Complexity and Self-Sustainment in Disaster Response Supply Chains

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ABSTRACT

Governmental organizations play a major role in disaster relief operations. Supply chains set up to respond to disasters differ dramatically in many dimensions that affect the cost of relief efforts. One factor that has been described recently is self-sustainment, which occurs when supplies consumed by intermediate stages of a supply chain must be provided via the chain itself because they are not locally available. This paper applies the concept of self-sustainment to response supply chains. A mathematical model of a self-sustaining response supply chain is developed. Analysis of this model yields insights about the relationships and interactions among self-sustainment, speed of disaster onset, dispersion of impact, and the cost of the relief efforts.

1. INTRODUCTION

Disasters in the recent years have offered many poignant lessons for governmental organizations. One of them is the economic reality of the cost of a disaster. The cost has risen dramatically, from US$16.1B/year in 1992-2001 to US$40B/year in 2002-2011 (Jones, 2013) and military logistics also contributes substantially to disaster response (Kress, 2002). Disaster relief consists predominantly of logistics and operations (Van Wassenhove, 2005; Thomas & Mizushima, 2005). Humanitarian logistics has been defined as "that special branch of logistics which manages response supply chain of critical supplies and services with challenges such as demand surges, uncertain supplies, critical time-windows in face of infrastructure vulnerabilities and vast scope and size of the operations" (Apte, 2009).

Disaster-response supply chains are generally much less efficient than commercial supply chains for many reasons, among them rapid set-up, short duration, limitations on infrastructure, and frequent changes and unpredictability in supply, demand and network configuration. A further driver of the relatively high cost of disaster-response operations is that, by their very nature, they often occur in regions where local infrastructure cannot be counted on to provide basic supplies like fuel and food and water for logistics personnel at the locations where they are required. In most supply chain models, the availability of the supplies for logistics activities is not modeled – implicitly, it is assumed that they are available at constant commercial prices. However, for response supply chains in disaster-struck regions this presumption does not hold true.

We define a self-sustaining response supply chain (SSRSC) as a supply chain that is set up in response to a disaster, where resources that are not locally available are consumed in intermediate stages and hence must be supplied through the chain itself. In a self-sustaining supply chain, the amount of resources that must be delivered at the beginning of the supply chain is substantially larger than the amount delivered to the ultimate consumer at the end of the supply chain. Due to this ‘multiplier effect,’ it has been shown that self-sustaining supply chains require more resources, manpower and equipment than locally supplied supply chains, resulting in significantly higher cost (Regnier, Simon, & Nussbaum, 2012; Regnier, Simon, Nussbaum, & Whitney, 2014).

Given that for every dollar spent in preparing for a disaster, seven dollars are saved during response (United Nations, 2007; World Meteorological Organization, 2010), an important lesson learned from recent disasters is to be prepared. Practitioners (Eisner, 2007; Fenton, 2008; Nelan, 2008) and scholars (Van Wassenhove, 2005; Kovács & Spens, 2007; Holguín-Veras, Jaller, & Wachtendorf, 2012; Celik, Ergun, Johnson, Keskinocak, Lorca, Pekgun, & Swann, 2012) agree that preparation is a significant part of a relief effort. To identify the most cost-effective preparations, it is critical to understand their true cost-saving impact in complex disaster-response operations. For example, resource-efficient transportation platforms such as amphibious vehicles may be more cost-effective than helicopters, especially in complex, self-sustaining operations. The capability of rapidly replacing nonfunctional infrastructure with workable structures such as portable bridges might also improve the supply chain’s resource-efficiency and cost effectiveness.

We investigate the impact of self-sustainment and complexity of the humanitarian response on the cost of operating SSRSCs. Disasters have been classified using the level of difficulty potentially present in humanitarian operations (Apte, 2009). The two dimensions for this classification are time (speed of onset) and location (dispersion) as classified by Apte and Yoho (2011) and reproduced in Figure 1. Our objective in this study is to investigate the impact of complexity on the cost in a self-sustaining supply chain, as a consequence of difficulty in humanitarian operations due to speed of onset and geographical dispersion. Given the focus of our research, our contribution is towards strategic planning rather than operational decision-making.

