A NEW SYSTEMS ANALYSIS: PERSPECTIVES ON SYSTEM-OF-SYSTEMS AND REGIONAL TRANSPORTATION PROOF-OF-CONCEPT STUDY

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Abstract

In aerospace, systems analysis generally refers to the process whereby systems (typically technologies and/or aircraft configurations) are evaluated in order to determine their appropriateness to a given operating environment. We propose that a new version of systems analysis is needed that, while having the same general purpose, possesses the ability to expand the scope to a system-of-systems setting. In this expanded (and increasingly more relevant) setting, the focus of analysis is on multiple systems that interact in a dynamic, multi-layered, heterogeneous environment. In this paper, the differences between the traditional and new system analysis are articulated. Since the system-of-systems approach for analysis has been documented in the literature, in this paper we instead focus on a proof-of-concept study treating regional air transportation.

1 Introduction

1.1 Definitions and Research Motivation

In aerospace, *systems analysis* (SA) generally refers to the process whereby new systems are developed and evaluated in order to determine their appropriateness to a given operating environment. Often, these analyses are used to identify and prioritize "the required technologies needed for mission and/or vehicle development efforts" [1]. Specifically, SA is "the integration of advanced concept/architecture generation coupled with the application of various technologies where benefits and sensitivities are assessed" [2]. Embedded within this definition of SA is the concept of *architecture*, which is an arrangement of functions and forms that satisfies some objective. In other words, an architecture defines the organization of systems designed to accomplish a specific purpose [3]. Some architectures, such as those for air transportation, are complex, and there is increasing interest in how other-than-technological aspects (e.g., political, operational, or economic) affect the architecture's capacity for obtaining its objective [4, 5]. One challenge in analysis of architectures lays in dealing with the differing perspectives of the various stakeholders and contexts of systems that interact within the architecture.

Perspective and context are important in that they shape how a given problem (or system) is viewed. Consider the case of an aircraft. Depending on one's *context* ("the interrelated conditions which exemplify a system's state of being and which describe its purpose, scope, and meaning for services it may offer" [6]), the aircraft may be perceived quite differently. From the context of an aircraft manufacturer, it is a product to sell (or to compete against). For a resident near an airport, it may be perceived as simply another source of noise. For an air traffic controller, only the state (position, velocity, emergency status, etc.), intent (destination, approach for landing, overflying airport, etc.), and capability (navigation and communication) are germane. While this cacophony of perspectives (among many others) is often muted when performing SA for a single system, it becomes increasingly untenable to do so as multiple systems are brought together and interact in a dynamic, multi-layered, heterogeneous environment. These latter characteristics largely describe a *system-of-systems*.

System-of-systems (SoS) have unique properties which directly impacts their definition for analysis: evolutionary and emergent behavior, operational and managerial independence, and interconnectivity of systems in networks [7]. Evolution results primarily from *porous boundaries*, which (depending on the context) can refer to several different aspects of the SoS, including geographical, system, or operational boundaries. Once again, the various stakeholders in the SoS may see the systems (or entities), structure, purpose, and/or boundaries differently. Furthermore, the SoS boundaries—and even the entities within a SoS—may change with time, as depicted in Fig. 1. Each β_i is a collection of α-level systems. The result of the interactions at the α-level is felt at the corresponding β-level. In addition, there is evolution at play in the constitution (due to a porous boundary) and connectivity (due to interdependence of systems) during any interval of time. For example, there is an undirected relation between α_1 and α_2 at time t_1 while there is only a one-way relation between them at time t_2. Also, new entities appear and existing entities depart over time. Due to these changes among different α-level constituents, the performance of the β-level entities is altered by both evolution and emergence. Unanticipated new configurations lead to altered interactions between the α-level constituents and thus emergent behavior. Response to this behavior may subsequently alter the state of future β (i.e., higher) level realizations.

An SoS approach seeks to structure organization in a manner that exposes the multiple levels of abstraction that are present. In particular, the structure represents connectivity of the multiple, heterogeneous, participating systems in the context of stakeholder and exogenous influences and distinguishes holistic analysis from more traditional system analysis. While SoS-oriented SA is necessary, it is by no means easier. SoS problems are particularly challenging due to their large scale and scope, the presence of dynamic effects at a multitude of levels, and the abundance of stakeholders operating under their unique perspectives. Table 1 compares traditional and SoS-based systems analysis.

