An Architecture Model of the U.S. Air Transportation Network

Paper summary

Introduction & Methodology

This paper proposes an architecture model of the United States (US) Air Transportation Network (ATN). The ATN has begun to emerge in the early in 20th century. As time goes by, its fundamental elements such as trip demand, airport, and aircraft have varied. It, on one hand, contains common characteristics of general graph like scale-free and small-world. On the other hand, however, it is far more complex than how it looks as there are numerous important and complicated factors which make the ATN distinguished from other graphs.

Ironically, its distinctive nature attracted numerous scientists and researchers in various disciplines. Network scientists have studied the structure and associated characteristics by using a variety of network metrics in terms of nodes and segments, whereas researchers in logistics tried to understand how the ATN works and what the driving forces of the ATN are, etc. to find out the causality of the operating mechanisms of the ATN. Moreover, scientists from industrial engineering have tried to build or optimize the current ATN that is able to better fulfill what they aiming at such as minimize traffic congestion, maximize total network social welfare, etc.

These studies are certainly conducive to unravel the pieces of the overwhelmingly complex entity, the ATN, in many aspects as to the 'form' and the 'function' of the ATN. However, it is still elusive to master the core dynamics of the ATN since they have not received critical attention. Hence, the established studies can barely shed light on answering to the essential questions on the core dynamics of the ATN; How and why does the ATN looks the way it is? What has the ATN been through in its evolution?

In this perspective, there arises a strong need to build a holistic and comprehensive modeling-and-simulation environment where a lot of assumptions and ideas can be explored to understand the core dynamics by linking the form and function of the ATN. This paper develops a novel architecture model of the ATN attempting to ease the equivocal understanding of the core dynamics. The main issue is that whether the ATN can be represented with parsimonious terms or not. Our decision against this issue addressed two requirements: the essential components and the simple but also essential mechanisms they are getting on.

Our selections of the essential components were airports, segments, aircraft fleets, and airlines and we also built the simple mechanism by employing various terms such as the evolution, airlines' adaptive network construction policy, preferential attachment, Pareto and Pseudo-Pareto optimum, multi-tiered network, etc. Some were abstracted based on the established knowledge while others were implemented by ourselves for this research.

All of these are mingled together to create an architecture space that virtually explore and simulate the deployment of the ATN teeming with architecture statements. We name it Network Evolutionary algoriThm (NET). We started with this by studying how the evolution of the ATN has been deployed throughout the history by tracking down the evolution of the airport (spatial expansion) and volume (enplanement: chronological progression). In addition to these, aircraft is the enabler that actually creates the network. Finally, these three components are incorporated in order to create a threedimensional virtual space dubbed 'evolution space' (ENV) that portrays how the evolution has been deployed over history. The continuous spectrum is represented as discrete events in this space. Hence, ENV is a set of components: airports (A), trip demand (T), and aircraft fleets (Ψ).

Besides, airlines are the core entity that adaptively make decisions to survive in the market under the given environment. At every evolution time step, they are enforced to weave their strategies to minimize their operation cost and to efficiently accommodate the trip demand based on the given evolution environment and the current existing ATN and thus the ATN at the time step t_{k+1} is represented as a functional form as follows:

$$ATN(t_{k+1})=POL(t_k, ATN(t_k), ENV(t_k)),$$

where t_k is k-th time step representing the notional historical timelines ($t=\{t_k \mid k=1, 2, \cdots, f\}$), POL notionally indicates to the airlines' network construction policies that is dependent to time, and $ENV(t_k)=\{A(t_k), T(t_k), \Psi(t_k)\}$. Every element monotonically increases along the time step and defines the corresponding environmental conditions. As seen in the above equation, the ATN of the next time step is created by the airlines' policy concerning time, the current ATN, and the environment, having a recursive manner that also shows the evolution of the ATN. As the airports, 298 commercially operating ones are used to model the ATN, five different aircraft classes are engaged as the set of aircraft fleet, and the demand source is obtained from the public data whose name is DB1B and provided by the Bureau of Transportation Statistics (BTS).

Considering that the strong Hub-and-Stroke (H&S) structure of the ATN is the predominant so that top 50 airports covers approximately 90% of the total volume of the network, we decompose the demand and corresponding airports into two tiers: Tier-P as the primary tier of the top 50 airports and Tier-S as the secondary tier of the rest. Tier-P is where we are committed to building on the H&S network by employing corresponding architectural statements whereas the Tier-S is to be constructed that exploits the pre-established segments of the Tier-P to minimize the operation cost. Because we know that the H&S structure is the accumulated consequence of the airlines' tendency called 'preferential attachment', we focus on how to infuse the preferential attachment to the airlines and how to encapsulate their principal dynamics in terms evolution. We call the algorithms in NET for constructing the Tier-P and Tier-S as NET-P and NET-S, respectively.

In the beginning of NET-P, airlines firstly import the environment information. Then for each Origin-Destination (OD) pair of demand, airlines evaluate the relevancy or fitness of all viable routes allowing up to one hub. In Tier-P, airlines are the agents which accommodate the demand for all i-j pairs. NET-P involves 50 airports whose list starts from #NY (New York City metroplex airport), approximately 85% of the demand, and 5 aircraft fleets. For each time step, airlines calculate the relevancy of all trip i-j pairs.

