Shipping Network Optimization

With analysis of models performed using python

Jason Quon§
School of Engineering
University of Guelph
Guelph, Ontario, Canada
jquon@uoguelph.ca

Carter Porter¶
School of Engineering
University of Guelph
Guelph, Ontario, Canada
cporte05@uoguelph.ca

Abstract

In order to reduce the resource consumption related to the transportation of goods, our project aims to observe, analyze and potentially optimize the shipping networks across the United States. As one of the world's largest economies by GDP and geographic scale, the optimization of shipping networks in the US could be used to improve shipping efficiency across the globe. Our project will model the shipping networks of major courier delivery service companies as graphs using a Jupyter notebook.

Keywords

node, complex network, superhub/supernode, edge, distribution centre

I. Introduction

The ability to travel, trade commodities, and share information around the world with unprecedented efficiency is a defining feature of the modern globalized economy. More specifically, the ability to move parcels quickly and efficiently as 8% of global trade is done via aircraft and airport hubs[7]. In 2006, 820 million tons of goods were shipped by air globally.[13] This case study was devised with the intention of modelling and optimizing the efficiency of three major courier delivery services in the United States. The three couriers being The United Parcel Service (UPS), FedEx, and United States Postal Service (USPS). It should be noted that both FedEx and UPS use a more centralized model, whereas USPS uses a more distributed model.

II. Process

The study began by modelling the shipping networks of each company where each distribution centre represents a node and the straight line distance between a given pair of nodes represents an edge. The nodes were plotted using the location's longitude and latitude as x and y coordinates. The colour of the nodes were made to correspond with the colours found in the given company's logo. The number of edges in each system is determined by the network model that each company uses. For each model, the length of the connections between nodes was calculated using a process provided by Andrew Hedges[12] to determine distances based on longitude and latitude. In the centralized model used by UPS and FedEx connections were made between the specified superhub and each distribution centre while the decentralized system used by USPS had each node connected to each other node to form a complete graph. Each of these networks were then plotted to gain visual insight into the networks in place by each

§ Jason Quon provided technical aspects of the system analysis.

¶ Carter Porter provided system design overview and optimization.

company. From here, several functions were created to extract details from each graph. Such details include the shortest, longest, and average path length. These properties of each graph were chosen to better understand the differences, subtle or not, of each system. The assumptions that were made in the derivation of these methods was that for the centralized models, there is no travel between nodes unless it is through the supernode. In reality, this is unlikely as some travel between regular nodes is necessary. Another assumption that was used in this analysis is that all travel paths are treated evenly, when in reality some paths are more likely to be traveled as shipping traffic may require.

Our project will make use of concepts outlined in a study called *The architecture of complex weighted networks* conducted at the University of Rome in 2004[7]. Furthermore it will use these concepts to conduct a study similar to the study on global cargo ship transportation routes published by The Royal Society in 2010[8]. This study found that global shipping routes exhibited small world behaviour that was conducive to analysis for further study. The recommendations made for the optimization of each network is based on the article *Simultaneous optimization of schedule coordination and cargo allocation for liner container shipping networks*[9] but uses a more logical method compared to the mathematical model presented in the article.

III. Results

An analysis of American courier aircraft shipping movements exhibits two types of models. A more centralized model, as seen in Figure 1 and Figure 2, and a distributed model as seen in Figure 3.

Figure 1: UPS air freight centralized model

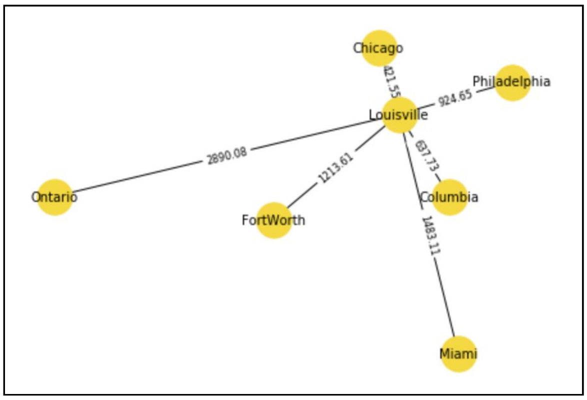
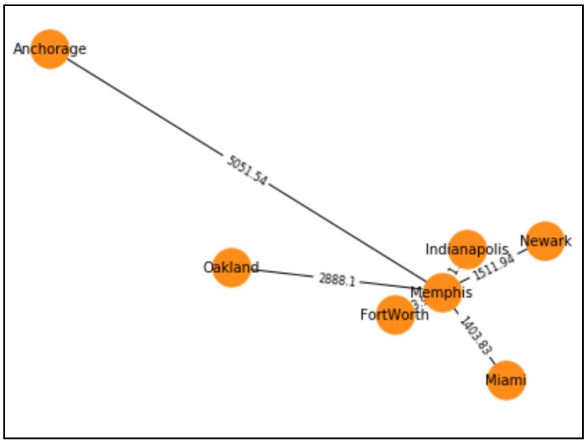