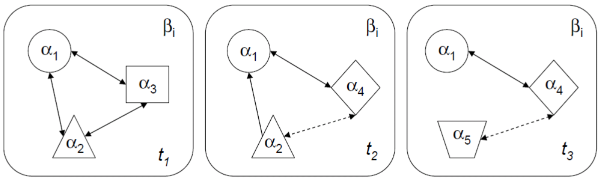


Fig. 1 Illustration of evolution and porous boundary in a system-of-systems

1.2 An inverse design analogy for new systems analysis

In addition to the distinguishing features just described, our recommended SA approach is top-down versus bottom-up. An analogy helps explain the rationale. In designing a new wing, aerodynamicists deploy an array of tools to analyze a proposed airfoil shape and plot (among other things) the pressure coefficient (c_p) on the upper and lower surfaces. Subsequent computations produce lift and drag estimates that determine the performance of a new wing design. *Inverse design* reverses the process—rather than starting with the physical characteristics, one starts with the desired performance, in the airfoil case the cp distribution, and then seeks out the airfoil that best matches the desired distribution.

This is especially useful in contexts where the desired performance is not solely a function of the characteristics of a specific system. For example, reduced delays and airspace congestion in the air transportation system is a desirable performance metric which may be studied. However, achieving this result requires more than simply redesigning the aircraft. That said, while it is a function of many non-technical influences, a search for methods that achieve desirable per-

Table 1 Summary of key differences between traditional and SoS-based systems analysis

	Traditional SA	**SoS-based SA**
Dynamics	Static	Time-varying w/ feedbackResources
Scope	Mostly Technical	Technical, economic, regulatory, operational
Number of systems	Single (or few)	Multiple interacting systems
Levels	Single-level	Multi-tiered
Boundary	Closed	Porous

formance levels may yield insights into technical solutions (such as new aircraft or airspace systems). This, in turn, enables designers to determine which aircraft design capabilities provide the preferred SoS behavior. *So, the preferred behaviors of the SoS as a whole can illuminate the best (set) of capabilities required of participating systems.*

Furthermore, this approach can assist policy makers in shaping the performance of the system-of-systems. Often, regulatory entities such as the FAA have limited power over the actions of other stakeholders in the air transportation SoS. In order to achieve its own goals, the regulator establishes sets of rules, and policies (e.g., landing fees). Upon the introduction of these policies, the other stakeholders react and settle into a new equilibrium position, which may or may not result in the behavior desired of the SoS in the first place. However, by better understanding the interconnectivity of the various stakeholders and their influence and operations in the SoS, more effective policies can be explored. The idea is to design rules of behavior that are *natural* and/or attractive to stakeholders and lead to beneficial SoS performance. Rather than relying solely on economic stimuli (e.g.,, fees and taxes) to incentivize certain behaviors (or discourage others), establishing a set of policies which allow the other stakeholders to achieve their own goals offers a (potentially) more stable solution.

Transformation of the U.S. air transportation system is underway as evidenced by shifts in both the private industry and public sectors. The industry is transforming due to the combined pressures of fare competition, fuel price increases, and limitations on flexibility in reducing overall operational costs as well as new opportunities enabled by technological advances. Mainline carriers are seeking to remold service and cost structure to compete for the fare-conscious travelers being increasingly attracted by low-cost carriers (see discussion in [8]). The government is seeking to transform the air transportation infrastructure to face the system-wide challenges brought by more operations and increasing demand, especially in areas of capacity and reliability. This effort is encapsulated in the NextGen effort led by the JPDO [9]. Within the mixture of both private and public sector convulsions, new ideas are emerging that could impact the "transformational" interests of both groups. These ideas range from new aircraft technologies and novel configurations (e.g., blended wing body) to advanced navigation performance and highly automated separation functions in the airspace domain. The intent for a new system analysis is to support traditional questions ("Which technologies?", "How much technology?", "How much will it cost?", etc.) in the midst of a much larger, more heterogeneous, and dynamic decision space that includes interactions between advanced air vehicle and air traffic management solutions. Again, the notion of boundaries comes to the forefront, since this new approach brings new stakeholder contexts—with their respective boundaries, relevant interactions, and so forth—as illustrated in Fig. 2.

