ICAS 2016
30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

A REVIEW AND A CLASSIFICATION SCHEME FOR AIR TRANSPORTATION NETWORK RESEARCH

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Keywords: *Network Discovery & Design, General & Specific Topology, Classification*

Abstract

The U.S. air transportation system is undoubtedly a complex system-of-systems: a collection of diverse 'things' that evolve over time and organized at multiple levels. This paper reviews the literature with respect to the air transportation network (ATN) research to support the creation of an integrated modeling and simulation environment. The foundation begins with an abstraction of the air transportation system-of-systems, a holistic frame of reference, in which the relationships between four basic entity groups are identified and explained. A classification scheme was devised to efficiently organize the literature. Using this scheme, various published works were discussed in an effort to better understand and address the relationships between them.

1. Introduction

The U.S. Air Transportation System-of-Systems (ATS) is a complex system both in the colloquial and technical sense of the word. Complexity in the ATS stems primarily from three properties: the heterogeneity of constituent systems, the distributed nature of these systems [1], and the presence of "deep uncertainty" [2] in exploring its alternatives or future state. In order to quantitatively tackle the grand challenge of understanding and forecasting the ATS, a strong need of architectural tradeoff on a variety of scenarios arises.

For this goal, the authors have been committed to building an integrated modeling and simulation (M&S) framework for the ATS. This framework aims to spur the inter-disciplinary and multi-domain research in contemplating the future ATS architecture. As a starting point, a mental model is created to represent the 'living' ATS involving an 'everything on the table' point of view. Fig. 1 illustrates the abstraction of the ATS, a holistic portrayal of the ATS which is reconfigurable by cascading changes in economic, societal, and technological development marching with time.

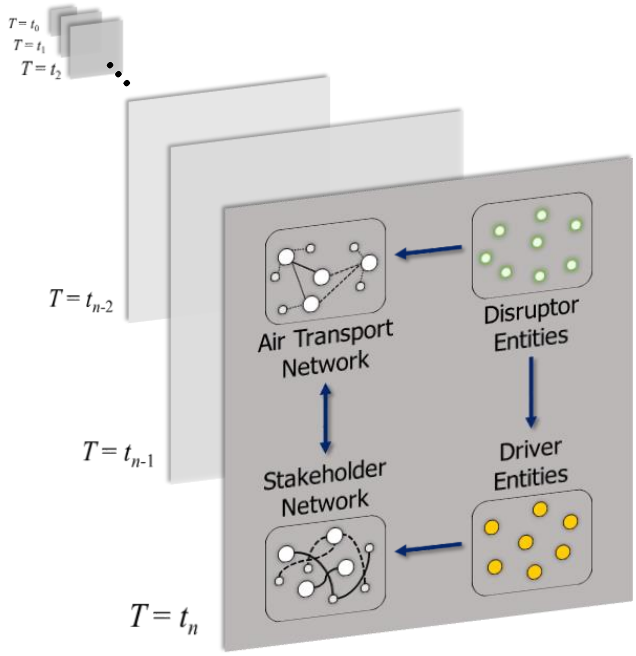

Fig. 1. A Conceptual Time Series of the Air Transportation System-of-Systems

The two networks in the left side represent the air transportation network (ATN) and its stakeholder network. The ATN is a collection of complex, multi-layer, heterogeneous systems consisting of the overall airspace and airport environments utilized for aircraft operations. Airlines, travelers, and regulatory agencies are the members of the stakeholder network where one stakeholder may interact with another and other stakeholders influence particular part of the ATN. The column in the right includes entities affecting the left side in a various way. The driver entities are largely concerned with economic, societal and psychological circumstances that influence the stakeholder network whereas the disruptor entities affect the ATN and/or a portion of the driver entities such as weather and terrorism.

The aforementioned integrated M&S framework can be regarded as a tangible implementation of Fig. 1. The knowledge and insights from the literature will extend a solid comprehension of the ATN and will eventually facilitate the future research towards the construction of the architectural tradeoff framework. Moreover, it is expected the following discussion on literature items to help ATN researchers cross-fertilize innovative ideas.

2. The Classification Quadrants

Acknowledging the complexity of the ATN, many researchers have studied and investigated the ATN through various approaches to retrieve meaningful insights and information. We identified some major research areas of the ATN as follows.