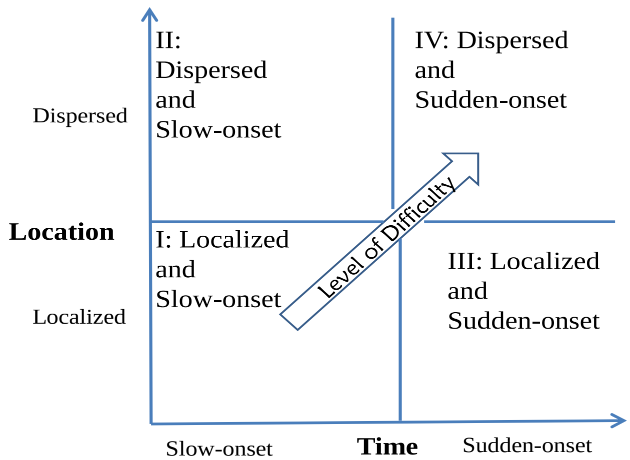

Figure 1: Classification of Disasters and Operational Complexity

We propose a model for costs of a SSRSC and use it to show that the total cost of operating a SSRSC increases based on the level of difficulty as described in Figure 1, and verify that there is a positive interaction effect between speed of onset and dispersion. We also show that self-sustainment is a driver of cost and its impact is higher for more complex supply chains. We believe these insights into the cost impact of self-sustainment, further influenced by speed of onset as well as dispersion of the disaster, will facilitate better decision making. With many competing demands for resources, a clear understanding of operational costs is imperative for improved planning and allocation decisions.

The article is organized as follows. In Section 2 we review the literature for sustainable supply chains and response supply chains. Section 3 describes the problem, and Section 4 develops and identifies the model. In Section 5 we present the results, and in Section 6 we offer the conclusion.

2. LITERATURE REVIEW

Our work synthesizes ideas from response supply chains and from self-sustainment. Supply chains in general have received substantial attention with the primary goal of unveiling the underlying causes for significant costs in any operation, in all sectors, private or public (Chopra & Meindl, 2013; Jacobs & Chase, 2013). The emphasis is often on demand uncertainties (Lee, 2002) and optimal distribution across a stable existing network (Chopra, 2003; Robeson & Copacino, 1994). For stable networks, optimization models are usually designed to balance cost with flexibility in managing significant disruptions in the supply network (Lim, Bassamboo, Chopra, & Daskin, 2008).

Recently, environmental legislation and social consciousness have shifted the focus to the closed loop and sustainability in supply chain management, leading to increased consideration of the environment and existing resources as factors in supply chain analysis (Ferguson & Souza, 2010; McKinnon et al., 2010). Walmart has been influential in bringing sustainability into the mainstream of supply chain management (Plambeck & Denend, 2010), illustrating the trend of companies realizing that profits and sustainability can co-occur.

Sustainability has been gaining traction in popular literature (McDonough & Braungart, 2010) as well as in academic literature (Seliger, 2007; Dey, LaGuardia, & Srinivasan, 2011; Wang & Gupta, 2011; McKinnon, Browne, & Whiteing, 2012).

Sustainable supply chains often achieve better short and long-term performance through reduction, reuse, and recycling—the latter two "R's" are often performed outside of the traditional supply chain (Kleindorfer, Singhal, & Van Wassenhove, 2005).

Sustainability is often achieved through a closed-loop supply chain (Guide & Van Wassenhove, 2009). In closed-loop supply chains, goods are refurbished or remanufactured after their initial use. Analyzing these supply chains requires expanding the perspective on resources – for example, goods once delivered may become inputs to further production – and a broader perspective on the supply chain. Cost can no longer be the only measure of resource requirements in the network, and therefore closing the loop requires additional modeling complexity.

Similarly, self-sustaining supply chains require a broader analysis than traditional supply chains, as models must account for the provision of the supplies and manpower consumed by logistics activities, which may not be assumed to be procured on the local commercial market. By definition, self-sustaining supply chains require that resources consumed while transporting supplies to their destinations be provided via the supply chain itself. Researchers (Dubbs, 2011; Hathorn, 2013; Regnier & Nussbaum, 2011) have identified the multiplicative effects of additional transportation distance and additional stages on cost in such situations. Self-sustaining supply chains occur commonly in military operations in austere environments, particularly in the early stages (Regnier et al., 2014).

Response supply chains are often set up and operated in extreme conditions in response to a crisis (Coombs, 1999). Whybark, Melnyk, Day, and Davis (2010) discussed the new realities and management challenges for disaster relief supply chains that function under extreme conditions. Private sector supply chain managers may get discouraged in these situations; however, there are lessons to be learned from them (Van Wassenhove, 2006). These supply chains in severe environments have to be researched for better planning.

