

# SYSTEM OF SYSTEMS: AN INTRODUCTION OF PURDUE UNIVERSITY SCHOOLS OF ENGINEERING'S SIGNATURE AREA

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## INTRODUCTION

In August of 2002, the Schools of Engineering at Purdue University began an effort to identify “signature areas”<sup>1</sup> as part of the commitment to reinforce the Schools’ standing as a preeminent academic engineering institution. The University administration has allocated 75 new faculty positions, above the current number of engineering faculty, to pursue highly relevant, multidisciplinary activities in discovery, learning and engagement. During the Spring 2003 semester, signature areas were identified based upon proposals submitted by engineering faculty members. The eight selected areas are: Advanced Materials and Manufacturing, Global Sustainable Industrial Systems, Information, Communication and Perception Technologies, Intelligent Infrastructure Systems, Nanotechnologies and Nanophotonics, Renewable Energy and Power Systems, Tissue and Cellular Engineering, and System of Systems. Academic planning, multidisciplinary collaborations, and faculty searches for these eight areas began during May of 2003.

This paper will present an introduction of the System of Systems Signature Area. This includes discussion about system of systems, an overview of the signature area – including the main research areas and current efforts, and finally an overview of three example problems that could be used as starting points for discussion and research into problem formulation and solution techniques for systems of systems. While the following discussion will rely upon aerospace and defense examples, because of the author’s familiarity in this domain, other non-aerospace-centric examples exist.

## SYSTEM OF SYSTEMS

The idea of “system of systems” as an emerging and important multidisciplinary area for Purdue University’s Schools of Engineering arose as faculty members began to recognize significant changes in government and industry, particularly in the aerospace and defense areas. Major aerospace and defense manufacturers, including (but not limited to) Boeing,<sup>2</sup> Lockheed-Martin,<sup>3</sup> Northrop-Grumman,<sup>4</sup> Raytheon,<sup>5</sup> and BAE Systems<sup>6</sup> all include some version of “large-scale systems integration” as a key part of their business strategies and, in some cases, these companies have established entire business units dedicated to systems integration activities.

One reason for this new emphasis on large-scale systems is that the customers of these companies – notably the Department of Defense – have changed their approach to acquisition. These customers now want solutions to provide a set of capabilities, not a single specific vehicle or system to meet an exact set of specifications. This illuminates two important contexts for discussing large-scale systems.

## CURRENT CONTEXT: AEROSPACE VEHICLE AS A LARGE-SCALE SYSTEM

Commercial aircraft (like the Boeing 737-800 in Figure 1), military aircraft, missiles, spacecraft, and launch vehicles are commonly used as illustrative examples of large-scale systems. These vehicles consist of a multitude of subsystems and components that must be integrated into a complex large-scale system. The constituent components and subsystems number on the order of hundreds of thousands to millions; design textbooks often cite the number of parts in a commercial transport aircraft (4 to 5 million) to emphasize the complexity of these systems.<sup>7</sup> The interaction among the various components and subsystems in an aerospace vehicle are complex



**Figure 1 The Boeing 737-800 commercial transport aircraft, a large-scale system.**

and sometimes only loosely understood. Designing and manufacturing these systems is not an easy task; it requires large organizations of highly trained individuals to tackle these problems. The development of the Boeing 777 involved over 10,000 people.<sup>8</sup>

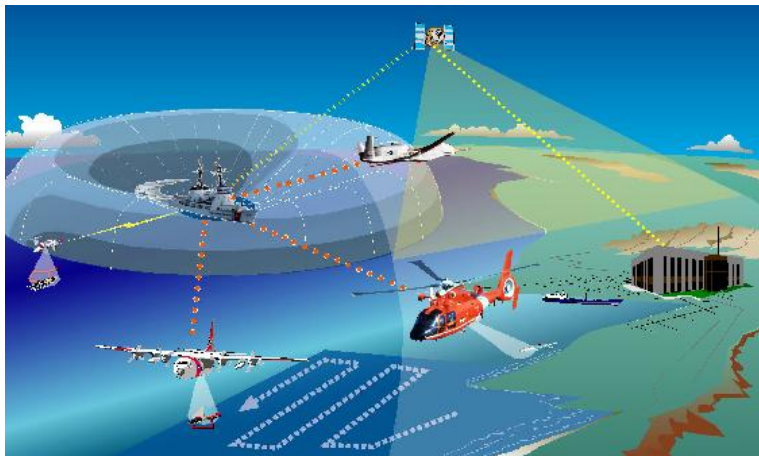
Providing solutions to this kind of large scale system problem has been a traditional strength of the major aerospace companies, although both domestic and foreign competition is fierce. One of the ways the industry has approached these complex problems is by adopting some form of integrated product teams to help bring multidisciplinary skills and abilities to bear on the complex interactions that must be addressed during the design of an aerospace vehicle. Systems engineering as a discipline, and its associated practices, has established itself within large companies as necessary to manage the challenges associated with the design and development of aircraft, spacecraft, launch vehicles, etc. It is in this context – where an aerospace vehicle is considered a large-scale system – that much of today’s aerospace systems work is focused.

