A Simulation Model for Retail Forecasting During the Threat of a Hurricane*

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Outline

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Problem Description

- Forecasting and replenishment problem for a Texas Gulf Coast retailer during a hurricane threat.
  - Greater focus in this presentation: forecasting model
- Multiple retail locations segmented into two regions.
- Multiple products.

Problem Description (cont'd)

- The retailer's forecasting and replenishment system has two modes:
  - Regular operations
    - Forecasting: highly automated with limited manual intervention.
    - Replenishment: pull system using point of sale scanner data.
  - Hurricane operations
    - Forecasting: centralized "war-room" mode with a great deal of manual intervention.
    - Replenishment: push system.

Decision Framework

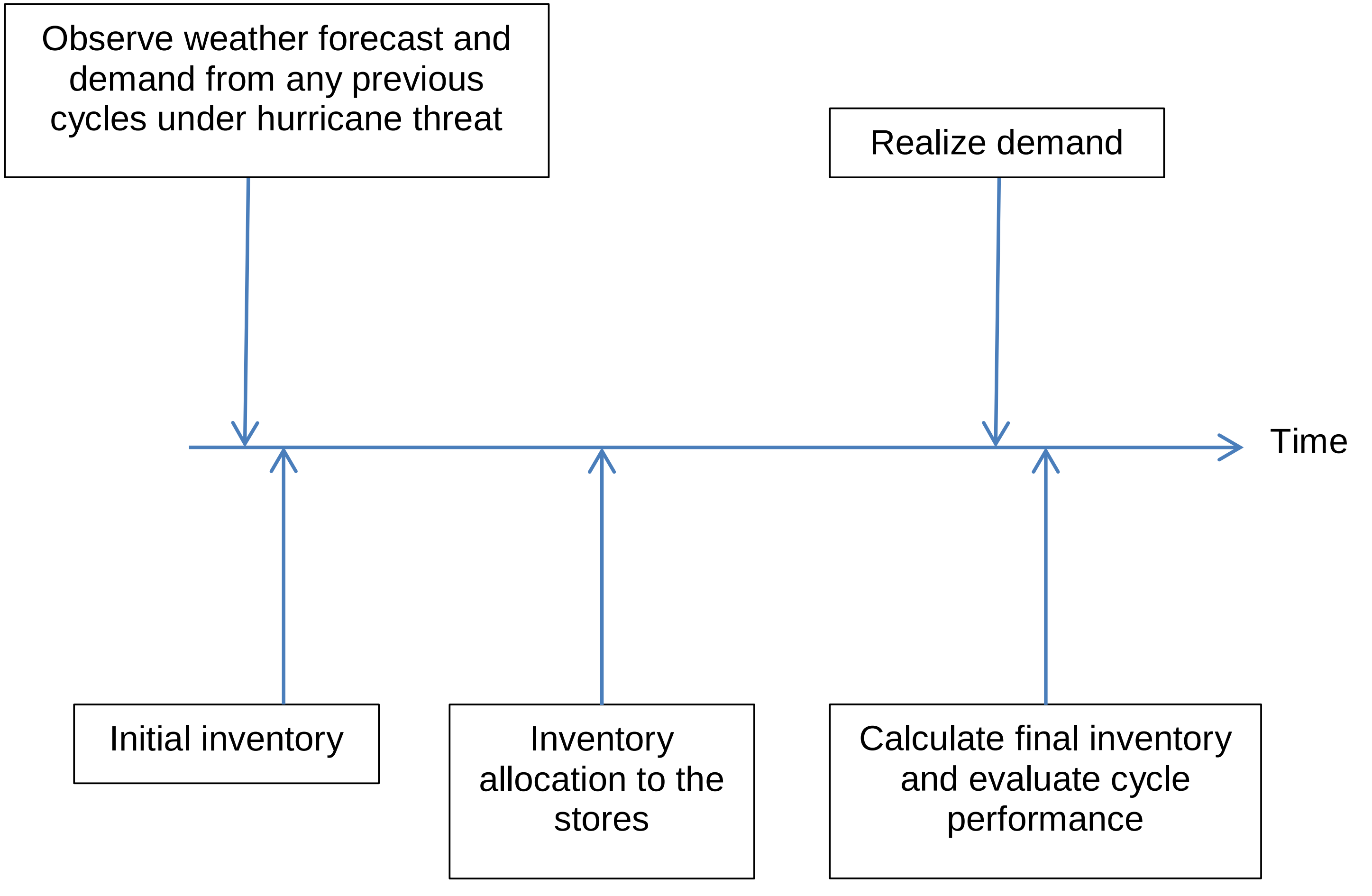


Figure 1: A cycle in the forecasting and replenishment decision-making process during the threat of a hurricane