Disaster response supply chains must be set up quickly with existing and available resources such as information and manpower (Dash et al., 2013), while the objective to minimize cost is always relevant. Apte (2009) provided a detailed look at the various forces at play in response supply chains. The field of response supply chains has been getting more attention as researchers identify the complexities involved in rescue operations. For example, Pedraza Martinez, Stapleton, and Van Wassenhove (2011) applied fleet management techniques to response supply chains. Guide and Van Wassenhove (2003) highlight the fact that disaster relief is an important and complementary area of study to sustainable supply chains.

To measure the cost incurred as a function of the level of complexity in a self-sustaining supply chain, it is important to be able to compute the 'real' fully burdened cost of resources as they are consumed and distributed across the supply chain. The impact of self-sustainment for logistics activities and the fully burdened cost associated with it is described by Regnier et al. (2014), which introduces terms such as 'self-sustaining supply networks' and 'fuel multiplier.' The underestimation of the costs in one particular resource – fuel – is critical to the United States Department of Defense.

3. THE PROBLEM

Our problem posits a supply network with three node types: Sources, coordination (warehousing) nodes, and demand nodes. Figure 2 shows the supply network with supplies sourced from outside the affected region, transported through coordination nodes, and delivered to meet demand in the affected region. We use the term austere, as in Figure 2, to refer to the region in which supplies are not available commercially and must be provided by the supply chain. Austerity is common in post-disaster environments, and therefore self-sustainment is often required. An open question is what impact the characteristics of disaster-response supply chains, such as speed and dispersion, have in a self-sustaining supply chain.

The source nodes supply resources such as water, food, and fuel. There may be many source nodes because there are different resources from suppliers, such as the franchises of Nutriset in several countries that produce and supply Plumpy'Nut to the malnourished children in the Horn of Africa through UNICEF (Swaminathan, 2009). There may also be different supply nodes because there are many donors. At coordination nodes, provisions or emergency supplies can be warehoused or handed off to be sent to the affected regions. Coordination node operations resemble the military practice of warehousing and coordinating defense inventory ashore or at sea to be used in the event of a conflict or disaster, as done during 2010 earthquake in Japan by US Navy.

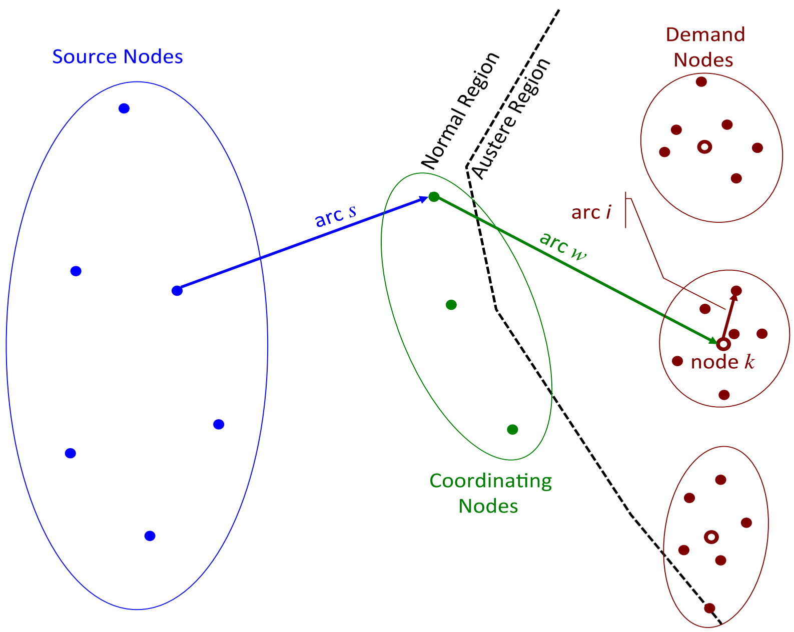

Figure 2: The supply network

The demand nodes make up the affected region; the intended consumers receive the transported resources at the demand nodes. When Hurricane Sandy left thousands of New Yorkers starving, the National Guard ended up providing 2.1 million Meals Ready to Eat (MREs) and more than 1 million bottles of water (Gibbs & Holloway, 2013) that were sourced from outside the region. In our network, the demand nodes may be grouped by region with coordination points within the region, as in a dispersed disaster that may cover many municipalities or countries.

Connecting nodes are arcs that represent the activities that are required to move resources from the originating node to the arc's destination node. This may involve convoy operations, including unloading, handling, distribution, and coordination activities at the destination node.