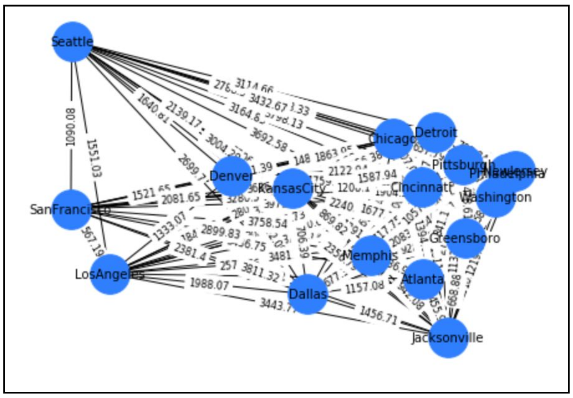
Figure 1 represents the UPS air freight distribution routes between their 7 hubs in the United states, with Louisville being the superhub. The graph has the hub location as nodes and the travel distances as edges. It should be noted that the node locations were depicted relative to each other via their longitudinal and latitudinal coordinates.

Figure 2: FedEx air freight centralized model



Like Figure 1, Figure 2 graphs the centralized FedEx air freight model. However, it varies slightly with an outlier node all the way in Anchorage, Alaska. An odd place for a hub, however this node is strategically placed for it provides the most optimal route, based on the Earth's curvature, for transcontinental shipping to Eastern Europe and Asia.

Figure 3: USPS distributed model relative to the U.S



Unlike Figure 1 and 2, Figure 3 does not have a supernode which all other nodes centered about, this is a more distributed model where each node connects to each other node, creating a complete network.

Table 1: Results of each courier service

Courier	Shortest Path (km)	Longest Path (km)	Average Path Length (km)
UPS	421.55	2890.08	1261.79
FedEx	611.6	5051.54	2031.82
USPS	69.12	4111.75	1740.49

As we can see, the shortest path of 69.12 km from New Jersey to Philadelphia can be found in the USPS graph. This is mainly due to the sheer number of distribution centres found in this model. With more nodes covering the same amount of geographic area, the USPS model was bound to have the shortest path.

From Table 1, the longest path found in any of the systems is the path from Memphis to Anchorage with a distance of 5051.54 km. Even before running the function to find the longest path, it was clear that this would be the longest path due to the fact that Alaska is not part of the "Contiguous United States" due to its separation from the lower 48 states. likely to significantly increase the average path length within the context of domestic shipping, it is an extremely beneficial distribution centre for international cargo coming or going west.

While the shortest path can be found in the USPS graph and the longest found in the FedEx graph, it is the UPS model which has the shortest average path length of 1261.79 km.

IV. Optimization

Experiment 1 - Moving Supernodes

In this experiment we set out to see if it were possible to modify the current supernode location for each courier (a theoretical supernode location for USPS) to see if there were locations with overall lower average path lengths. A significantly lower average path length for the courier would result in a more efficient shipping operation.

This experiment consisted of taking the known supernode locations and shifting there latitude and longitude by intervals of $\pm 1°$ and recalculating the average path lengths. As the United States spans roughly 60° longitude, and 30° latitude (excluding Alaska and Hawaii), the supernode location was altered to roughly span the entirety of the country. This approximation resulted in a total of 1800 supernode shifts per courier. This allowed for a list of coordinates that had better average path lengths to be determined for that couriers model.

As a result of this it was seen that for UPS current model, there were 26 potential supernode locations with higher average path lengths than the company's current supernode, Louisville. While 25 of the locations were in small counties and districts making a supernode there not viable, there was 1 possibility that may

While this node is have been overlooked. The most notable of these potential locations is located at 36°N, 87°W which is right in the centre of Nashville making Nashville International airport a viable hub. A superhub here would give the model an average path length of 1243 km vs in Louisville 1261 km.