A State-Space Model for Hurricane Demand Based on Weather Forecasts

- The US National Weather Service provides forecast updates every six hours during a hurricane. Since 2003, each forecast includes 3- and 5-day forecast cones.

Figure 2: Five and Three-Day Weather Forecast for Hurricane Emily (2005) (Source: www.nhc.noaa.gov/archive/2005/EMILY_graphics.shtml)

Texas Gulf Coast Regions

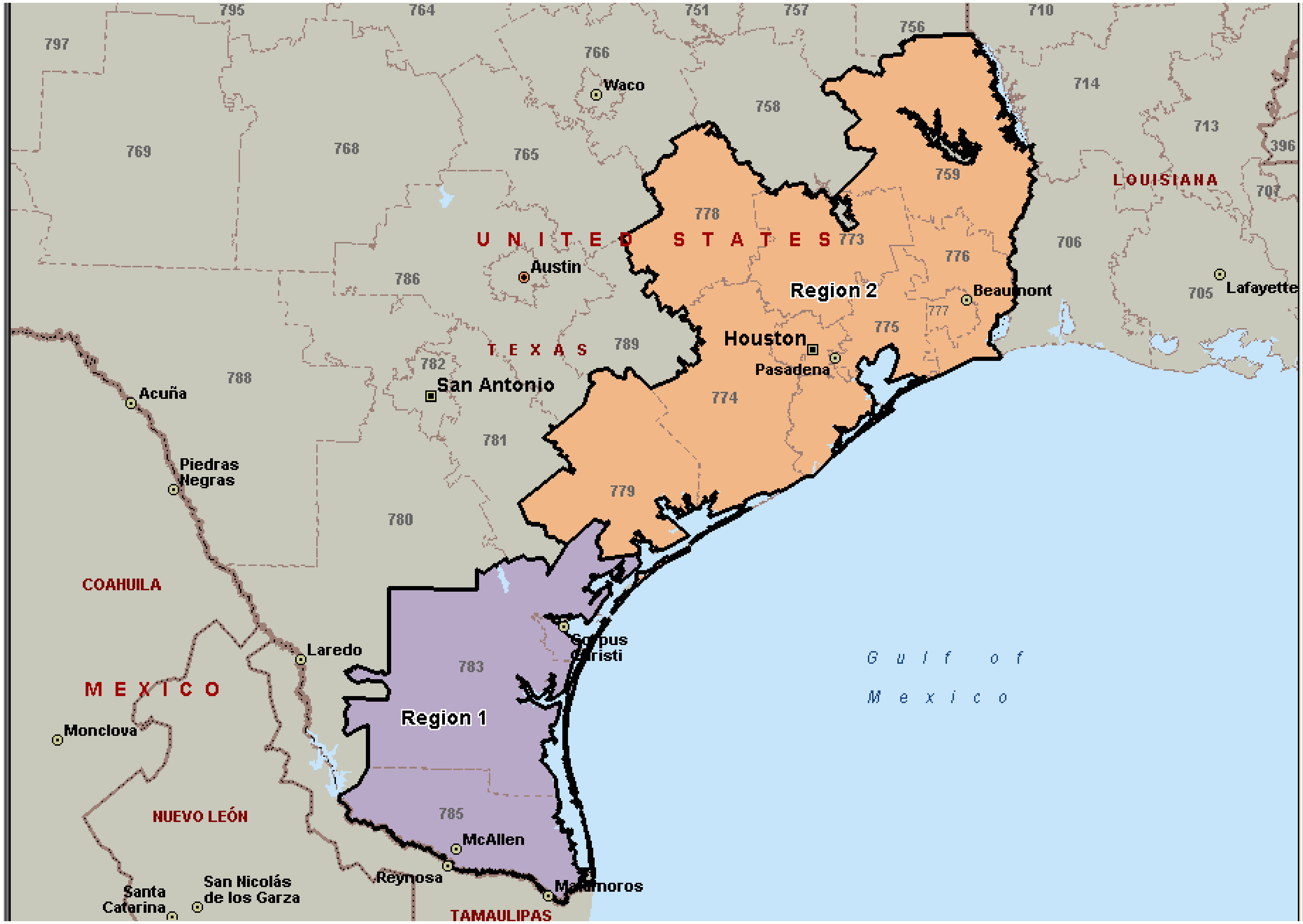


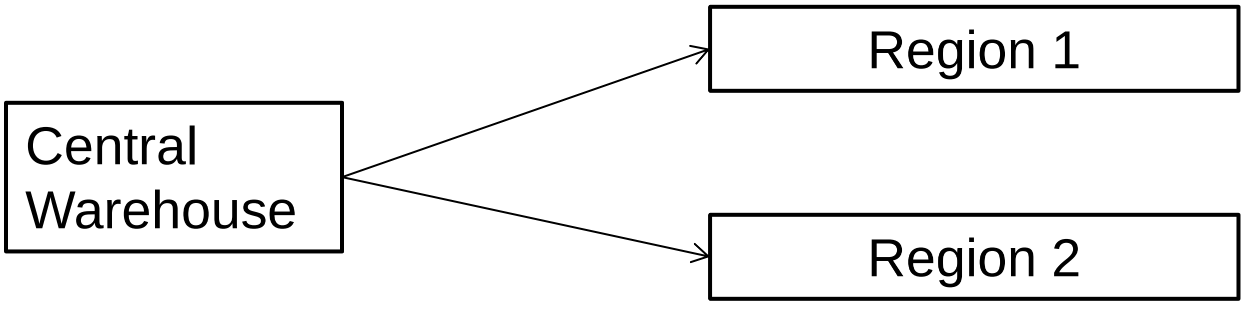
Figure 3: Regions along the Texas Gulf Coast Defined by Three Digit Zip Code Clusters (Source: Microsoft MapPoint)

Hurricane Threats

- Any hurricane that forms in the Atlantic (which includes Caribbean Sea and the Gulf of Mexico) is monitored by the retailer.
- The retailer makes an allocation decision only when the hurricane becomes a threat to at least one of its regions.
- There are two main threat epochs which trigger an allocation:
  1. the first time the 5-day forecast cone intersects at least one region and
  2. the first time the 3-day forecast cone intersects at least one region.
- In the eyes of the retailer and its customers, these represent different levels of threat so the allocation decisions need not be equivalent.

Proposed Inventory Allocation Model

- We consider a two-phase, two-location model.



Why?

1. Good place to start mathematically for insights.
2. Hurricane inventories are released out of a centralized warehouse (depot).
3. A two-phase release of hurricane inventory coincides with the 5 and 3-day forecasts.
4. There are two main population regions impacted by two main types of storms along the Texas Gulf Coast.

Related Literature

- Hurricane/Disaster Management
  - Bril (1995), Elsner and Jagger (2004)
  - Regnier and Harr (2006), Regnier (2008)
  - Taskin and Lodree (2009, 2010), Lodree (2011)
- Inventory Management
  - Eppen (1979), Eppen and Schragge (1981)
  - Federgruen and Zipkin (1984), McGavin (1997)
  - In the spirit of Song and Zipkin (1993, 1996)

Threatening Storms Between 2003-2008

Table 1: Threatening Storms between 2003 and 2008 Along with Their Characteristics