Disasters have been classified based on speed of onset and source (Van Wassenhove, 2005; Ergun, Heier, & Swann, 2008). In this research we use the classification given by Apte (2009) that is based on speed of onset and geographical dispersion. Sudden-onset and highly dispersed disasters have greater complexity in response operations due to lack of lead time and area affected.

3.1 Geographical Dispersion

Localized disasters can be distinguished from dispersed disasters on the basis of number of administrative entities, such as countries, states, or cities, across the affected geographical area (Apte & Yoho, 2011). A disaster affecting many municipalities, or even countries, will have a much larger geographical dispersion than a disaster striking a city or other small, administratively unified region. The large and scattered demand may increase the need for coordination among organizations, thus increasing the complexity of operations.

A supply network may also have many supply and coordinating nodes or long distances between them. One of the consequences of the modern highly dispersed supply chain is that many suppliers know little about where the items they provide come from (Fisher, 2011). In the case of a response supply chain with extreme characteristics of demand, supply, and infrastructure, this lack of understanding compounds the complexities. However, our focus in this work is primarily on geographical dispersion as it relates to affected area.

For example, the Indian Ocean Tsunami occurred in 2004 as a result of 9.1 magnitude earthquake and ended up taking 227,000 lives. More than 1.5 million persons were displaced in 12 countries. This disaster is classified as a highly dispersed disaster.

Although the damages occurred along the coastal region, they were spread across many countries, making the last-mile distribution efforts very challenging. On the other hand, Hurricane Katrina and the 2010 Haiti earthquake were localized, relative to the 2004 Indian Ocean Tsunami.

3.2 Speed of Onset

A sudden-onset disaster may be operationally complex even if it is localized because the short lead time prevents relief providers from preparing. On the other hand, for slow-onset disasters such as pandemic or famine, there can be more time to educate the public, identify and prepare distribution and coordination facilities, and pre-position appropriate inventory. In a slow-onset disaster, the supply network can incorporate economies of scale, as by using larger convoys and larger lot sizes due to the available lead time. In a sudden-onset disaster, shorter lead times, especially for resources such as food (Fisher, 2007), are necessitated due to the urgency and uncertainty of demand. Convoys may not always be full when deployed. Moreover, the food shortages caused by the disaster may force involving more out-of-region suppliers (Mahanta, 2013), leading to more and longer trips. Routing in response supply chains, in case of sudden-onset disasters, is difficult due to high and urgent demand, which often leads to repeated visits by vehicles, perhaps at the same destination, due to split deliveries (Ozdamar, 2013). In addition, damaged infrastructure may force longer routes despite the urgency of the demand.

For example, an earthquake is classified as a sudden-onset disaster; it strikes with almost no warning, making it difficult to provide immediate relief. A slow-onset disaster offers some advance notice, as in the case of Hurricane Katrina in 2005. It was known days in advance that the landfall might be in New Orleans. This allowed for some preparation, though it was deemed inferior from lessons learned subsequently (Holguin-Veras, Perez, Ukkusuri, Wachtendorf, & Brown, 2007).

3.3 Self-Sustainment

On many occasions, when a disaster strikes, basic supplies such as water become unavailable. We define the supply network, or the response supply chain, to be 'self-sustaining' if resources consumed by the relief activities must be provided through the supply network itself. The multiplier effect occurs when, due to self-sustainment in an austere region, the total resource requirement is substantially larger than the enduser demand. As first noted by Regnier & Nussbaum (2011), if the fuel required by transportation vehicles must be transported by the supply chain, then a naïve cost estimate of a multistage supply chain will underestimate the true cost of supplying the enduser. Equivalently, the fuel delivered to the enduser will be substantially less than the total fuel entering the chain. Figure 3 (Figure 1 from Regnier & Nussbaum (2011)) illustrates this in an example with a three-stage supply chain consuming and delivering a single resource – fuel. The consumption by the three stages is, respectively, 15%, 30%, and 20% of the amount delivered. To deliver 1000 gallons of fuel at the end of the supply chain, the initial supply must be 1794 gallons. This result demonstrates the multiplier effect. The multiplier for a given stage is an increasing and convex function of distance (Regnier et al. 2013). As we will observe shortly, it also depends on characteristics of the supply vehicles.

