

## ABSTRACT

Ports play a vital role in the economy of nations and provide a critical link in the supply chain. Ports form the gateway by which essential goods are received within large geographic regions. Because of their function, ports are exposed to substantial risk of flooding, storm events, sea-level-rise, and climate change. The resiliency of ports is essential for the economy, the people, and national readiness. The contribution of this research work is in providing a methodology to quantify port resiliency that is applicable at the individual port level and regionally. The research approach first defines a quantifiable measure of systematic resiliency. Then applies this measure to quantify the resiliency of six ports located in the Southeast U.S. impacted by Hurricane Matthew (2016). Based on the analysis of these individual ports, a regional resiliency assessment is then applied to quantify the regional resiliency of the impacted area. In general, the results showed that regionally, ports are more resilient to disruptive events than the individual ports that make up the region. This was likely because as one port enters the disrupted state, another may be entering the recovery state providing regional continuity. This may suggest that port clusters rely upon each other during disruptive events to increase the overall resiliency of waterborne commerce. In general, the study ports struggled to absorb the impact of the storm and subsequent closures, whereas adaptability and recovery were significantly higher.



## INTRODUCTION

Hurricanes, oil spills, and labor disputes can all be sources of port disruptions. Hurricane Sandy in October 2012 closed the Port of New York/New Jersey for over a week from full operations. The hurricane caused flooding, loss of power, and damages to the port that prevented the ports from reopening immediately. It was estimated by the Port Authority of New York and New Jersey (PANYNJ) that the port closure cost \$170 million [1]. Between the time the port partially reopened (three days after landfall) and the time the port returned to full operation (eight days after landfall), dwell times of vessels trying to enter the port climbed as high as 50 hours [2]. The overall impact of a disruption on a port is a function of vulnerability of the port and the severity of the disruption. The resiliency of ports and inland waterways is critical for maintaining the flow of essential goods throughout the United States and is critical to national security and defense readiness.

According to the National Science Foundation, **resiliency is the ability “to prepare and plan for, absorb and recover from, or more successfully adapt to actual or potential adverse events”**. [3] This definition can be quantified for a value between zero and one for all discrete systems.



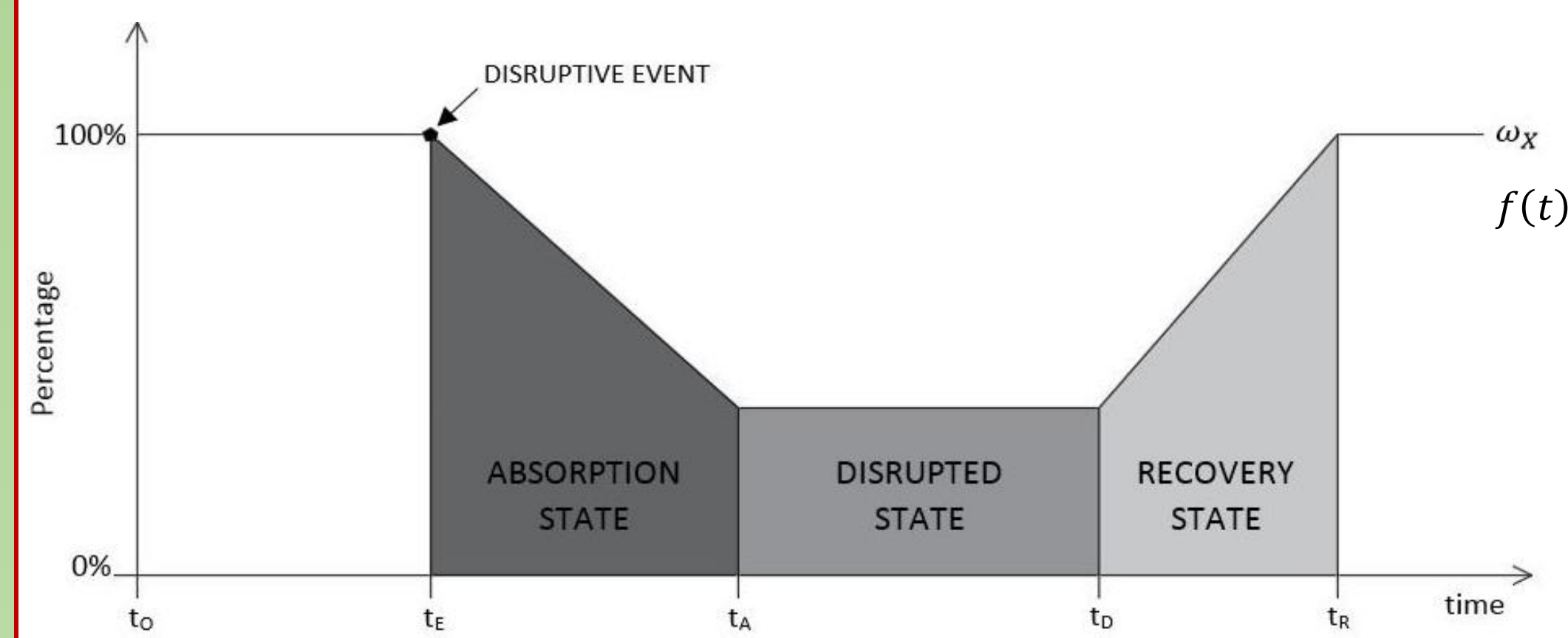
[1] Smythe, T. C., PhD. (2013, May 31). Assessing the Impacts of Hurricane Sandy on the Port of New York and New Jersey's Maritime Responders and Response Infrastructure  
[2] Farhadi, N., Parr, S. A., Mitchell, K. N., & Wolshon, B. (2016). Use of Nationwide Automatic Identification System Data to Quantify Resiliency of Marine Transportation Systems.  
[3] National Science Foundation. Resilient Interdependent Infrastructure Processes and Systems (RIPS). 2006.