Storm Name	Year	First Time 5-day Forecast Cone Intersects Region				First Time 3-day Forecast Cone Intersects Region			
		Date	Forecasted Region of Impact	Current Intensity	Forecasted Intensity	Date	Forecasted Region of Impact	Current Intensity	Forecasted Intensity
Bill	2003					6/29/2003	2	Tropical Storm	Not Available
Claudette	2003	7/8/2003	Both	Tropical Storm	Not Available	7/10/2003	Both	Tropical Storm	Not Available
Erika	2003					8/14/2003	1	Tropical Storm	Not Available
Grace	2003					8/30/2003	Both	Tropical Depression	Not Available
Ivan	2004					9/22/2004	Both	Tropical Depression	Tropical Storm/Tropical Depression
Cindy	2005					7/3/2005	Both	Tropical Depression	Tropical Storm
Emily	2005	7/14/2005	1	Category 2	Hurricane	7/16/2005	1	Category 4	Hurricane
Rita	2005	9/18/2005	Both	Tropical Depression	Hurricane	9/20/2005	Both	Category 1	Hurricane
Dean	2007	8/17/2007	Both	Category 2	Hurricane				
Erin	2007					8/14/2007	Both	Tropical Depression	Tropical Storm/Tropical Depression
Humberto	2007					9/12/2007	2	Tropical Depression	Tropical Storm
Dolly	2008					7/20/2008	1	Tropical Storm	Tropical Storm
Eduardo	2008					8/3/2008	Both	Tropical Depression	Tropical Storm
Gustav	2008	8/27/2008	2	Tropical Storm	Hurricane	8/30/2008	2	Category 2	Hurricane
Ike	2008	9/7/2008	2	Category 4	Hurricane	9/9/2008	Both	Category 1	Hurricane

A State-Space Model For Hurricane Demand

Table 2: Description of the State-Space Model Variables

Variable	Description
Type of Forecast	• Assumes the value 1 when the first forecast cone to intersect at least one retailer region is the 5-day forecast cone. It no longer assumes the value 1 when the 3-day forecast cone intersects at least one retailer region or no forecast cone intersects at least one retailer region (note: the storm may move off in a different direction and cease to be a threat to the retailer regions). • Assumes the value 2 when the first forecast cone to intersect at least one retailer region is a 3-day forecast cone. It ceases to assume the value 2 when the storm makes landfall or no forecast cone intersects at least one retailer region. • Assumes the value 3 when a 3-day forecast cone that follows a 5-day forecast cone intersects first intersects at least one retailer region. It no longer takes on the value 3 when the storm makes landfall or no forecast cone intersects at least one retailer region.
Forecasted Region of Impact	1 = Region 1; 2 = Region 2; 3 = Both.
Current Intensity	1 = Tropical storm/tropical depression; 2 = Category 1 or 2 Hurricane; 3 = Category 3, 4, or 5 hurricane.
Forecasted Intensity	0 = Tropical storm/depression; 1 = Hurricane;
Region	1 = Region 1; 2 = Region 2

State Dependent Demand Forecasts

- We examined the retailer's point-of-sales data for two products (referred to as "Product 1" and "Product 2") that were included as part of the hurricane inventories from 2003 to 2008 for stores in Regions 1 and 2.
- The data set for each product contained over 300,000 records.
- Sales (or "censored demand") were used as a proxy for demand because the retailer tries to achieve very high levels of in-stock service during hurricanes which captures most of the true demand.
- The products were chosen due to their differing characteristics:
  - Product 2 has more variable regular sales but is considered an important staple during a natural disaster.
  - Product 1 has the opposite characteristics. In other words, Product 1 has relatively predictable regular sales and is considered desirable but less vital during a crisis situation.
  - By analyzing multiple products, we demonstrate that patterns found in the data due to a hurricane threat are common across products, even with differing characteristics, and that these patterns can be modeled in a similar fashion.

State Dependent Demand Forecasts

- Step 1: A Model for Regular Sales
  - Same model is used for both products

$$Sales_i = \beta_0 + \sum_{k=2}^{12} \beta_{Month_k} Month_k + \beta_{time} Time + \sum_{j=1}^{n-1} \beta_{store_j} Store_j + \sum_{j=1}^{n-1} \beta_{store_j time} Store_j Time + \varepsilon_i \quad \textbf{(1)}$$

Table 3: Variable Definitions for the Regression Model for Regular Sales

Variable	**Description**
Month	Season dummy variables (January is base case)
Time	Time trend (monthly)
Store	Stores are indexed from i=1,…,n with each i representing a different store. $Store_i = 1$ if the observation is from $Store_i$ and 0 otherwise. Store n is left as the base case.
Store*Time	Interaction term that accounts for changes in store demand over time. This should account for expansion in store size or changes in the population served. Changes in demand to due to addition or removal of stores in the area should also be captured.