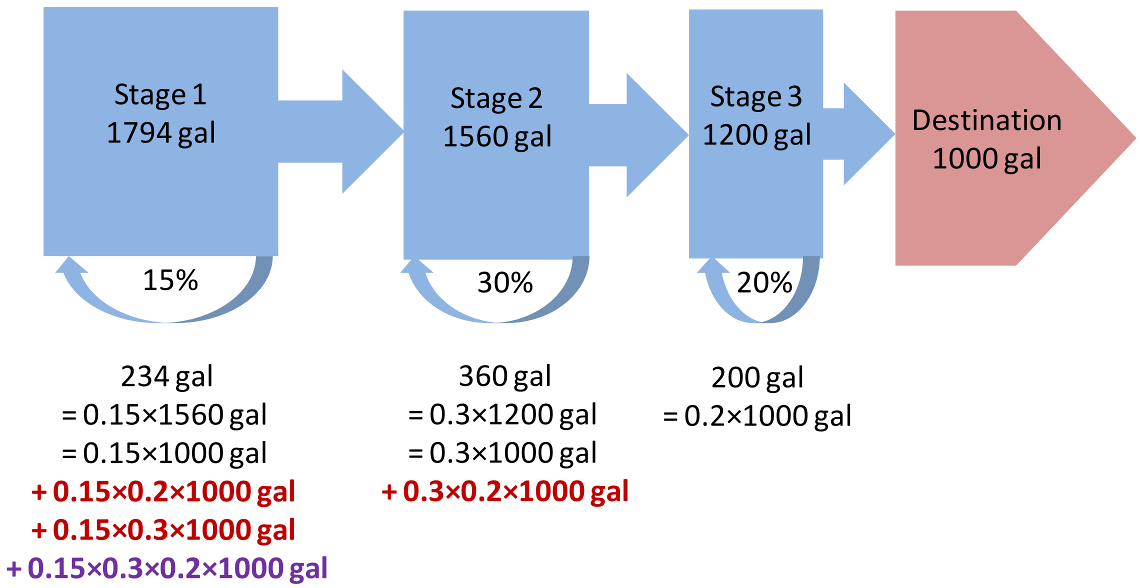

Figure 3. An Illustration of the Fuel Multiplier in a Self-Sustaining Supply Chain. Adapted from Regnier and Nussbaum (2011).

Dubbs (2011) and Hathorn (2013) estimated the fuel multiplier in real supply chains. Dubbs (2011) estimated that in Helmand Province in Afghanistan, the supply chain from Camp Leatherneck to a remote forward operating base consumed 72% as much fuel as it delivered. While sea-based transportation is generally more efficient, Hathorn (2013) estimated that, depending on the convoy composition, a supply route from San Diego to the Spratly Islands may consume 25% to more than 90% as much supply as it delivers to the warfighting vessel. In these models, the enduser is assumed to be a warfighting unit rather than a disaster-affected population, but the concept and impact of self-sustainment are the same.

4. MODEL

To explore the cost impact of speed of onset and dispersion in a SSSRC, we developed a mathematical model of SSSRCs. In our model, resources are transported from supply nodes to coordination nodes, on to regional demand nodes and finally to demand nodes.

Each arc is characterized by its resource consumption, to include consumption by activities such as unloading and distribution at the destination node.

To simplify the exposition, all resources are measured in standardized units, which may be thought of as volume or weight. It is further assumed that the appropriate proportions of various resources are transported on each stage. Relaxing this assumption would make each stage less efficient, and therefore further increase the cost impact of dispersion, speed of onset, and self-sustainment. In addition, all demand and consumption parameters are normalized to a fixed time interval which may be periodic (e.g. per day or per week) or to cover the entire period during which the SSRSC operates in the given configuration.

In general, a response supply chain becomes self-sustaining only in the affected region, which is often austere. Therefore, although we could model the impact of dispersion and speed of onset in the sources and warehouse/coordination portions of the supply network, we focus primarily on complexity in the portion of the supply network in the affected region, i.e. demand nodes and the arcs originating at coordination nodes.

Our model uses the following parameters:

Q_k: total demand in region k

n_k: number of demand centers in region k

z_a: round-trip distance on arc a

p_a: total capacity per trip on arc a

r_a: resource consumption per unit distance on arc a

q_a: amount delivered per trip on arc *a*, note that $q_a \le p_a - r_a d_a$

u_a: frequency of deliveries on arc *a*

c: average per-unit cost of resources

Arcs may be differentiated by type, $a \in \{s \in S, w \in W, l \in L,\}$, as illustrated in Figure 2, where *S* is the set of arcs from a supply node to a coordination node, *W* is the set of arcs from a coordination node to a demand transshipment node, and *L* is the set of arcs within the austere region from a demand transshipment node to a demand center.