## METHODOLOGY OF RESILIENCY INDEX

### DEFINITION OF RESILIENCY

According to the National Science Foundation, resiliency as the ability “to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events”.

To find a quantifiable value for resiliency in correspondence to this definition, the functionality after the disruptive event has been broken down into three states. The absorption state, disrupted state, and recovery state. This model shows functionality vs time.



### ABSORPTION STATE

System functionality between  $t_E$  and  $t_A$  can be used as a direct measure of absorption. In particular, the change in time with respect to functionality, i.e. the inverse of the slope, is an intuitive measure of the system's ability to absorb. This value can also be normalized between zero and one, by the inverse tangent function. Equation 1 represents the system's ability to absorb the impact the event. If the absorption state is 1.0, the disruption had no effect on the system. However, a sharp, negative slope indicates poor absorption and results in value closer to zero.

$$R_A = 1 - \left| \frac{2 \tan^{-1} \left( \frac{\Delta Y}{\Delta t} \right)}{\pi} \right|$$

### DISRUPTED STATE

The functionality during the disrupted state represents the system's ability (or lack thereof) to adapt to the adverse conditions and overcome the disruption. While system performance is no longer decreasing, the inability to “bounce back” is measured in the disrupted state. Equation 3 provides a measure, between zero and one, for the system's ability to quickly adapt to the new conditions which exist after the disruption.

$$R_d = 1 - \frac{t_0 - t_a}{t_r - t_e}$$

### RECOVERY STATE

Similarly, the system's ability to recover, can also be measured by the inverse of the slope within the recovery state,  $t_D < t < t_R$ . Equation 2 quantifies the system's recovery after a recovery action has been taken.

$$R_R = \left| \frac{2 \tan^{-1} \left( \frac{\Delta Y}{\Delta t} \right)}{\pi} \right|$$