Now then they calculate the disutility that quantifies the conflicting criteria in creating segments. It consists of the airlines' operation cost and the monetary value of passengers' flight duration. Each of these evinces the sense of disutility of the target segment (edge) for the aspects of airlines and passengers. Airlines want to minimize their operation cost (*AlnCost*), whereas passengers want to minimize their flight duration (*PaxCost*). By giving weight (w), the disutility is calculated. Therefore, it is a multi-

attribute decision making problem.
The number of candidate disutilities can be virtually the number of airports-1. One for direct via *i-j* and others for indirect via *i-h-j*). Among N airports in the current time step, the hub airport h can be N-2, excluding i and j. For all N^2 trips, each trip considers N-1 path options (thus N-1 disutilities), and each disutility considers all combinatorial cases involving the number of aircraft fleets. Once all disutilities are evaluated for a trip, the Pareto and Pseudo-Pareto optimum path options for every trip *i-j* pair are chosen to distribute the demand. Considering the relative magnitude of the disutility, the demand is distributed throughout the chosen segments. These procedures are repeated until all trips are accommodated.
Once the Tier-P is constructed, NET-S comes into play. As the root of the ATN is demand, high demand is encouraging but low demand is discouraging in terms of motivation for airlines to create segments. The distinctive nature of the ATN that there are any fixed segments and they can be created by dynamically by the airlines' decision. Thus, airlines found that for the secondary demand, exploiting the pre-established Tier-P segments was the best leverage that can reduce the disutility best. Considering this, we enforce airlines to maximize the Tier-P segments in dealing with the Tier-S demand.
Firstly, a regional demand from Tier-S airports is heading to its closest Tier-P airport for tier-switching. Then they fly through the shortest distance paths found by the Dijkstra's algorithm to get to the destination. If the destination is also a Tier-S airport, the tier-switching from Tier-P to Tier-S is done again and go to the destination. By doing this at every time step, the entire ATN emerges and evolves, recursively.
Once the time step reaches the step right before the final one, an optimization problem is solved to find the optimum hub discount factor of the selected major hub airport to model the preferential attachment. If it finds the optimum set, it moves onto the final time step and else, the time step gets back to the first one and the entire NET processes start over with updated hub discount factors.

Result & Discussion

The final results of the NET simulation are verified and validated with the reference data by comparing the row-sum of the enplanement matrix. We could also confirm the effect of the preferential attachment due to the hub discount factor in #DA (Dallas, TX metroplex airport), ATL, and CLT showing a significant amount of connection volume. Especially, ATL fills up its total volume by 50% of connection. NET, moreover, showed the deployment of evolution at each time step to us so that we can see the emergence of hub airports by creating a lot of spoke airports in the vicinity of them in the history of evolution.
Finally, various network metrics are engaged to perform a reverse-engineering and to retrieve the corresponding knowledge insights from the function revealed by the metrics. Through the metrics, the hidden features of the function of the ATN can be investigated then we can ultimately and gradually understand the core dynamics of the ATN. The metrics are the degree, strength, betweenness centrality, and closeness centrality. The degree and strength shows the connectivity of airports. The degree is the most common metric and just show the adjacency of an airport so that it cannot capture the importance or weight of its segments. Whereas, the strength can measure the significance of segments so the total

sum of the segment associated with an airport allows us to identify which airport is a big contributor to the ATN.

Besides, considering the strong H&S structure of the ATN, we employed two complex metrics that evaluate the airport centrality in two different perspectives. The betweenness centrality (BET) measures how much influence an airport exerts on the network in its local area while the closeness centrality (CLO) captures the average satisfaction of trips of all airports in the ATN. The BET revealed the most important top major airports and their significant roles in the ATN as the significant ones to maintain the stability of the ATN since numerous Most-Weighted Paths (MWP) defined in our research pass through those airports to get to the destinations.

On the contrary, however, the CLO values are not distinctive to each other. The function CLO captures is how 'efficiently' the passengers can reach their destinations from an airport. Here, 'efficiently' means that the taste of the MWP. Therefore, the CLO explains the fairness and balances between airports. Although there were neither ultimate architects who designed the ATN nor airlines who collaborated intended to create an optimized ATN, the locally optimized and adaptive struggle of airlines converged to an equilibrated and well-balanced ATN through evolution. In this perspective, we can reinterpret the BET; the different values of the BET between airports inform us that the top major airports such as #NY, #LA, #DA, #CH, and ATL are not selfish or balance-breakers but rather carry out their significant roles to maintain the stability of the ATN.

Conclusion

An architecture model as a virtual environment to study the core dynamics of the ATN is developed. A promising leverage under this principle is to link the form and function of the ATN. In retrospect, the core questions in this paper can be summarized as whether the ATN can be represented with parsimonious terms or not in two perspectives: components and mechanisms.

NET succeeded to simulate the ATN by yielding the form and function validated by the reference data. The function captured by network metrics from NET were investigated to enhance understand the core dynamics of the ATN, as expected. The strength showed the hidden characteristics of the segments which the degree could not capture. Besides, the betweenness centrality and closeness centrality even emphasized the centrality of airports in different perspectives, which in turn gained us lots of insights and knowledge on the dynamics of the ATN. Through the BET and CLO, we acknowledged that although the current ATN looks quite dependent on several major hubs, it has evolved into a system with fairness as well as equilibrium in terms of MWPs as the corollary of the numerous versatile and adaptive strategic behaviors of airlines during evolution.

Our architecture model is a cyber-physical architecture space where more elaborate and sophisticated architecture statements will be implemented and investigated to enhance our understanding of the core dynamics. Then, the function from NET would gradually mimic the behavior and dynamics of the real ATN. Various architectural statements like multiple heterogeneous airlines in the network and increasing the granularity of the hub discount factor are the short-term research topics.