To investigate the increased costs of such supply chains, it is useful to compute a multiplier for any given arc *a*, denoted λ_a. The multiplier specifies the amount of resources that must be delivered to the beginning of the arc per unit delivered to the end of the arc. If the resources consumed on arc *a* can be purchased or produced locally over the arc, then $\lambda_a = 1$; the only resources transported to the beginning of arc *a* are those which must be delivered to the end. However, if the resources consumed on arc *a* are *not* locally available, then $\lambda_a > 1$. In the latter case, we can compute λ_a based on parameters of the arc. If the transport vehicles are full at the start of the trip, then $q_a = p_a - r_a z_a$, and the multiplier can be computed as:

$$\lambda_a = \frac{p_a}{p_a - r_a z_a}. \tag{1}$$

If the transport vehicles are not filled to capacity, then $q_a < p_a - r_a z_a$, and the multiplier is instead computed as:

$$\lambda_a = \frac{q_a + r_a z_a}{q_a} . \quad (2)$$

(Note that these two expressions are equivalent for $q_a = p_a - r_a z_a$.) The total cost C_{swl} associated with delivering each unit of supply to demand center l from supply node *s* through warehouse node *w* (and the transshipment node in the region of demand center *l*) can then be expressed as:

$$C_{swl} = \lambda_s \lambda_w \lambda_l c . \quad (3)$$

The multiplier effect shown in (3) is caused by increased demands at intermediate nodes necessitating an increased number of round trips in earlier stages. The expression in (3) applies only when the total amount of resources supplied by the chain is large and many round-trips on each arc are required to meet demand.

As discussed earlier, speed of onset has multiple effects on the supply network, including smaller, partial, or poorly targeted loads and other inefficiencies. We operationalize speed of onset in this model in terms of $u_l, l \in L$, the frequency of deliveries required to the demand nodes. One way that frequency of deliveries affects costs is by decreasing the amount q_a delivered per trip on each arc — at least on the final arc, from transshipment node to demand center. For the focus of this paper, we will assume that u_l is equal for all l within region *k*, and that demand at each node is equal within region *k* (both u_l and q_a can be thought of as averages over region *k*). If the total demand in region *k* is Q_k, then $q_l = \frac{Q_k}{n_k u_l}$ for all $l \in L$ within region *k*.

A second impact of speed of onset is on the efficiency parameter r_a. Sudden-onset disasters may require the use of inefficient but available transportation assets, which would lead to larger value of r_a. We do not offer a specific functional form for these effects that would be difficult to generalize across disaster scenarios; instead we model this by assuming that:

$$\frac{dr_a}{du_a} = r_a'\left(u_a\right) \geq 0 . \qquad (4)$$

Dispersion also affects some of the parameters in the model. We model greater dispersion as reflecting a larger number of demand centers n_k in a given region and/or longer distances $z_l, l \in L$ within the region.

5. RESULTS

We consider the impact of the two components of complexity – speed of onset and dispersion – along with sustainment on the total cost per unit of supply delivered to a demand node by the supply network. To explore these relationships, we first analyze the qualitative impacts of the complexity parameters u_l, z_l and n_k and then present a numerical example.

Complexity affects cost in (3) via the multiplier on λ_l. Thus we will first show that there is a positive linear relationship between λ_l (or any single-arc multiplier) and total per unit cost. This is straightforward; we observe that the first derivative of C_{swl} with respect to λ_l is positive, and the second derivative is zero:

$$\frac{dC_{swl}}{d\lambda_l} = \lambda_s \lambda_w c > 0 \qquad (5)$$

and:

$$\frac{d^2 C_{swl}}{d\lambda_l^2} = 0. \tag{6}$$

Speed of Onset

Recall that speed of onset increases the frequency u_l of deliveries to demand nodes, and leads to a smaller amount delivered per trip, as well as an increase in consumption rate r_l (and perhaps increased consumption rate on earlier arcs as well). We can obtain an expression for λ_l that includes speed of onset by substituting the expression for q_l into (2), and noting that r_l is a function of u_l:

$$\lambda_l = \frac{Q_k / u_l n_k + r_l(u_l) z_l}{Q_k / u_l n_k} = \frac{Q_k + u_l n_k r_l(u_l) z_l}{Q_k}. \tag{7}$$

We can then differentiate (7) with respect to u_l to obtain the relationship between λ_l and the frequency of deliveries, recalling that $r_l'(u_l)$ is positive:

$$\frac{d\lambda_l}{du_l} = \frac{Q_k \left(n_k z_l \left(u_l r_l'(u_l) + r_l(u_l)\right)\right)}{Q_k^2} = \frac{n_k z_l \left(u_l r_l'(u_l) + r_l(u_l)\right)}{Q_k} > 0. \tag{8}$$

That is, an increase in the speed of onset with which resources must be delivered results in an increase in the final arc multiplier, and therefore an increase in total per unit cost.