When analysing these decision made by couriers, the mean population center should be considered, which for 2018 is located at (37.4°N, 92.4°W). As this will impact the average travel distance per package. This is the average location of all the United states residence, so a hub close to this is optimal. Comparing Louisville and Nashville to the mean center, Nashville is roughly 50 miles closer than Louisville, proving to be a better supernode location given the criteria. This opportunity may have been passed for a couple of reasons, the main one being the initial assumption that all travels paths are even. If UPS on average has more eastbound packages, it is more worthwhile to have a more east superhub, which Louisville is.

FedEx has 67 potential better supernode locations than Memphis. One of which is the same Nashville coordinate as seen for UPS. The optimized average path lengths for this model range drastically varying up to 50 km. Comparatively to UPS, the average path lengths only varies by 22 km.

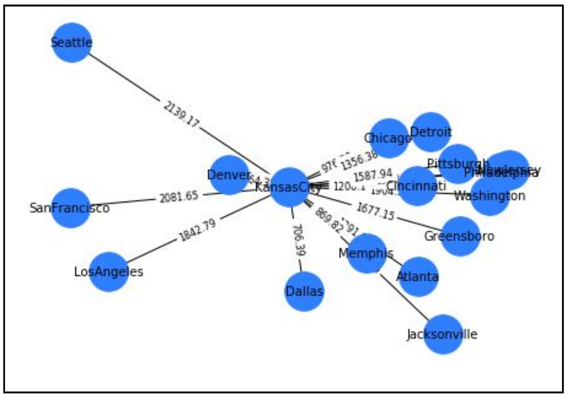
As seen in Figure 6, this experiment was run using the theoretical superhub of Cincinnati for USPS as it is one of its most central hubs. This assumption performed well in the experiment leaving only 15 locations with better average path lengths, varying only a maximum of 10 km from the original.

Overall, this experiment provided a means to analyze and potentially optimize the couriers already well-laid out system.

Experiment 2 - USPS: Distributed to Centralized

The experiment began by using the nodes of the distributed model used by USPS to create a centralized model with the superhub being the most geographically central distribution centre. In this case, Kansas City was used as the superhub.

Figure 4: USPS system as a centralized model with Kansas City as the superhub



We can note that visually, most of the edges are similar in length with the exception of a few outlier nodes which are closer. This means that before even doing any calculations, we can predict that the average path length for this model will be similar to its longest path length.

Next, Memphis was chosen as the superhub to allow for a direct comparison with the system used by FedEx as they have its superhub in the same city. This will further allow for a more direct comparison with UPS as their superhub is located in Louisville which is relatively close by.

Figure 5: USPS system as a centralized model using the same superhub (Memphis) as FedEx

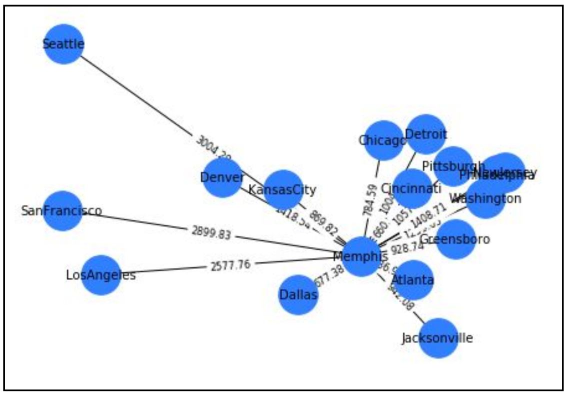


Table 2: Comparison of centralized systems using approximately equal superhubs

Courier	Superhub	Shortest Path (km)	Longest Path (km)	Average Path Length (km)
UPS	Louisville	421.55	2890.08	1261.79
FedEx	Memphis	611.6	5051.54	2031.82
USPS	Memphis	536.93	3004.28	1344.2

From Table 2 we see that the transformation of the system used by USPS from a distributed model to a centralized model creates a system with each attribute (shortest, longest, and average path length) less optimized than UPS but better optimized compared to FedEx.

In the final iteration of the experiment, the superhub was placed approximately centred within an area of highly clustered distribution centres to understand how this placement may affect the system attributes.

