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Supporting hurricane inventory management decisions with consumer demand estimates

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ABSTRACT

Matching supply and demand can be very challenging for anyone attempting to provide goods or services during the threat of a natural disaster. In this paper, we consider inventory allocation issues faced by a retailer during a hurricane event and provide insights that can be applied to humanitarian operations during slow-onset events. We start with an empirical analysis using regression that triangulates three sources of information: a large point-of-sales data set from a Texas Gulf Coast retailer, the retailer's operational and logistical constraints, and hurricane forecast data from the National Hurricane Center (NHC). We establish a strong association between the timing of the hurricane weather forecast, the forecasted landfall position of the storm, and hurricane sales. Storm intensity is found to have a weaker association on overall inventory decisions. Using the results of the empirical analysis and the NHC forecast data, we construct a state-space model of demand during the threat of a hurricane and develop an inventory management model to satisfy consumer demand prior to a hurricane making landfall. Based on the structure of the problem, we model this situation as a two-stage, two-location inventory allocation model from a centralized distribution center that balances transportation, shortage and holding costs. The model is used to explore the role of recourse, i.e., deferring part of the inventory allocation until observing the state of the hurricane as it moves towards landfall. Our approach provides valuable insights into the circumstances under which recourse may or may not be worthwhile in any setting where an anticipated extreme event drives consumer demand.

1. Introduction

Pre-positioning of critical supplies for an anticipated disaster like a hurricane, typhoon, or some other predictable event is an important humanitarian problem (Rawls and Turnquist, 2010; Salmeron and Apte, 2010). In this paper, we take advantage of a detailed dataset from a Texas Gulf Coast retailer that allows us to investigate how consumers respond to hurricane forecasts and how the retailer should manage hurricane inventories to meet consumer needs. Retailers of hurricane supplies play an integral role in hurricane disaster management. Hurricanes as devastating and costly as Sandy and Katrina focused a lot of public attention on retailers' planning and preparation as well as their responsiveness to these major disasters (see, for example, Assimon, 2009; Horwitz, 2009; Banjo, 2012; Target, 2016). Consequently, the focus of this paper is on key problems faced by a retailer providing supplies to customers preparing for such disasters: estimating hurricane demand and using this information to improve inventory management *before* a hurricane strikes.

As a hurricane advances across the Atlantic Ocean and into the Gulf of Mexico, consumers on the Texas Gulf Coast are faced with decisions regarding when to purchase supplies before the hurricane makes landfall. The retailer also faces difficult choices in terms of inventory management: if it reacts too quickly, it risks sending inventory to the wrong location, but if it waits to learn more about the location of the storm's landfall there is a risk that inventory shipments will not arrive in time to serve pre-landfall demand increases. Both of these outcomes result in unmet demand and lost sales. Unmet demand is particularly critical because it has the potential to exacerbate a humanitarian crisis. Even if no crisis materializes, shortages can still damage the retailer's reputation and lead to a loss of customer goodwill.

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There is a great deal of uncertainty in a hurricane's behavior, but, as we demonstrate in this paper, consumers do react to hurricane forecasts and purchase some products in a predictable fashion. In turn, retailers can use these patterns to establish inventory management policies to better serve consumers and meet their own goals. Using a large point-of-sale data set, operational and logistical constraints faced by the retailer, and hurricane forecast information from the National Hurricane Center (NHC), we build a state-space model for hurricane demand in the spirit of Song and Zipkin (1993, 1996). We calculate the state-space transition probabilities and then use regression to estimate demand in each state. To our knowledge, this is the first paper to estimate empirically hurricane demand and then determine the best inventory management policy.

Around this demand model, we develop an inventory management model for satisfying consumer demand prior to a hurricane's landfall. The retailer serves two separate regions out of a central distribution center (DC). Each region consists of many demand locations (i.e., retail stores), but since stores are clustered in each region around a population center some distance from the DC, we consider each region a point location relative to the DC. In addition, the DC releases inventory over at most two stages without the possibility of transshipment due to practical logistical and safety constraints. To match the retailer's logistical constraints, we use 5- and 3-day forecasts to define the two stages of the inventory management system. Thus, we model this situation as a two-stage, two-location inventory allocation model from a centralized DC. It is important to note that our modeling approach is not limited to a two-stage, two-location model. In other words, more stages and locations can be incorporated into our model if the requirements of the problem warrant it. Of course, more stages and more locations increase the number of states in the state-space model making it more complex to solve and requiring more data for accurate demand estimates.