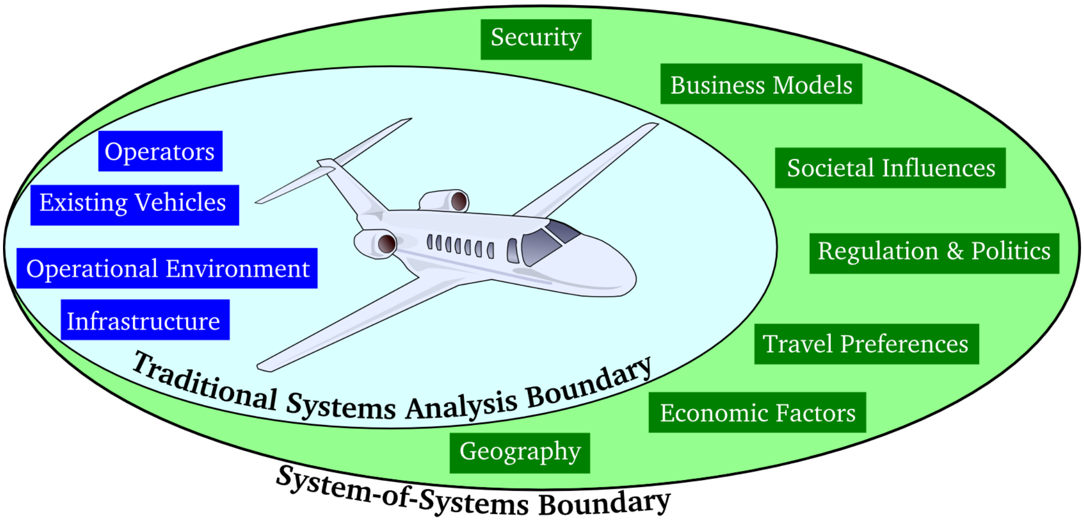


Fig. 2 Systems Analysis in support of NextGen requires the new, SoS-oriented analysis approach boundaries

1.3 Importance of a New Perspective on Systems Analysis

Systems analysis has developed a powerful set of tools for analyzing various aspects of a technical system. These tools and approaches are extremely well suited to the purpose for which they were developed. The new perspective and approach presented here is not intended to diminish or marginalize the importance of these established methods. Rather, the objective is to augment these tools by improving the scope and breadth of the analysis. The ultimate purpose of both approaches is to better understand which decisions (technical, economic, regulatory, etc.) have the biggest impact on the SoS.

2 Technical Approach

Our prior work presented at the 2006 Congress [10] introduced the modeling and simulation (M&S) approach for air transportation system analysis problems as a system-of-systems. The approach combined agent based models for transport service providers (e.g., airlines) and infrastructure providers (e.g., FAA) with a dynamic network topology model to enable the ability to simulate and measure network performance under a variety of driver and disruption scenarios. A modeling abstraction for air transportation architectures introduced in [11] underlies the M&S.

In this paper, we adopt and expand upon this M&S approach to demonstrate some aspects of the new systems analysis that we advocate and to draw attention to how this viewpoint changes the way systems analysis is done. We use a regional air transportation example as proof-of-concept. In the regional transportation domain, one idea that has come to the fore is that of “On-demand Air Service” (ODAS). Derived in part from NASA research conducted over the past five years in the Small Aircraft Transportation System program [12], ODAS represents an extremely flexible service that may be attractive to consumers seeking efficient origin-to-destination travel while also relieving congestion at hub airports which is the primary source of delay in the larger air transportation system.

To demonstrate the M&S approach for an ODAS application, we chose a small region for which data on available airports and population demographics was easily available to us: the state of Indiana. Indiana in isolation is not a realistic market for ODAS (or any regional transport enterprise), but it serves the purpose for our proof-of-concept needs. A related study using this region was performed by the authors [13]. Once demonstrated and verified, larger and more realistic applications with improved data, more airports, and more detailed business models can be addressed.