  - The model in (1) has adjusted-R^2 values of approximately 0.77 and 0.26 for Products 1 and 2, respectively

State Dependent Demand Forecasts

- Step 2: A Model for Hurricane Sales
  - Model (1) was used to remove the regular sales from the data. The residual sales were used to obtain a model for hurricane demand in each state.

Table 4: Definitions of the Main Effects Predictor Variables in the Hurricane Sales Regressions

Variable	Notation	Description
Type of Forecast	TOF_i	$TOF_i = 1$ if the type of forecast is i; 0 otherwise, for $i = 1,2,3$.
Forecasted Region of Impact	FRI_i	$FRI_i = 1$ if the forecasted region of impact is i; 0 otherwise, for $i = 1,2,3$.
Current Intensity	CI_i	$CI_i = 1$ if the current intensity is i; 0 otherwise, for $i = 1,2,3$.
Forecasted Intensity	FI_i	$FI_i = 1$ if the forecasted intensity is i; 0 otherwise, for $i = 1,2$.
Region	R_i	$R_i = 1$ if the region is i; 0 otherwise, for $i = 1,2$.
Product	P_i	$P_i = 1$ if the product is i; 0 otherwise, for $i = 1,2$.
Residual Lagged Sales	RLS	Residual hurricane sales from any previous cycle

State Dependent Demand Forecasts

- Step 2: A Model for Hurricane Sales (cont'd)
  - Results for Product 2:

Table 5: Hurricane Sales Residuals Regression Model Results for Product 2

Model	**Adjusted-R^2**
Y=$\beta_0 + \beta_{RLS}RLS + \beta_{FRI_3}FRI_3 + \beta_{FRI_1*R_1}FRI_1 * R_1$	0.63
Y=$\beta_0 + \beta_{TOF_3}TOF_3 + \beta_{FRI_3}FRI_3 + \beta_{TOF_3*R_1}TOF_3 * R_1 + \beta_{FRI_1*R_1}FRI_1 * R_1$	0.60

  - Results for Product 1:

Table 6: Hurricane Sales Residuals Regression Model Results for Product 1

Model	**Adjusted-R^2**
Y=$\beta_0 + \beta_{RLS}RLS + \beta_{TOF_3}TOF_3 + \beta_{TOF_3*R_1}TOF_3 * R_1 + \beta_{FRI_1*R_1}FRI_1 * R_1$	0.56
Y=$\beta_0 + \beta_{TOF_3*R_1}TOF_3 * R_1 + \beta_{FRI_1*R_1}FRI_1 * R_1$	0.47
Y=$\beta_0 + \beta_{TOF_3}TOF_3 + \beta_{FRI_3}FRI_3 + \beta_{TOF_3*R_1}TOF_3 * R_1 + \beta_{FRI_1*R_1}FRI_1 * R_1$	0.50

- Note:
  1. The response (denoted by Y) in the above regression models is the square root of the shifted hurricane sales residuals
  2. Differences in storm intensity (either current or forecasted) did not show as significant factors. Forecasted timing and location of storms were significant.

Estimating State Transition Probabilities

- From Table 1:
  - $\hat{P}(TOF_1 = 1) = 0.4$ and $\hat{P}(TOF_2 = 1) = 0.6$
  - $\hat{P}(TOF_3 = 1|TOF_1 = 1) = 0.83$

Table 7: Conditional Probabilities Estimates for the Forecasted Region of Impact on $TOF_1 = 1$ and $TOF_2 = 1$

	$FRI_1 = 1$	$FRI_2 = 1$	$FRI_3 = 1$
$\hat{P}(FRI_i = 1\|TOF_1 = 1)$	0.167	0.333	0.5
$\hat{P}(FRI_i = 1\|TOF_1 = 2)$	0.222	0.222	0.556