### RESILIENCY INDEX

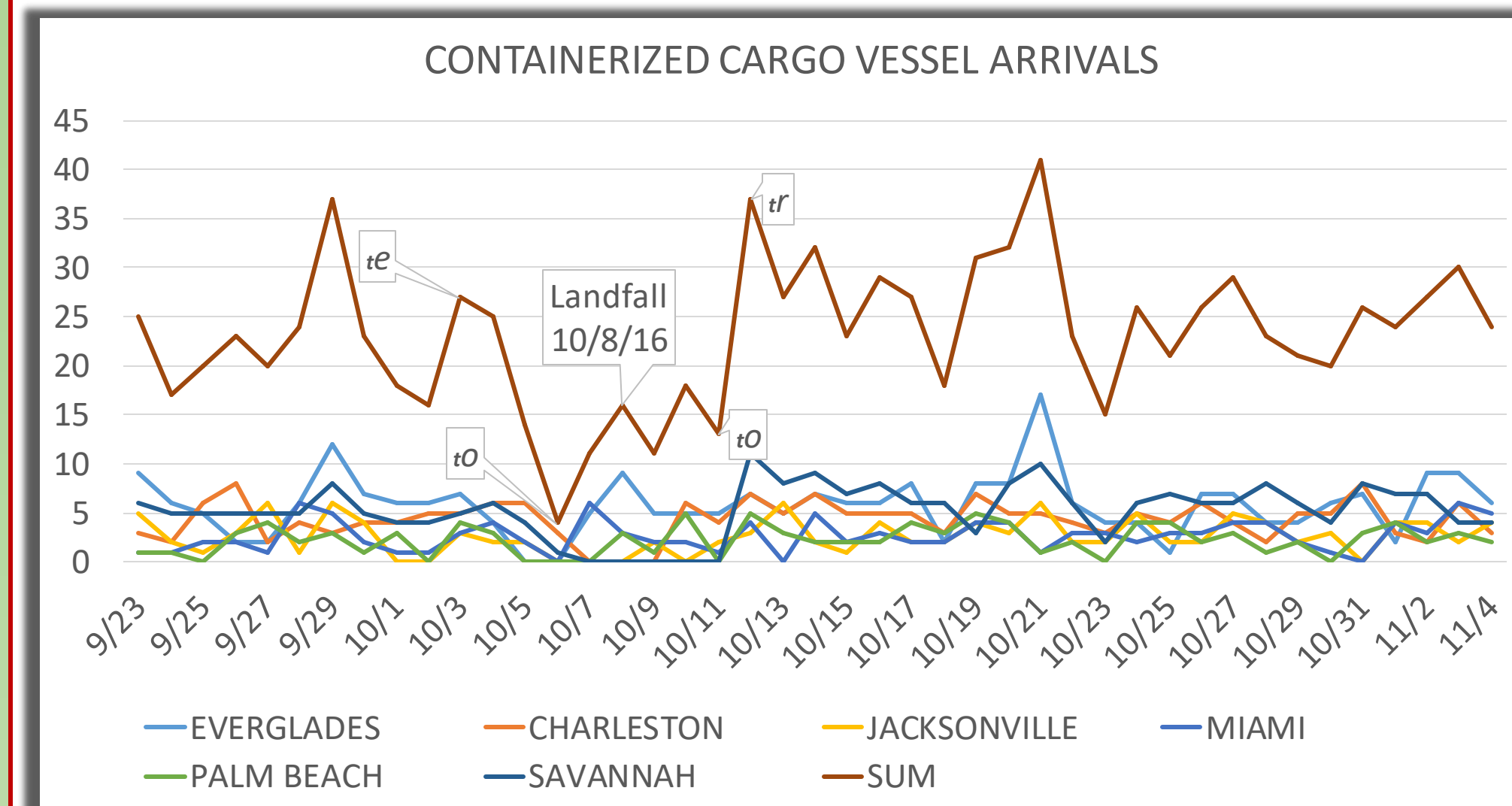
Resiliency is a measure of the systems absorption (Equation 1), recovery (Equation 2), and adaptability (Equation 3), then a quantifiable measure of resiliency is given as Equation 4.

$$R = R_A * R_D * R_R$$

This formulation of resiliency suggests that a system must be able to absorb, adapt, and recover to be resilient and effectively bounce back, else  $R = 0$ .

## RESULTS OF DAILY ARRIVALS

The results focus on containerized cargo vessel arrivals and dwell times because only this vessel class was pervasive at all six ports. The results first present functionality plots generated from the AIS data for each of the six ports. Then, resiliency measures were calculated for individual ports and the region as a whole. Daily containerized cargo vessel arrivals and average daily dwell times were used as the performance functionality measures