The general flow of the analysis is shown in Fig. 3. Demographic information was obtained for each Indiana ZIP code from the US Census Bureau [14, 15]. This was linked to airport location [16] to determine the relative size and characteristics of the market each airport could serve in a dispersed, ODAS system. From this information, airport "fitness" was calculated as a function of the population served, number of businesses near the airport (and their total payroll), and their connectivity to the other airports (both how well connected the network as a whole was and the strength of the given airport's connections). Each airport origin-destination pairwise fitness was calculated, establishing the likelihood of travel between the given airport pair by creating a surrogate model of how attractive a given origin-destination airport pair was to a potential traveler. This in turn provided a demand matrix, which denoted the potential demand for service from each airport to every other airport in the state.

From this demand network, the number of potential ODAS customers was found. This section of the analysis was aided by choice models developed in a recent study of stated traveler preference between existing modes (commercial air or automobile) and a new on-demand air service for regional, inter-city travel [17]. The models developed from the survey relate a traveler's level of education and income, the cost difference between car and ODAS travel, and proximity of ODAS to job location to the likelihood of a given person to switch to ODAS. These three factors were found to be most important to the mode choice. For the current analysis, only business trips were taken into account (a separate model was developed for personal trips in [17]). In future work, these choice models (developed from actual stated preferences) could be incorporated into more sophisticated travel demand generators, such as the *Mi* tool [18] or the Transportation Systems Analysis Model (TSAM) model [19].

The ODAS network was then determined by applying the aforementioned travel mode switching model to the demand matrix. Each eligible ODAS customer (determined by his/her demographic characteristics) in the demand matrix was given the option of choosing ODAS over driving, and some—based on the defined probability of switching—chose ODAS. These travelers formed the basis of the ODAS network and represent the number of individuals an actual on-demand air service operator would attempt to serve. In this study, approximately 16% of all business travelers in Indiana switched to ODAS. Constraints and enablers are also shown as inputs to network development in Fig. 3. Though not yet implemented for this initial proof-of-concept, these externalities add relevance to the scenarios that can be studied, especially for assessing the impact of NextGen concepts on regional air transportation.

Finally, specific aircraft design and route allocation activities can be performed in an attempt to realize the developed ODAS service network. Recent work at Purdue University exemplifies these important activities in "closing the loop" [20, 21]. This process may be repeated with the injection of policy, demographic, and economic perturbations to investigate the time-variation in performance categories such as transportation efficiency, economic viability, and infrastructure sustainability. Following the inverse design analogy discussed above, rather than focusing first on the individual system (the aircraft, airport etc.), the emphasis is on a top-down design with feedback on SoS performance to earlier portions of the analysis. Further, the scope of analysis is broader, encompassing aspects such as the operating environment and potential market forces (demand, incumbent convenience of auto travel, etc.).

Though only a proof-of-concept study, results from the Indiana study can illustrate the type of insights the new systems analysis can provide. For instance, many of the origin-destination pairs have very few travelers, which is almost entirely due to the cost-effectiveness of driving shorter distances. Indeed, none of the travelers selected ODAS if the origin-destination distance was less than 100 mi (160 km); the percentage of trips