Geographical Dispersion

Greater dispersion in the demand region is reflected in larger values of both z_l and n_k. We can compute the effect of each change on λ_l by differentiating the expression given in (7) by z_l and by n_k:

$$\frac{d\lambda_l}{dz_l} = \frac{u_l n_k r_l\left(u_l\right)}{Q_k} > 0 \tag{9}$$

and:

$$\frac{d\lambda_l}{dn_k} = \frac{u_l r_l\left(u_l\right) z_l}{Q_k} > 0\,. \tag{10}$$

Thus, each parameter change results in an increase of the final-arc multiplier. However, differentiating the expression in (7) by *both* parameters reveals that there is also a positive interaction between these changes:

$$\frac{d^2\lambda_l}{dz_l dn_k} = \frac{u_l r_l\left(u_l\right)}{Q_k} > 0\,. \tag{11}$$

Thus, total per unit cost is not only increasing in both z_l and n_k, but is increasing at a faster rate in each one when the other is larger. This is perhaps not a surprising result, but it helps validate the nature of the relationship between dispersion and cost analytically.

Complexity

As illustrated in Figure 1, the most difficult and hence complex humanitarian operations are in response to disasters which are *both* dispersed *and* sudden-onset, and thus combine the effects of the two factors just discussed. We find that, just as there was a positive interaction between the two components of dispersion, there is also a positive interaction between dispersion and speed of onset. This result is obtained by differentiating the expression in (7) with respect to both u_l and either n_k or z_l:

$$\frac{d^2\lambda_l}{du_l dn_k} = \frac{z_l\left(u_l r_l'(u_l) + r_l(u_l)\right)}{Q_k} > 0\,, \tag{12}$$

or similarly:

$$\frac{d^2\lambda_l}{du_l dz_l} = \frac{n_k\left(u_l r_l'(u_l) + r_l(u_l)\right)}{Q_k} > 0\,. \tag{13}$$

Self-Sustainment

In this section thus far, we have considered only the impact of speed of onset and dispersion on the final-arc multiplier λ_l and the proportionate impact on total cost. However, the multiplier effect in a multistage network further amplifies resource requirements and supply costs associated with self-sustaining networks. If the arc from the warehouse to the demand transshipment node is also self-sustaining, then $\lambda_w > 1$. We can obtain an expression for this multiplier using the same approach as was used for λ_l. The two differences here are that no term for the number of demand centers is needed, and the total demand must be multiplied by λ_l to account for the resources consumed by the vehicles on subsequent arcs.

$$\lambda_w = \frac{\lambda_l Q_k / u_w + r_w(u_w) z_w}{\lambda_l Q_k / u_w} = \frac{\lambda_l Q_k + u_w r_w(u_w) z_w}{\lambda_l Q_k}\,. \tag{14}$$

As observed earlier for the final arc, an increased speed of onset will result in a higher u_w, and hence a smaller amount delivered per-trip on this arc, and a greater consumption rate r_w. As done previously for the final arc, we can find the impact of an increased speed of onset by differentiating (14) with respect to u_w:

$$\frac{d\lambda_w}{du_w} = \frac{z_w\left(u_w r_w'(u_w) + r_w(u_w)\right)}{\lambda_l Q_k} > 0. \tag{15}$$

Thus, an increase in speed of onset results in an increase in both λ_l and λ_w. This is noteworthy, because yet another positive interaction arises; differentiating (3) with respect to these two multipliers yields:

$$\frac{d^2 C_{swl}}{d\lambda_l \lambda_w} = \lambda_s c > 0. \tag{16}$$

Therefore, for a multi-stage SSRSC, increased speed of onset is likely to have a considerable impact on total per unit cost.

Numerical Example

To explore the effects of complexity, we consider a numerical example with four cases: localized with slow-onset, localized with sudden-onset, dispersed with slow-onset, and dispersed with sudden-onset, with parameters shown in Table 1. We assume that resources are locally available only on the first stage, hence $\lambda_s = 1$ and $\lambda_w, \lambda_l > 1$.

Using the formulas in this section, together with (2) and (3), we can compute λ_w, λ_l, and C_{swl} for each case. Note that in this example, for each case and for every arc a, $q_a \le p_a - r_a z_a$, hence (2) is used instead of (1).