- Comparative study: identification of characteristics of the ATN compared to other types of network (ground transportation, social network, etc.)
- Network optimization: problem definition & solving, developing algorithms, topology manipulations, etc.
- Structural analysis: understanding the characteristics of the ATN in a variety of aspects using network-associated metrics
- Historical observation: investigating the changes impacting the ATN throughout its history
- Examination of specific networks: H&S, P2P, hybrid network system, and other ATN types and their distinct properties
- Network modeling: methodologies to design a network for a specified purpose or scenario
- Machine learning on the ATN: developing models to predict, regress, and reconstruct the ATN
- Impact analysis: retrieving clues from the impacts by endogenous and exogenous factors

Admittedly and quite understandably, the diversity exists within the research objectives, scopes, depths and methods. In an attempt to help ourselves understand the literature in a more organized manner, four classification quadrants were created based on two classifier sets. The column-wise and the row-wise classifiers are introduced to generate the classification quadrants as shown in Fig. 2.

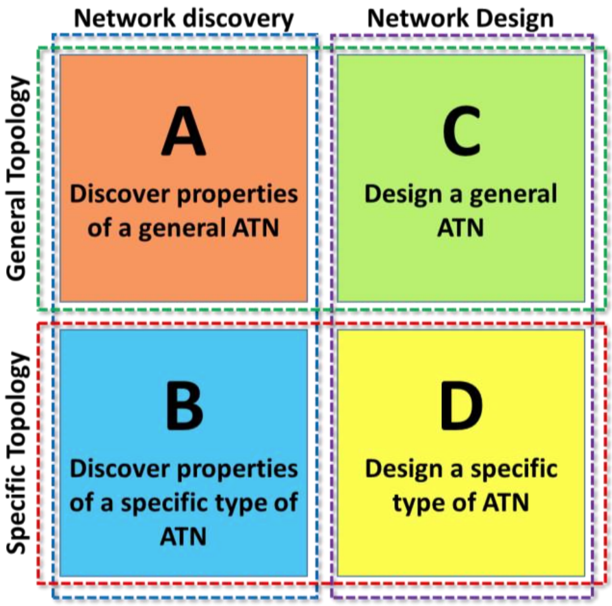

Fig. 2. Classification quadrants

The column-wise classifier (dubbed C-classifier) delineates between studies focusing on discovering characteristics out of a given ATN or designing a network topology based on the knowledge retrieved from the ATN. The left column is called discovery column whereas the right column is called design column.

On the other hand, the row-wise classifier (dubbed R-classifier) is about the scope of the target network of research. If the research is interested in a general ATN rather than a specific type of ATN, it is classified as specific topology and mapped to the upper row. If it is committed to studying on certain specific types of the ATN such as H&S, P2P, mixtures of these, etc., it corresponds to the bottom row dubbed specific topology. Detailed explanations about each quadrant are addressed in the subsequent sections.

2.1 Quadrant A: Discovery ∩ General Topology

This region is the top-left quadrant. This quadrant is for papers discovering characteristics of a general ATN topology. In this regard, network researchers with different perspectives used various network metrics to quantify the properties of the ATN. Many studies confirmed small-world and scale-free characteristics in the ATN that were observed in other networks.

Billie & Kincaid [3] analyzes the U.S. ATN mainly based on the historical changes. Starting from mentioning the small-world and scale-free characteristics, the paper revisits the emergence and advancement of the U.S. airline industry while summarizing historical events such as the outbreak of World War I, deregulation and their consequences. The authors come up with a list about how the airline industry compares to the criteria of complex networks. In the course of this discussion, the history of point-to-point and hub-and-spoke networks is also readdressed.

Neal [4] focuses on the various aspects of the ATN by scale (airport vs. metropolitan area), species (business vs. leisure), and season (summer vs. winter). Motivated by the limitation that the past research has focused on the network of routes flown between airports, the author attempts to analyze the differences and similarities of the various aspects of the ATN topology. This is expressed "The devil is in the details." Similarities are scale-free, small-world, and modular community structure. Claiming that quite different characteristics are masked by the similarities that complex network metrics indicate, the author argues that a variety of differences of the different ATN topologies should be understood in detail.

Guimera, Mossa, Turschi & Amaral [5] investigates the global structure of the worldwide air transportation network. Specifically, they focus on investigating the ATN as infrastructure that is vital to the economy. Starting from discovering the scale-free small-world network characteristics from the ATN, the paper discovers some anomalous characteristics by analyzing betweenness centrality. Anomalous characteristics mean that the nodes with more connections are not always the most central in the network. The paper conjectures a multi-community structure of the network as the root of this behavior and then argues that the multi-community structure in the ATN cannot be fully explained solely based on geographical constraints and that geopolitical considerations have to be addressed.