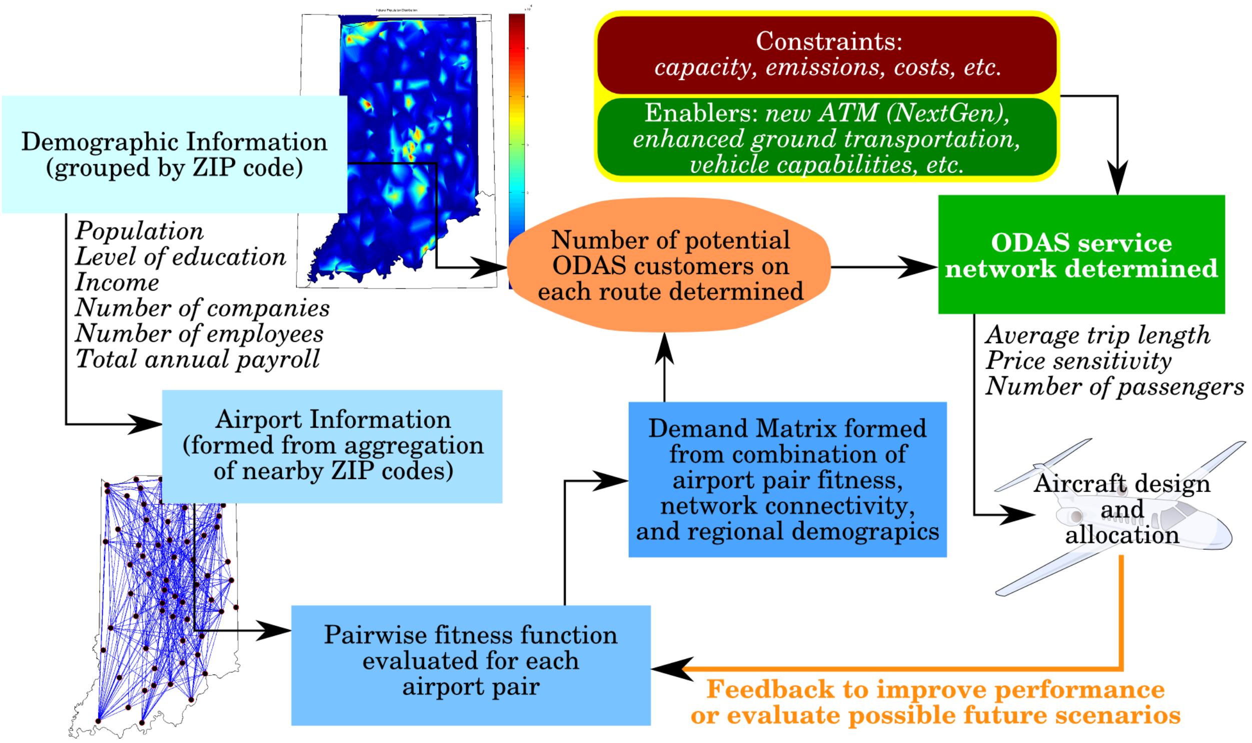


Fig. 3 Flow of information and relationship of various aspects of the analysis

flown in the ODAS versus distance are shown in Fig. 4(a). While the lower bound of 100 miles is not surprising, the decreasing trend is somewhat unexpected. It would seem logical that the longer the route, the more people would choose flying over driving. What Fig. 4(a) shows is an artifact of the particular service area and capacity chosen. That is, there are only a limited number of origin-destination airport pairs in Indiana which are 250 mi (400 km), or greater, apart. Examining the data further, we see that the ODAS served an increasing amount of the long-distance travel, as seen in Fig. 4(b). In fact, all travelers going 270–300 miles used the ODAS rather than drive. On the shorter ranges (100–230 mi), the percent of origin-destination pairs served by the ODAS decreased to around 15% as more travelers chose to drive.