The inventory model is designed to determine when and how much to allocate to each location prior to a hurricane strike by trading off the benefits of waiting to gain more precise demand information against the risk of responding too late to the hurricane demand and running short of pre-strike inventories at the stores. Additionally, the inventory model is used to evaluate the benefits of a full recourse policy over a no recourse policy. Recourse refers to the retailer's ability to make an initial allocation to each region and then make a second allocation decision after gathering more information about the forecasted landfall of the storm, including the possibility of learning that the storm is no longer a threat. This comparison is important to the retailer because additional costs (e.g., extra transportation) and extra safety issues (e.g., sending out personnel and equipment) are associated with the full recourse policy where decisions are made closer to a storm's landfall.

We contribute to two streams in the disaster inventory management literature. First, we know of no other study that explicitly estimates the linkage between storm forecast data and pre-strike consumer demand as opposed to making stylized or simplifying assumptions about this relationship. This empirical analysis reveals that the consumers' perception of and reaction to hurricane risk should be key drivers of the retailer's operating decisions. In particular, the demand risk of the retailer is not always proportional to the uncertainty of the hurricane's eventual landfall location. In addition, this analysis reveals two additional things. First, weather forecasts available to consumers through the news media contain a significant amount of predictive information on hurricane demand. Second, while we are able to establish a strong association between the timing of the hurricane weather forecast, the forecasted landfall position of the storm and hurricane sales, we observed that the hurricane storm intensity was not as influential.

As a second contribution, we construct an inventory management model based on our empirical analysis to explore subtle and complex relationships among the determinants of the value of a recourse action. Our inventory model informs managers about when to follow a recourse policy and partially defer inventory allocations to gain more precise information about the possible path of the hurricane. Since simplifying assumptions of the previous literature do not directly apply to our model and the optimal inventory policy is not myopic, we solve a two-stage stochastic program with recourse and show how the following parameters impact the value of recourse: (1) initial DC inventories, (2) shortage costs relative to holding costs, (3) transportation costs relative to holding costs (4) forecast of the hurricane's landfall location, and (5) hurricane path uncertainty. We find high initial DC inventories motivate the managers to defer inventory allocations though the effect exhibits decreasing marginal returns. Uncertainty in the hurricane's path has a similar effect and motivates the managers to wait more before making large inventory allocations. During the threat of a hurricane, shortage costs tend to dominate as a reflection of the retailer's efforts to help mitigate a humanitarian crisis and maintain customer goodwill. As a result, we analyze the impact of increased relative shortage cost on the value of recourse. Counter to intuition, relative shortage cost does not have a monotone effect on the value of recourse. Its impact depends on the level of DC inventories as well as the initial forecast of the hurricane's landfall location. Not surprisingly, increasing transportation costs dampen the value of recourse. Lastly, we find the initial forecast of hurricane landfall location is a key driver of the value of recourse which ranges from 5% to more than 40%.

Our work allows the retailer to be more effective at hurricane inventory management and humanitarian relief because it provides a more rigorous evaluation of recourse. Historically, the retailer had used a single allocation, no recourse approach, and had moved to experimenting with ad hoc two-stage allocation policies. We were able to provide improved policies and demonstrate the value of recourse under differing circumstances. Ultimately, our work, in conjunction with other initiatives, enabled the retailer to participate in a statewide initiative to improve hurricane disaster preparedness in the state of Texas (Texas Emergency Management Digest, 2009), particularly for residents of the Texas Gulf Coast. Such public-private collaborations have become common during natural disasters as chronicled in Raths (2010). This article describes partnership arrangements between retailers and state officials in California and Texas. In Texas, retailers work directly with state officials and the state emergency operations center during hurricanes and other natural disasters to provide humanitarian relief.

2. Literature review

Our work is related to Regnier and Harr (2006) who develop a Markov model for hurricane path analysis and show how decision makers can benefit from the option to wait for updated hurricane forecasts when managing evacuations. Regnier (2008) applies a stochastic model of hurricane paths in a dynamic decision-making framework for evacuation policies. Our paper differs from these studies in several respects. First, we take the perspective of a retailer seeking to allocate hurricane inventory to its retail stores to meet pre-strike demand. Second, in addition to the hurricane's path, customer response to the evolution of the hurricane's location and intensity is stochastic in our model. We present an empirical analysis of customer demand to identify the linkage between the hurricane's intensity and forecasted path, and retail demand which is used as an input to our inventory model. Finally, unlike an evacuation decision which is difficult to adjust, inventory

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