In addition to observing the small-world and scale-free characteristics, the complex network topology has hidden its numerous unique characteristics from being noticed and understood. This complexity precipitated network scientists to develop a variety of network metrics to mathematically describe corresponding characteristics.

Cheung & Gunes [6] analyzes the U.S. ATN by exploring the statistical data for 20 years with ten-year interval metrics: 1991, 2001, and 2011. Using these various metrics and tracking down the changes between these decades, this paper identifies the growth of the ATN that is easily viewed by the increase of the number of airports and flight routes.

Similarly, Gegov, Gegov, Atherton & Gobet [7] analyzes the U.S. ATN by exploring the trends of the ATN with the three snapshots of 1990, 2000, and 2010 using various network metrics. Metrics of interest to view the historical growth of networks include number of airports, total connections, connected airports, average degree, average hops, clustering, the number of airports without connections, and scaling factors. The metrics are populated in multiple two-dimensional charts to help one visually grasp the trends of the ATN. One important observation is that the ranked passenger distribution appears to follow a logarithmic trend, implying high heterogeneity in passengers on different connections.

Bonnefoy & Hansman [8] focuses on the capacity issue as a key point in the air transportation system. This is associated with the concern that the ATN will hardly be able to meet the forecasted future demand. The paper investigates the airports' scaling mechanisms and the factors that influence on the structure of the network by using various network metrics. The results are that airports have been able to accommodate the demand by adding capacity and improving operation efficiency while satisfying the infrastructure constraints and that once their infrastructure constraints are reached, higher-level scaling mechanisms such as the emergence of new airports are triggered. The paper suggests a possible solution from the perspective of viewing the ATN as an aggregated multi-airport level system. The paper also claims that regional level scaling mechanisms will be key to accommodating future needs.

Recently, machine learning (ML) techniques are frequently employed to study the ATN. Employing machine learning can be an optimized approach to extract information from the ATN topology as it helps researchers regress the mathematical structure of the ATN.

Sales-Pardo, Guimera, Moreira & Amaral [9] introduces an unsupervised ML method that identifies the levels in the organization of complex systems and extracts the relevant information at each level from complex biological, social, and technological networks. As a real world case study, the world-wide ATN and other types of networks are tested. The modular and complex hierarchical structure of the ATN is extracted from continents and country boundaries.

Ma, Yu, Wang & Wang [10] develops a model to predict the pattern of congestion using deep learning theory, which considered one of the most promising techniques to study tremendously high-dimensional data, for large-scale transportation networks. The paper attempts to understand how congestion in a transportation network can and be exacerbated and how it can cause ripples throughout large-scale transportation network. A deep Restricted Boltzmann Machine and Recurrent Neural Network architecture are utilized to retrieve the information on traffic congestion.

Busquets, Alonso & Evans [11] proposes a model to forecast the future of the ATN by using off-the-shelf data mining and ML techniques. This is motivated by an existing method developed by Federal Aviation Administration (FAA) and based on relatively simple regression and growth models. Existing data mining applications in air traffic forecasting are incorporated with logistic regression and discrete choice modeling to retrieve the detailed information from the ATN. Finally, the paper suggests a two-stage log-log model that is used to identify important differences among inputs and to detect the issues of endogeneity and multi-collinearity. The major network metrics used are degree, weight, eigenvector centrality, and clustering coefficient.

Kotegawa [12] proposes an “airline service route network evolution model” that can forecast route addition and removal. To identify patterns and knowledge from historical ATN data it used network metrics. The forecast model consists of various ML algorithms such as logistic regression, random forests, and support vector machines (SVM). The overall accuracy of the model ranges from approximately 20% to 40%. The ML techniques used in this research focus on finding the logistic relationship or dynamics of the right choice among new link candidates from the historical data.

In the course of investigating the ATN, many network scientists studied the properties of partial aspects or components of the ATN such as demand, enplanement, and operation. However, not every airport is created equal. History, geography, population, infrastructure, etc. have added to the complexity of the relationships. Detailed studies to unravel these entities have been also conducted.