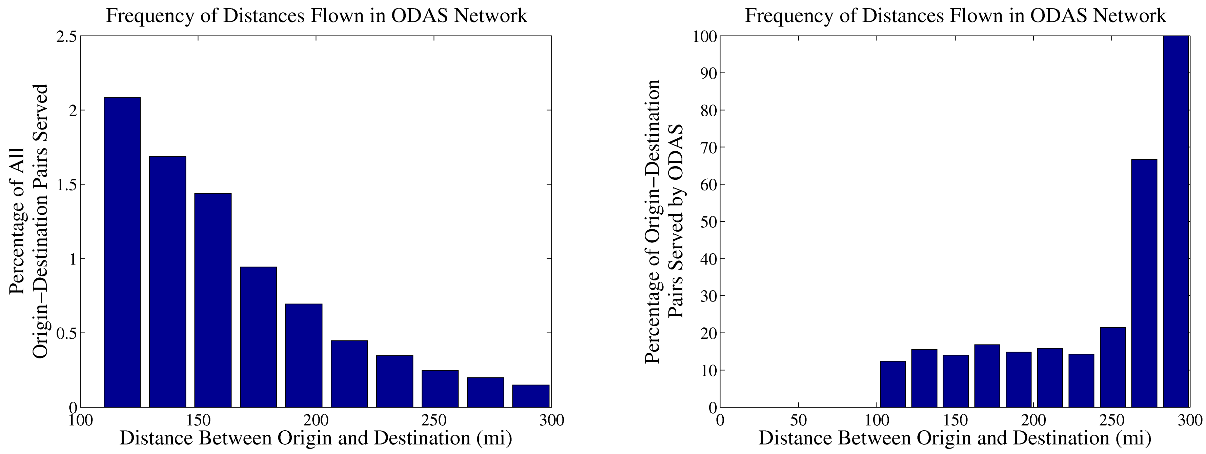
One meaningful measure of how well the ODAS network meets the travel demand is the *transporting efficiency*. This metric is defined by a set of network theory parameters, the exact derivation of which is beyond the scope of this paper, but which are admirably described in [22]. The first step in its calculation combines the ODAS network structure and demand matrix into a weighted shortest path, given by:

$$l_i^w = \frac{\sum\limits_j l_{ij} w_{ij}}{\sum\limits_j w_{ij}} \qquad (1)$$

where l_{ij} is shortest path between airport i and airport j (the number of flights required to link each airport i and j) and w_{ij} is the demand between airport i and airport j. Using Eq. 1, the shortest path weighted by the demand is computed leading to the average weighted shortest path of a given node, denoted by l_i^w. In this formulation, l_i^w is larger when demand is greatest between pairs with longer shortest path. This weighted shortest path is then converted (by means of reciprocal sum) to the transporting efficiency:

$$E_t = \frac{1}{N} \sum_i \frac{1}{l_i^w} \qquad (2)$$

The values of Eq. 2 fall between zero and one.



(a) (b)

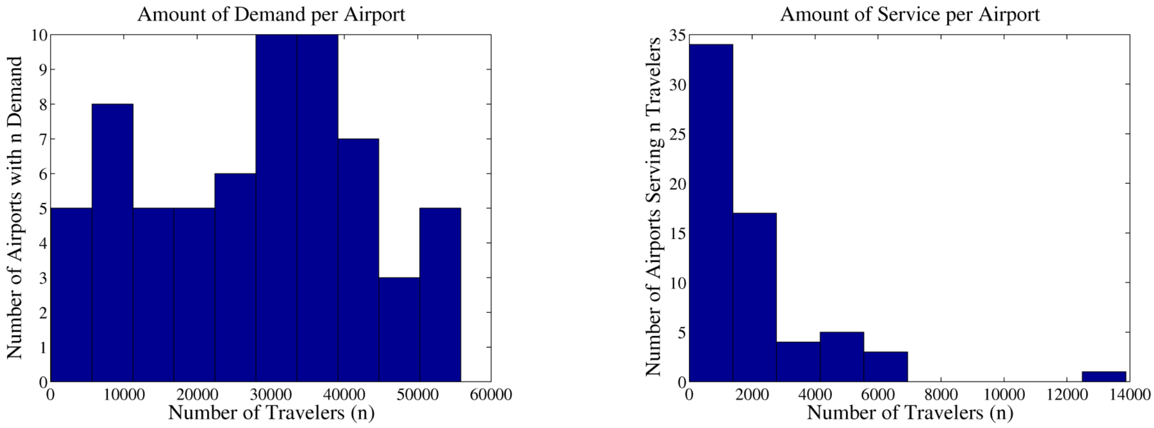
Fig. 4 Number of trips flown by ODAS in distance

This compact metric thus captures the coherence between the mobility network (demand) and the ODAS network. In the case where all existing demand pairs are connected with direct link, the maximum of transporting efficiency is reached (though at cost of high density). In this case, the transporting efficiency of the ODAS network was 63%, which is quite good, considering that a large amount of the travel demand is met by ground transportation. As a comparison, hub-and-spoke networks generally have a transporting efficiency of 49–52%. This value also indicates that the *topology* of the ODAS network matches fairly well with the demand network, allowing a large number of travelers to be efficiently transported.