The figure above shows the daily arrivals for containerized vessels at each of the study ports and regionally. In the days leading up to landfall, the storm threatened nearly the entire eastern coast of the Southeast US, ultimately coming ashore in South Carolina. The dates corresponding to the event ( $t_E$ ), the end of the absorption state ( $t_A$ ), the end of the disruptive state ( $t_D$ ), and the end of the recovery state ( $t_R$ ), are also provided for the regional impact. These dates, however, were not universal between the six ports. Some ports felt the impact of the storm earlier or later and were disrupted for different periods of time. Their recoveries were also individualized. Ports further to the south, were generally, less disrupted than ports to the north. However, each of the study ports showed a measurable impact from the storm

PORT OF CALL	ABSORPTION	DISRUPTION	RECOVERY	RESILIENCY
MIAMI	0.156	1.000	0.874	0.136
EVERGLADES	0.177	0.800	0.861	0.122
W. PALM BEACH	0.126	1.000	0.874	0.110
JACKSONVILLE	0.500	0.600	0.705	0.211
SAVANNAH	0.295	0.500	0.942	0.139
CHARLESTON	0.205	0.600	0.895	0.110
AVERAGE	0.243	0.75	0.859	0.138
REGIONAL	0.161	1.000	0.90	0.145

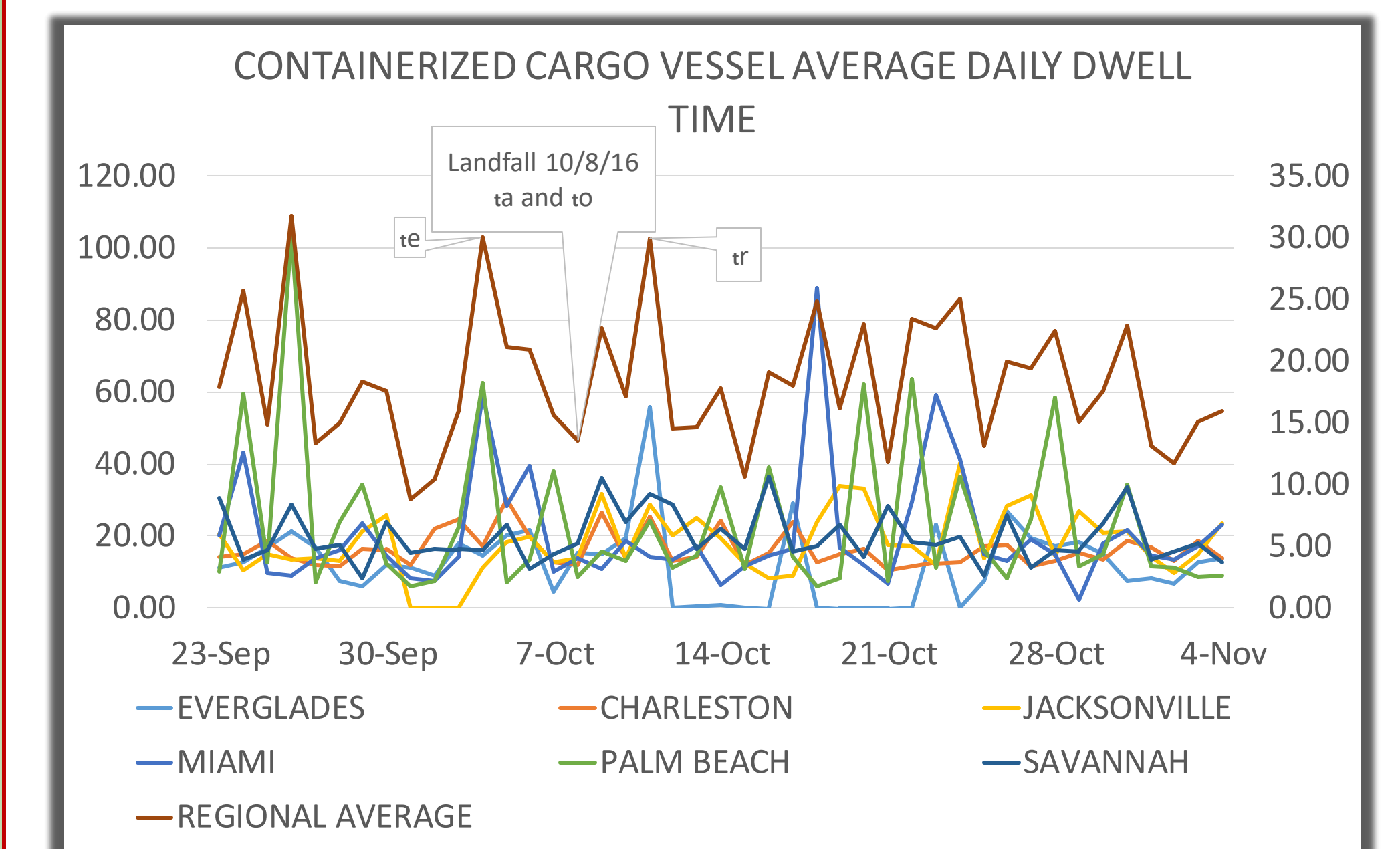
The table shows the resiliency results calculated for each port and the region as a whole. The average absorption was only 0.243, with the regional absorption calculated at 0.161. The Port of Jacksonville showed the strongest absorption at 0.5 whereas the Port of West Palm Beach was the weakest at 0.126. The poor performance of the absorption was expected because closures tend to bring a sudden halt to operations. With no vessels arriving, a rapid drop in vessel arrivals was expected.