Yang, Lewe & Mavris [13] presents an approach that focuses on modeling a true origin-destination demand prediction model. The model is inspired by analogous properties between the gravity law and aviation demand. To overcome the limitations of established demand analysis, this paper proposes a method to breakdown total enplanements into Production, Attraction and Connection Enplanements. Adopting this ‘PACE’ scheme, the paper discovers a generic rule that governs production and attraction enplanements at airport level. The demand forecast model also uses this method and validates the model with the historical reference data.

Wandelt & Sun [14] investigates the evolution of the international ATN in various countries such as the U.S., England and France from 2002 to 2013. This paper approaches the data from two perspectives: ATN topology and the functional network. The paper clarifies the definitions of two different network metrics: topological criticality and functional criticality. Topological criticality refers to the degree of each airport in the network; the higher the degree, the higher the airport's criticality. Functional criticality is about the enplanements of a network link; the more enplanements a link has, the more important the origin and destination airports are. The former is similar to adjacency while the latter is similar to weight. By analyzing the historical data, the paper discovers some insights. First, the international ATN is a scale-free and small-world network. Second, the ATN evolved towards a symmetric state. In a detailed study concerning the criticality, the paper employs various network metrics: betweenness, degree, clustering coefficient, etc., The authors assert that the two criticalities are highly correlated with each other and with socioeconomic measures such as the GDP of the corresponding country.

2.2 Quadrant B: Discovery ∩ Specific Topology

This quadrant classifies research devoted to discovering characteristics of some specific types of ATN. Because H&S and P2P are dominant in ATN, many works attempt to understand the distinct properties of them. Naturally, many publications deal with real cases on these network types. Improving network performance and reducing complexity are also popular research topics.

Cook & Goodwin [15] studies fundamental disparity in characteristics of H&S and P2P systems, by focusing on the economic and operational characteristics and by using various attributes such as scope, connectivity, dependence, demand, market size, frequency, pricing, asset utilization, cost of operation, and fleet requirement. This paper strategically compares legacy airlines and low-cost-carriers (LCC), also known as regional airlines, based on real data. By understanding that most of the LCC operate as H&S, this paper emphasizes the contribution of the route selection architecture that gives LCC competitive advantages. This paper also claims that the notable advantage of H&S over P2P is being able to cover most or all of the airports in the network with a limited amount of resources. For a P2P market, the main advantages are limited to the largest markets. The LCCs in a P2P network had advantages over H&S in reduced total travel time and cheaper cost in the early era of the 20th century. However, as time goes by, legacy carriers improved their cost efficiencies by reconstructing their labor systems over history, causing these advantages to be significantly diminished.

Song & Ma [16] focuses on the economic perspective of the ATN rather than the network itself by analyzing the nature of H&S operations in ATN systems and the dynamics of the emergence of hub airports after the deregulation of 1978. Based on their observation, the authors find three major economic effects of hub airports to local economy. The primary effect is the significant income increase thanks to the advent of services or expansion of existing services at airports. The second effect arises from running the airport in the long-term as well as indirect multiplier effects due to the on-going flow of income originating from the airport’s operations. The last one is the economic benefits from attracting and hosting many associated companies and industries into the locale in order to enable the high-quality air transport to be available. The paper concludes that proximity to a hub airport has significant structural advantages for the economic development both in short-term and long-term.

2.3 Quadrant C: Design ∩ General Topology

This quadrant encompasses papers designing or modeling a general ATN based on scientific approaches. In this research field, one of the major strategies is employing a network optimization methodology. Trending issues focus on how complex optimization problems can be appropriately defined and efficiently solved. With these efforts, the possibility and capability to improve the given ATN can be virtually explored. Some challenging properties of ATN optimization problems are as follows. First, the problem generally has very stringent equality and inequality constraints. Second, many of the variables are discrete such that algorithms considering continuous variables can seldom be used. Third, the topology generally has large combinatorial cases to examine. Lastly, defining the relevant design variables or factors for optimization is extremely elusive as they are either too abundant to consider and too complex to curtail. Despite these obstacles, many network optimization works on a general ATN have been published.

Guimera & Sales-Pardo [17] proposes a mathematical and computational framework to deal with the problem of the reliability of source data in complex networks. The algorithm is capable of identifying both missing and spurious interactions between nodes in noisy networks. The test network topology for experiments is created from the original reference topology by purposely manipulating the topology via removing some links (missing links) and creating some dummy links (spurious links). The algorithm recovers the correct links to yield a refined network data with better accuracy than the other established data. As a typical test case, the paper applies the framework to the European ATN. The final results reduced the original 60 missing and 60 spurious links to 52 each, which is a 13% improvement. Through this framework, the paper claims that the input noisy ATN data can be reconstructed for better understanding of the ATN.