Table 1 illustrates the relationships between speed of onset, geographical dispersion, and per unit costs. The per unit costs are higher in the dispersed cases and in the sudden-onset cases, and there is a positive interaction between the two impacts. Since the per unit price of resources at the start of the chain is 1, the additional per unit cost due to the resource consumption of the supply chain is 0.20 in the localized & slow-onset case, and 2.00 in the dispersed & sudden-onset case. That is, ten times more resources are consumed by logistics activities in the dispersed with sudden-onset disasters.

		Speed of onset	
		Slow-onset $r_w = r_l = 0.1$ $u_w = u_l = 10$	Sudden-onset $r_w = r_l = 0.2$ $u_w = u_l = 20$
Dispersion	Dispersed $z_l = 50$ $n_k = 8$	$\lambda_w = 1.07$ $\lambda_l = 1.40$ $C_{swl} = 1.50$	$\lambda_w = 1.15$ $\lambda_l = 2.60$ $C_{swl} = 3.00$
	Localized $z_l = 25$ $n_k = 4$	$\lambda_w = 1.09$ $\lambda_l = 1.10$ $C_{swl} = 1.20$	$\lambda_w = 1.29$ $\lambda_l = 1.40$ $C_{swl} = 1.80$

Table 1. Numerical example showing the impacts of speed of onset and geographical dispersion on per unit costs between four hypothetical self-sustaining response supply chains. In this example, total demand $Q_k = 1000$; round-trip arc distances on the first two stages are $z_s = z_w = 100$; per-trip vehicle capacities are $p_s = p_w = 200, p_l = 100$, and the average per unit cost of resources $c = 1$.

The results of the numerical example demonstrate quantitatively the qualitative relationship suggested in Figure 1; the total per unit cost increases as the complexity due to increased difficulty of humanitarian operations increases.

6. CONCLUSION

Humanitarian operations are especially challenging –and costly–for reasons described earlier. The multiplier effect associated with self-sustainment, previously unexamined in the disaster response literature, contributes to the higher cost relative to traditional supply chains, since portions of disaster relief supply chains operate within austere regions. We find that the multiplier effect of self-sustainment not only adds to but compounds the cost impact of complexity – in terms of speed of onset and geographical dispersion. There is a positive interaction effect on cost between the two components of complexity, as well as between complexity and self-sustainment, indicating that logistical operations in complex self-sustaining disaster response supply chains will consume far more resources than a naïve model would predict.

This suggests that investments in resource-efficiency of disaster response logistics are especially valuable, and that certain categories of investments are more valuable than they would appear if the self-sustainment multiplier effect is neglected. A naïve cost-benefit analysis comparing two transportation platforms or two designs of coordination operations would compare the cost impact on a single arc in isolation. Our analysis shows that resource demands associated with logistics operations are more important than planners may realize, because in a self-sustaining supply chain, those resources incur indirect costs of transport to their point of use. A platform, such as an amphibious vessel, that has a high up-front cost but a relatively lower operational resource requirement, may be more cost-effective than a cheaper but more resource-intensive option. To capture the benefits of such a platform fully in an analysis, it is necessary to have a model of the likely environments in which the platform will be used. If it is likely to be used in complex self-sustaining supply chains, the benefits of improved efficiency will be far greater than they might immediately appear.

Planners typically have no control over the speed of onset of a disaster. However, they may be able to mitigate its impact on logistical costs. The cost increases we observed for sudden-onset disasters were due to more frequent deliveries of supplies and greater resource consumption due to vehicles and convoys not being fully loaded. Pre-positioning vehicles and/or supplies to be able to respond to sudden spikes in demand more efficiently could reduce the magnitude of these effects.

Regarding dispersion, our focus in this research was specifically on geographical dispersion. However, dispersion may not necessarily be geographical; it may involve other issues, since many entities such as government, non-government, and military organizations, along with private sector organizations, can be involved in humanitarian operations. These organizations may have different mission objectives and political motivations, and coordination among these players of the response supply chains would thus add another level of complexity to the logistics operations. These types of organizational dispersion are unlikely to affect physical arc distances, but are likely to involve more demand centers. In addition, they are likely to have many of the same impacts associated with greater speed of onset. Coordination challenges may lead to smaller convoys and smaller lot sizes, and thus to deliveries that are more frequent and less efficient. The magnitude of the impact on resource consumption will vary depending on the particular situation, but the overall qualitative impact is similar to that of geographical dispersion: it increases the additional resource demand imposed by self-sustainment.

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