Many of the ports in the study reopened relatively quickly, following the passage of the storm resulting in high disruption state values. Recovery was relatively high, with an average recovery value of 0.859 and a regional recovery value of 0.900. This suggest that not only were the ports able to reopen quickly after the storm, they were accommodating as many vessels, or in some cases even more vessels, than prior to the storms passing.

Overall, the resiliency of each port was limited by its ability to absorb the impact of the event. The regional resiliency was 0.145 with the Port of Jacksonville having the largest resiliency value of 0.211. This was unexpected because of Jacksonville's proximity to landfall. Ports Canaveral and Charleston showed the lowest resiliency values of 0.110. Charleston's resiliency was limited by its ability to adapt (i.e. end the disrupted state). This was likely because Charleston was closest to landfall, possibly suffering infrastructure damage

## RESULTS OF AVERAGE DAILY DWELL TIME

The figure below provides the average daily dwell times for the study ports and the region. The x-axis provides the date and the primary y-axis shows the average daily dwell times for the six study ports. The secondary y-axis shows the average daily dwell time for the region, as a whole. Hurricane Matthew began impacting regional dwell times on October 4, 2016. This was evident in a sharp spike in average daily dwell times. Diminished dwell times continued until landfall, corresponding with port closures. However, as the ports reopened, dwell times began their ascent to normalcy, signifying a brief disrupted state on a regional level. By October 11, 2016 regional dwell times generally returned to their pre-storm levels.



The table below provides the resiliency results for containerized cargo vessel average daily dwell times. In general, the study ports struggled to absorb the impact of the storm and subsequent closures. However regionally, the absorption value was significantly higher than five of the six study ports. The Port of West Palm Beach was the only individual port able to absorb the impact of the disruptive event at a higher level than the region as a whole.

The disruptive state at individual ports was in general, longer for average daily dwell times and for vessel arrivals. This may suggest that while ports may be able to receive vessels, their ability to handle cargo may still be inhibited.

Interestingly, the regional dwell time showed no disruptive state, i.e. recovery coincided with the end of the absorption state. This was likely because while ports to the south were impacted by the storm first, they reopened sooner initiating a recovery while northern ports were still in the disrupted state. The resiliency at individual ports was generally lower for average daily dwell times when compared to vessel arrivals. However, the regional resiliencies were much closer in magnitude

PORT OF CALL	ABSORPTION	DISRUPTION	RECOVERY	RESILIENCY
MIAMI	0.058	0.250	0.994	0.014
EVERGLADES	0.049	0.750	0.935	0.034
W. PALM BEACH	0.283	1.000	0.931	0.264
JACKSONVILLE	0.038	0.400	0.965	0.015
SAVANNAH	0.032	0.286	0.969	0.009
CHARLESTON	0.050	0.667	0.921	0.030
AVERAGE	0.085	0.559	0.953	0.061
REGIONAL	0.151	1.000	0.885	0.134

## CONCLUSION

The results showed that regionally, ports are more resilient to disruptive events than the individual ports that make up the region. Based on the findings of this research it is expected the proposed resiliency quantification methodology can be expanded to other systems and areas of science. Future researchers will be able to build upon this work by identifying a level-of-resiliency measure based on the quantification methodology described here