Taylor & DeWeck [18] suggests an integrated air transportation system formulation that concurrently optimizes various vehicle designs and network flows in order to design an ATN. The architecture is more advantageous than traditional methods for designing an ATN that focus on either vehicle design or the network flow. The developed architecture expands the system boundary during the design process to the network routing, vehicle specifications, and operations that couple the vehicles of the network. This formulation decomposes the ATN architecture into multiple subsystems and applies a linear programming solver for each sub-optimization problem. Moreover, the paper applies this formulation to a virtual ATN for an overnight package delivery as a sample case. [19] In this problem, the design of transportation architecture is obtained by concurrently optimizing the vehicle and network decisions. The optimization problem is solved twice by using the traditional approach and by the integrated design methodology. As a result, it is confirmed that the integrated design methodology yields a better solution that is more than 10% of cost reduction in the tested example. Also, the resultant network topology is noticeably different from what traditional methods would generate.

Kotegawa, DeLaurentis & Sengstacken [20] develops and compares three algorithms that forecast the likelihood of un-connected city pairs being connected by service in the future, primarily based on the nodal characteristics of airports in the U.S. network. This research is motivated by acknowledging the limitation that FAA's ATN traffic forecast model assumes no link additions and removals in the future. The three proposed algorithms are logistic regression model, fitness function model, and an artificial neural network (ANN) model. All models are based on the historical change of ATN data and they apply corresponding methods to forecast the future network topology. Results show that the ANN outperforms others in predicting the link removals and additions. Finally, the author concludes with a future research plan to overcome disadvantages of the ANN: not knowing the dynamics in the algorithm and computationally expansive cost.

Hu & Paolo [21] proposes a genetic algorithm (GA) based on complex networks theory for designing an optimized ATN with various objectives. The GA embraces the complex network concepts and techniques to relevantly model the ATN. Considering the characteristics of GA, the paper focuses on developing a highly efficient crossover operator. In order to appropriately set up the network optimization problem, this paper defines and uses specific network metrics such as robustness, degree, and shortest path distance. Robustness is defined as a measure of the importance of each airport and route segment when the failure of an airport is concerned. In an exemplary experiment, the algorithm shows resultant European ATN topologies for different design objectives.

Lewe & Yang [22] develops an ATN design algorithm underpinned by an evolutionary approach. The evolution in this paper is defined as a logical concept that indicates a series of growths or changes of networks involving time, space, technology, and any other associated socioeconomic characteristics. In order to relevantly address the evolution in a network design, the concept of evolution space is devised where the concurrent environments are defined by setting the spatial expansion (serial debuts of airports) as the horizontal axis as well as the volumetric progression (increasing travel demands) as the vertical axis. This evolution space hosts an evolution path, a collection of discrete points representing the corresponding evolutionary environments. Based on the given environments, the model uses probabilistic trip distribution to mimic the adaptive behaviors of airlines for each evolution step. Probabilistic trip distribution is to mimic diverse route options for a travel in reality by multiple airlines in the ATN. Based on the developed ATN design algorithm, Yang [23] creates an object-oriented ATN model of which the result is validated against historical reference data. The model considers 66 US major airports in its network design. Also, a lot of 'what if' scenarios are conducted to evaluate the model's network design capability. For example, the significant enplanement decrease of Saint Louis (STL) airport in early 2000s was vividly captured by merely changing one design variable for the scenario.

Song, Lewe & Mavris [24] proposes a multi-tier evolution model of ATN as an advanced version of the previous model [23] by expanding the number of airports from 66 to 300. Based on the analogy between the evolution of the ATN and that of evolutionary biology, various evolutionary concepts are addressed into the model. The ATN is decomposed into two heterogeneous primary and secondary sub-networks. The primary tier is the main evolving H&S networks consisting of primary hub networks whereas the secondary tier is one for regional airports that switches tiers to travel. The primary tier is the backbone of the evolution of the entire ATN with a very strong H&S topology while the secondary tier co-evolves and interacts with the primary tier in the evolution process.