The utilization of airports with different characteristics (e.g., location, runway configuration, etc.) can also be analyzed. For example, examining the demand and service distributions (Fig. 5) shows that the majority of travel is conducted by less than a sixth of Indiana airports. Further analysis of these airports reveals that most of these airports are near the northern and southern borders and hence, provide the largest set of ”long-distance” flights. Additionally, some of these key airports are in fact quite small and lack the infrastructure of even medium-sized airports. As a specific example, Salem Municipal Airport has only a single 2738 ft (835 m) runway which is too short for jet aircraft, no tower, and had 8963 operations in 2005 [23]. However, the ODAS analysis shows 7211 one-way passengers traveling into and out of Salem each year. Even if these flew in four-passenger aircraft (the size generally envisioned for ODAS) at full load, this would mean an additional 3600 (round-trip) operations per year. If the aircraft fly at less than 100% capacity, as might be expected, this number increases to an even greater fraction of current airport operational level. Similar studies have also analyzed the impact of an ODAS on the national air transportation system [24].

This combination of high-level analysis and detailed analysis of individual systems is intended to enable decision-makers, such as NASA and the FAA, to see some of the (possibly unexpected) behaviors of the system to help them better invest in the proper areas to establish a new system-of-systems (such as an ODAS). These investments could be in research and development of technologies (advanced navigation, STOL capabilities etc.) or in infrastructure improvements (towers, additional runways, etc.) at these airports to make them capable of handling the kind of traffic implied by an ODAS.

While NASA and the FAA can use this information to guide their research and development investments, an ODAS provider may view this analysis from a different perspective. The service



(a) Travel demand distribution

(b) ODAS service distribution

Fig. 5 Distribution of travelers by airport showing a) demand and b) established ODAS network

provider sees a reasonable estimation of the number of potential users of the system and can perform further analysis into price sensitivity, marketing strategies bases on segment of population using the system, and set of aircraft to buy and how to deploy them. For example, if ODAS fares were reduced by 5%, an additional 4% of business travelers switched to ODAS. Detailed cost feasibility studies, based on approaches similar to [21], could then be performed to estimate setup and operational costs of the service. Additionally, a potential ODAS service provider may look at the characteristics of key airports and determine them to be undesirable from a lack of indigenous ground transportation accessibility standpoint (e.g., some airports are several miles from the city which they serve and local taxi service may not exist). Alternatively, they may decide to invest their own funds to improve a set of airports they primarily serve in order to improve the quality of service. Similarly, Manufacturers may use these insights to develop aircraft with even shorter ranges—potentially reducing the take-off gross weight and thereby take-off distance—to better suit this market of aircraft.

In summary, this example was meant to show how a wider-scope, higher-level analysis of a system (or system-of-systems) can yield new insights into the system as a whole, which can lead to improved decisions on individual system properties. This relates back to the idea of inverse design where we know generally what kind of performance we want (low cost, fast alternative to driving) and “back out” the characteristics of the system which enables that performance. Also, it shows the interconnectivity of the various aspects of system-of-systems (such as demographic characteristics, airport location, and socioeconomic forces) which can be used to develop a viable architecture whose form (e.g., mix of aircraft and operations) and function (e.g., capacity, costs, and deployment) work to achieve the stakeholder (or system) objectives.

3 Conclusions

Traditional systems analysis features a rich set of powerful tools for analyzing individual (technical) systems. These tools and the accompanying analysis can be augmented by broadening the scope of the analysis and incorporating economic, policy, and operational aspects of the system-of-systems under investigation. The proof-of-concept example presented here, did not focus on “solving” the on-demand air service problem, rather on demonstrating the method and insights gained from this new systems analysis. The particular analysis undertaken here could certainly be augmented with environmental and operational constraint or demand/service growth models.

One of the primary objectives of this type of analysis is to enable more effective decision-making, whether it be on a system, region, national, or global level. Finally, this approach is not confined to aerospace applications. Indeed, areas such as healthcare and national defense could benefit from this type of systems analysis which draws attention to the different perspectives of the various stakeholders in the system-of-systems.

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