Figure 6: USPS system as a centralized model using Cincinnati as the superhub

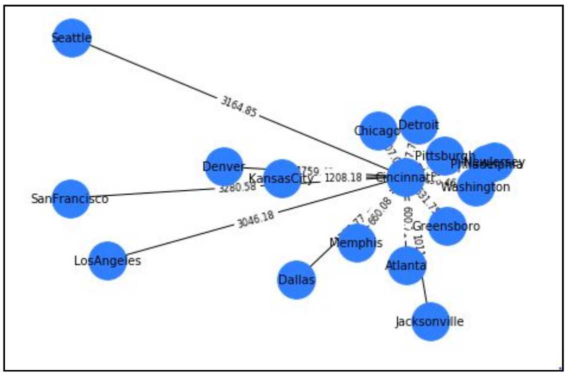


Table 3: Initial results and results for each iteration in Experiment 2

Superhub	Shortest Path (km)	Longest Path (km)	Average Path Length (km)
None	69.12	4111.75	1740.49
Kansas City	564.35	2139.17	1511.37
Memphis	536.93	3004.28	1344.2
Cincinnati	377.73	3280.58	1258.67

As seen in Table 3, each successive iteration of the experiment produced a graph with decreasing shortest and average path length but increasing longest path length. Interestingly, when compared to the original system, each experiment produced a longer shortest path with a more optimal longest and average path length. This observation can be explained by the fact that each successive iteration moved the superhub closer to an area of high clustering. As the superhub is moved closer to more nodes the shortest path becomes shorter while the current farthest becomes even farther. In doing this, most paths between nodes become shorter while few get longer which explains the decrease in average path length.

In this study, transportation of cargo is assumed to be distributed evenly from the superhub to its distribution centres. As such, we can conclude that Cincinnati served as the most optimal superhub of all the cities that were tested as it produced the system with the shortest average path length. This choice of Cincinnati as the best city for a superhub also provides further justification of its use a superhub in Experiment 1.

V. Conclusions

The shipping networks currently used each offer advantages and disadvantages when compared to its competitors though none of them have been completely perfected. as seen from our results in Experiment 1, each courier had numerous locations which had a better average travel length to the other airports. That being said, excluding factors such as economic feasibility, Nashville appears to be the most optimal location for both UPS and FedEx. Further investigation confirmed that the distributed model used by USPS could be optimized through conversion to a centralized model as seen in Experiment 2. Through this experiment Cincinnati was identified as a potential superhub location should USPS decide to adopt this system. Upgrading an existing distribution centre to a superhub could allow USPS to make these changes while reducing the need for extra infrastructure when compared to building a completely new superhub. This would allow them to reap the benefits of reduced cost and resource consumption gained by using a centralized system.

VI. References

[1] Allen B. Downey, "Thinking Complexity 2 (2nd. ed)". Green Tea Press, Needham, MA, U.S.A
[2] Allen B. Downey (2018), Lab 2: Graphs. https://github.com/AllenDowney/ThinkComplexity2
[3] Allen B. Downey (2018), Lab 4: Small World Graphs. https://github.com/AllenDowney/ThinkComplexity2
[4] Allen B. Downey (2018), Lab 5: Scale-Free Network. https://github.com/AllenDowney/ThinkComplexity2
[5] Jeff Martinez, "Why Does My Package Go Through Memphis?" https://about.van.fedex.com/blog/why-memphis/
[6] Jim Mayer, "UPS Air Operations Facts". *UPS Pressroom*. https://www.pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=FactSheets&id=1426321563773-779
[7] A. Barrat, M. Barth´elemy, R. Pastor-Satorras, and A. Vespignani. The architecture of complex weighted networks. Proc. Nat. Acad. Sci., 101:3747–3752, 2019
[8] Andrea Koelzsch, Michael T. Gastner, Bernd Blasius, "The Complex Network of Global Cargo Ship Movement". The Royal Society Interface, 1-10.
[9]Hua Wang, Shuaian Wang, Qiang Meng, "Simultaneous optimization of schedule coordination and cargo allocation for liner container shipping networks". Transportation Research Part E: Logistic and Transportation Review, 2014
[10] Unknown, "UPS Fact Sheet".https://www.ups.com/ca/en/about/facts/worldwide.page
[11] Daniel Terdiman. "Welcome to 'the Matrix': At FedEx's sorting hub, 1 night, 1.5M packages", https://www.cnet.com/news/at-fedex-sorting-packages-1-5-million-at-a-time/.
[12] Unknown, "USPS – Network Distribution Centers", usps.com
[13] Andrew Hedges (2002), "Finding distances based on Latitude and Longitude" https://andrew.hedges.name/experiments/haversine/
[14] United Nations conference on trade and development. Review of maritime transport. http://www.unctad.org/en/docs/rmt_2007en.pdf 2019.