Emission, noise, etc. are very important issues for ATN. Some network researchers have included the environmental issues in the network design problems. These studies are committed to investigating aircraft fleet and aircraft mission profiles rather than other ATN research, as they are also big contributors to the environmental issues. This focus comes with a great deal of design parameters to consider such that problems can often be complicated and challenging to obtain solutions.

Hsu & Lin [25] develops an airline network design model for minimizing airline operation cost to determine optimal air routes and flight frequencies, types of aircraft in response to airport noise charges. The paper takes into account the aircraft noise charges as well as the noise charge policies of airports from multiple perspectives during the problem setting and solving. Depending on the noise policies, the airlines adjust their operations resulting in change of the ATN topology. An empirical example using Chiang Kai-Shek International Airport as a test case shows that the airlines can reduce the impact of an increase in airport noise charges on their operating costs by changing aircraft types and flight frequencies such as direct to indirect or vice versa.

Braun, Koch, Dahlmann, Grewe & Gollnick [26] introduces a multi-target airline network design model considering emissions from a climate model. The methodology formulates the cost function of a network design model considering the balance between airline's profit and the climate impact in the network design optimization. For modeling the climate impact, a chemistry climate response model is used and allows the emissions associated with H_2O, CH_4, and O_3 to play roles as constraints. The ATN design model is based on a mixed integer program and its solution, an ATN topology, is constructed under the given specifications of the airline operational environment. Therefore, this research is not attempting to improve the existing ATN but to design a new ATN from scratch. In the preliminary results, the methodology is implemented and evaluated for a single airline owning a single aircraft configuration available.

2.4 Quadrant D: Design ∩ Specific Topology

This quadrant is similar to quadrant B. Papers that are classified into this quadrant focus on specific types of ATN such as P2P, H&S, etc. The ATN is so complex that even if the scope is narrowed from a general perspective to a specific type, the overall dynamics are still elusive.

O'Kelly [27] presents the first recognized discrete H&S design formulation as a quadratic integer program. Compared to his previous work, this paper deals with a *p*-hub location problem, where *p* is the number of hub airports per flight route. The objective is to minimize transportation costs by finding the optimum allocations of *p*-hub airports into the CONUS. As examples, two-, three-, and four-hub problems in 10, 15, 20 and 25 U.S. cities are examined. The algorithm chooses Chicago and Dallas-Fort Worth as the hub airports in all cases. This result partially substantiates the geographical advantage from which Chicago and Dallas Fort Worth benefit in the real ATN.

Campbell, Ernst & Krishnamoorthy [28] develops a model for optimizing the unit flow costs by locating hub airports in the U.S. ATN. The links are called arcs in this paper. A special constraint for the hub problem is that all travel must include at least one hub airport. In order to examine the performance of model, four different problems are formulated that have different constraints. Inferring from the results of the simulations, the authors emphasize the importance of discounts from the hub airports for the H&S topology to emerge and evolve.

Yang & Kornfeld [29] examines the optimality of the H&S principle by solving a set of network optimization problems using a mixed integer programming technique. The paper focuses on a cargo freight network system as the research object whose goal is to fulfill next-day air cargo delivery among a small number of city pairs. Considering that aircraft type, cargo demand, and city location can impact the optimal cost, this study seeks to figure out under what conditions the ATN transforms its topology from H&S to P2P and vice versa.

Han & Zhang [30] introduces a H&S ATN design model inspired by Newton's law of universal gravitation to address the influence of customer volume due to hub airport selection. The gravity model implements the tradeoff between reduced costs and increased flight times by using hub airports. The model involves demand, population, distance, and an influence parameter and the design objective is to maximize the total amount of social welfare of fifteen Chinese major cities. Employing a mixed integer programming, the results show that the ATN topology for maximum welfare as a tradeoff for enforcing hubs in the network.

Garcia, Landete & Marin [31] proposes a formulation of an integer programming technique and a new branch-and-cut algorithm (BCA) devised for solving *p*-hub location problems more efficiently. For this goal, the problem formulation and BCA are synchronized to handle larger instances of hubs in the ATN. For an appropriate problem setting, the "uncapacitated multiple allocation hub location problem" and "multiple allocation *p*-hub median problem" are formulated with a concept of transformation cost for a spoke airport to become a hub. The paper claims that the BCA algorithm helps to solve larger instances than those previously solved in the literature and thus performs "specially well" for relatively large values of *p*.