Table 8: Estimates for the Non-Zero Conditional Probabilities Associated with The Transition from 5 to 3-day Forecast Threat Levels

Conditional Probability	**Estimate**
$\hat{P}\left(FRI_1^{(3)} = 1\middle\|TOF_3 = 1, FRI_1^{(1)} = 1\right)$	0.8
$\hat{P}\left(FRI_3^{(3)} = 1\middle\|TOF_3 = 1, FRI_1^{(1)} = 1\right)$	0.2
$\hat{P}\left(FRI_2^{(3)} = 1\middle\|TOF_3 = 1, FRI_2^{(1)} = 1\right)$	0.8
$\hat{P}\left(FRI_3^{(3)} = 1\middle\|TOF_3 = 1, FRI_2^{(1)} = 1\right)$	0.2
$\hat{P}\left(FRI_3^{(3)} = 1\middle\|TOF_3 = 1, FRI_3^{(1)} = 1\right)$	1

Forecasting Simulation Algorithm

1) n = 0
2) Sample for the Type of Forecast, either 1 or 2.
3) Given the Type of Forecast from step 2), sample from the conditional distribution for the Forecasted Region of Impact from the conditional probabilities in Table 7.
4) Select the Region of interest.
5) Select the Product of interest.
6) Plug the values obtained from steps 2) - 5) into the appropriate regression model from Tables 5 or 6.
7) Sample from the error distribution associated with the regression model and add this to the result from step 6).
8) Square the result in step 7) and subtract off the appropriate shift parameter. Store the result.
9) If Type of Forecast = 1 then
    a. Sample to determine whether or not the Type of Forecast = 3.
    b. If Type of Forecast = 3 then
        i. Sample for the Forecasted Region of Impact using the conditional probabilities in Table 8.
        ii. Plug the values obtained from steps 4), 5), 9a), and 9b i) into the appropriate regression model from Tables 5 or 6.
        iii. Sample from the error distribution associated with the regression model and add this to the result from step 9b ii).
        iv. Square the result in step 9b iii) and subtract off the appropriate shift parameter. Store the result.

    Else storm dissipates; go to step 10).

   Else go to step 10).
10) n = n + 1
11) If n = N then
    a. Compute histograms for each state of interest.
    b. Stop.

   Else go to step 2).

Simulation Validation

- We constructed histograms of simulated residual sales for the six states defined by the pair of state variables $TOF_i, i = 1,2,3$ and $R_i, i = 1,2$ using Algorithm 1.
- We limited ourselves to these states because they capture the two of the most important factors of interest to the retailer management: threat level of the storm and location of hurricane sales.
- Trying to look at more states resulted in very limited amounts of historical data in certain states making validation difficult.

