of partially-participating behavior is diminishing as the trend of member HOs' demands becomes similar. They should carefully analyze demand patterns of disaster relief items which other member HOs store in warehouses of the UNHRD. The real time reports on member HOs' stocks provided by the UNHRD are a useful information source for them.

In closing the paper, we highlight four avenues for future research. The current model ignores the impact of member HOs' budget flexibility. Many HOs face several challenges of earmarked funds. How budget flexibility affects performance of horizontal cooperation is an important future research area. Secondly, considering the rapidly growing number of member HOs, how capacity of the UNHRD's warehouses and backup stock constraints affect horizontal cooperation is an important area for further research. Thirdly, a result obtained from the current model indicates that the UNHRD cannot set an applicable premium for backup stocks if some member HOs do not store their stocks in UNHRD's warehouses. The UNHRD may not have the authority to require member HOs to store a minimum stock level in UNHRD's warehouses. Exploring other coordination mechanisms under member HOs' partial involvement in the network is also an important future research area. Lastly, in the analysis of the multi-HOs case, comparing results between different stock allocation rules would be a promising research extension.

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Appendix: List of interviews

Organization	**Country**	**Types of organization**	**Position of interviewees**	**Date**
Cooperative for Assistance and Relief Everywhere (CARE)	US	NGO	Senior Manager Logistics and Operations Emergency	08.07.2014
United Nations Humanitarian Response Depot (UNHRD)	Italy	UN	Chief UNHRD Brindisi Manager & Deputy Network Coordinator	22.07.2014 08.07.2016
Japan International Cooperation Agency (JICA)	Japan	Government agency	Deputy Director General	30.07.2014
Lutheran World Relief (LWR)	US	NGO	Emergency Program Manager	04.11.2014
MercyCorps	US	NGO	Strategic Emergency Response Team	04.11.2014
Norwegian Church Aid's (NCA)	Norway	NGO	Head of Global Logistics	17.11.2014
World Vision	Australia	NGO	Global Lead - Emergency logistics	18.12.2014
ShelterBoX	UK	NGO	Supply Chain Manager	18.12.2014