Some papers seek to account for the unpredictability and complexity in the ATN by quantifying the uncertainty. These efforts are important since much of the established research assumes the ATN is deterministic. Some metrics that are frequently considered to have uncertainty are demand, operation delay, and hub failure.

Shahabad & Unnikrishnan [32] incorporates robust design optimization with a network design problem by considering an "uncapacitated single and multiple hub location problem" and assumes that the demand has uncertainty. Based on the devised uncertainty mechanism, by imposing perturbations on the mean demand, the model solves a min-max problem whose objective is to minimize the total cost of allocating hub locations. As an experiment, the paper conducts a simulation with respect to the correlation between the uncertainty budget, the strength of uncertainty, and discount factors on hubs. The results assert that the number of hubs is positively proportional to the uncertainty budget since higher values of the uncertainty budget and discounts outweigh the uncertainty for more hubs to emerge.

Alumur, Nickel & Saldanha-Da-Gama [33] addresses a multiple-hub location problem of the U.S. ATN by considering two sources of uncertainty: set-up cost and demand. Set-up cost is associated with certain factors such as land acquisition and construction. This paper proposes the use of a "min-max regret formulation" as a means to handle the uncertainty in set-up cost with various uncertainty scenarios. Demand is also assumed uncertain and delineated by a finite set of scenarios with different known probabilities. The authors conducted simulations considering the two sources of uncertainty separately and simultaneously. The study shows that the uncertainty in set-up cost in general outweighs the uncertainty in demand and some hub locations are robust to both uncertainties, which agrees with the known principle that geographical location is a major factor in determining hub locations.

3. Discussion

Most of the papers reviewed in the discovery column (quadrants A and B) analyze the ATN using various metrics. Some attempt to find the linkage between particular socioeconomic factors and the ATN, others study the history of the ATN by looking into changes of metrics over time, and yet other researchers try to identify aircraft operation patterns in the ATN. Regardless of the scope or the purpose of the study, the proper selection and use of metrics alleviates the difficulty in dealing with the inherent complexity and thus helps network researchers to decipher seemingly hidden properties of the ATN. However, relying on network metrics alone hardly informs the researchers of detailed network dynamics. This is unavoidable because metrics are not ingredients of the network; rather they provide glimpses of various aspects after the ATN is established. For example, Las Vegas and Denver airports may show similar degree as nodes but their characteristics and roles in the ATN are quite different. It is noteworthy that efforts have been made in an attempt to grasp a better understanding of the network properties and to overcome the limitation. Some employ network decomposition to study the sub-networks and their interactions. Others engage machine learning techniques such as the deep learning theory and thus many extremely large-scale network topologies are efficiently assessed. Moreover, various network prediction and regression models are developed and evaluated to extract the relationships between the networks residing in different timelines. These are great examples of recent research trends applicable and recommended toward the integrated M&S framework.

As to the design column (quadrants C and D), we can recognize two approaches to accomplishing network construction. The first approach seeks to reenact the complex events in the ATN while striving to gain a profound understanding of the dynamics. Various algorithms and models, inspired by such as gravity, evolution or other natural phenomena, are suggested to imitate the behavior of the ATN. Naturally, the veracity of the model as well as validation and verification is one of the most important issues in these endeavors. The second approach focuses on finding an improved or alternate ATN. It is challenging because network optimization problems are mathematically complicated and computationally intensive. As such, many efforts delve into enhancing the algorithm efficiency, often handling sophisticated constraints and diverse variables to better represent the network. Recently, more challenging problems are tackled considering uncertainties in demand, operation, government policies and so forth. Despite the advent of high performance computing and advanced algorithms, however, a collaborative effort from both approaches is rarely observed. This is a recommended research area which is expected to result in synergistic achievements by seamlessly combining exploration and optimization of the network.

4. Conclusion

The integrated modeling & simulation framework for the Air Transportation System-of-systems was envisioned for the ultimate purpose of carrying out a variety of architectural tradeoff studies. This framework will help researchers or stakeholders conduct decision-making process more efficiently and cohesively. The literature review was performed to support the creation of the framework. In the course of reviewing the literature, the classification scheme facilitated a better understanding of the state of the art and to what extent of the aspects of the ATN should be taken into account, regardless of diverse approaches and methodologies from various fields. Reviews on the four classification quadrants delivered detailed information on their achievements and contributions, followed by discussions about the recent trends and recommendations for future research.

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