Simulation Validation Results

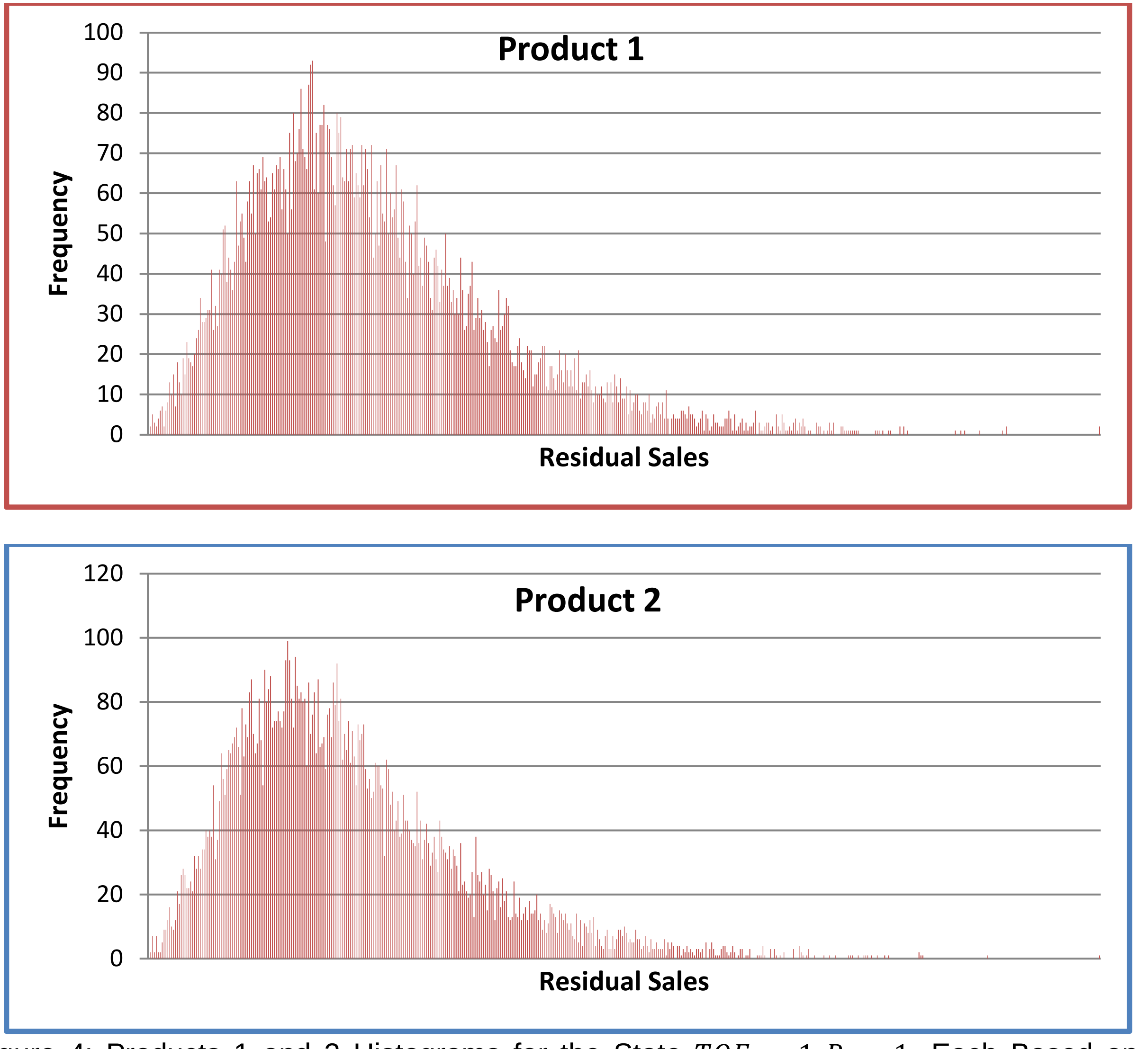


Figure 4: Products 1 and 2 Histograms for the State $TOF_3 = 1, R_1 = 1$, Each Based on a Simulation Sample Size of $N = 10{,}000$

Simulation Validation Results (cont'd)

Table 9: Percentage of Actual Historical Data for Product 1 Falling Between the 5th and 95th Percentiles of the Simulated Residual Sales Distributions.

	$TOF_1 = 1$ (# of Actual Historical Observations = 6)	$TOF_2 = 1$ (# of Actual Historical Observations = 9)	$TOF_3 = 1$ (# of Actual Historical Observations = 5)
$R_1 = 1$	83.33	89	100
$R_2 = 1$	100	100	100

Table 10: Percentage of Actual Historical Data for Product 2 Falling Between the 5th and 95th Percentiles of the Simulated Residual Sales Distributions.

	$TOF_1 = 1$ (# of Actual Historical Observations = 6)	$TOF_2 = 1$ (# of Actual Historical Observations = 9)	$TOF_3 = 1$ (# of Actual Historical Observations = 5)
$R_1 = 1$	100	89	80
$R_2 = 1$	100	100	60

Proposed Forecasting and Replenishment Procedure

1. Simulate weather forecast
2. Simulate demand based on the state of the hurricane weather forecast using the aforementioned regression models
3. Derive an inventory allocation policy that specifies the decisions of how much hurricane inventory to hold at the warehouse(s), and when, where and how much to allocate in order to minimize costs.

Next Steps: Inventory Model

- Two cases:

1. First forecast threat is a 3-day forecast: newsvendor model.
2. First forecast threat is a 5-day forecast: two-stage dynamic program.

Questions/Discussion