However, this is not the sole context of large-scale systems. The emerging system of systems context adds complexity beyond that of the current “vehicle as a large-scale system” view. Addressing this new complexity provides significant opportunities for academic endeavor.

### **EMERGING CONTEXT: SYSTEM OF SYSTEMS**

In the view of the Purdue Engineering System of Systems Signature Area, the emerging system of systems context arises when a need or set of needs are met with a mix of multiple systems, each of which are capable of independent operation but must interact with each other in order to fulfill the global mission or missions. The mix of systems may include existing and yet-to-be-designed aircraft, satellites, ground vehicles, ground equipment, and other independent systems.

One indication of the opportunity presented by this subject appears in recent government approaches to procurement. Instead of asking for a single aircraft, vehicle, or other specific individual system to meet a set of performance requirements, customers are now asking for more encompassing solutions that meet a broad set of needs. For example, the recent US Coast Guard Integrated Deepwater System program asked contractors to address



**Figure 2 The US Coast Guard Integrated Deepwater System concept involving multiple, independent systems.**

the issue that the Coast Guard needs to replace its aging assets while improving their technological capabilities. Instead of specifying the precise mix of assets, the Coast Guard described its offshore mission requirements and gave contractors free rein to come up with the best way to perform these missions.<sup>9</sup> The solution requires an appropriate mixture of existing and new independently operating systems. Figure 2 presents an artist’s concept of the various constituent systems working and communicating to perform the Coast Guard’s missions. Other recently proposed systems of systems include the US Army’s Future Force (including the Future Combat Systems effort, which itself is considered a system of systems) and envisioned concepts for future Air Traffic Management (ATM).

The phrase “system of systems” has been in use for several years now, but there is not a single, widely accepted definition of a system of systems. Several researchers have developed their own definitions for a system of systems, and the work by Keating, et al. provides a summary of several of these perspectives of system of systems.<sup>10</sup> Keating and his co-authors describe their view of systems of systems as metasystems that “are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography and conceptual frame.”<sup>10</sup>

When discussing its efforts for the Future Combat Systems Program, Boeing describes the program as: “a networked ‘system of systems’ – one large system made up of 18 individual systems, plus the network, plus the soldier.”<sup>11</sup> The US Coast Guard describes IDS as a system of systems that is “not just ‘new ships and aircraft,’ but an integrated, performance-based approach to upgrading existing assets while transitioning to newer, more capable platforms, with improved systems for Command, Control, Communications and Computers, Intelligence, Surveillance, Reconnaissance (C4ISR) and innovative logistics support.”<sup>12</sup>

The Department of Defense’s “AcqWeb”, the web site of the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, provides a frequently asked questions document about “systems of systems” and “family of systems”.<sup>13</sup> In this, the DoD describes a system of systems as “a set or arrangement of interdependent systems that are related or connected to provide a given capability.” It further describes a family of systems as “a set or arrangement of independent (not interdependent) systems that can be arranged or interconnected in various ways to provide different capabilities.” The DoD’s “family of systems” most closely matches Purdue’s view of system of systems.

The additional degrees of freedom associated with the ability of each system to operate independently within the system of systems add complexity above that encountered in the “vehicle as a large-scale system” context described above. A significant challenge in system of systems design is determining the appropriate mix of independent systems (both what type of aircraft, spacecraft, etc. and how many of each). This is further complicated as yet-to-be-designed systems are considered as potential options for the system of systems. Because the constituent systems are capable of independent operation, the systems could not only cooperate but also compete for subtasks within the system. The system of systems is a dynamic entity as new systems are added and current systems are replaced or removed. The operation of the system of systems occurs in an uncertain environment (for instance, an Air Traffic Management system of systems must handle weather conditions). “Interoperability”, which is defined by the DoD as “the ability of systems ... to provide data, information, materiel, and services to, and accept the same from, other systems...and to use the data, information, material and services so exchanged to enable them to operate effectively together,”<sup>14</sup> also poses a significant challenge.

### **PURDUE’S SYSTEM OF SYSTEMS SIGNATURE AREA**

There are numerous areas within system of systems that would benefit from academic endeavors. The Purdue System of Systems Signature Area will focus upon the methodologies and approaches needed to design and control a system comprised of multiple systems capable of independent operation. Purdue faculty members with ties to major aerospace and defense companies have observed that the ability to provide system of systems solutions is becoming necessary; however, the techniques and methods to generate the solutions in a formalized, repeatable manner are lacking in many areas. The System of Systems Signature Area will address issues associated with control of systems of systems.

Other Purdue Engineering Signature Areas will be pursuing work generally related to system of systems. For example, protocols and approaches needed to exchange data and information will be addressed by colleagues in the Information, Communication and Perception Technologies Signature Area; this will assist with interoperability issues. The Intelligent Infrastructure Systems Signature Area includes an emphasis on Intelligent Transportation Systems, which will include research into the sensors, devices, and information exchanges needed for operating advanced transportation networks and logistics systems. Much like the concept of system of systems itself, the Purdue Engineering Signature Areas will be research focus areas capable of independent efforts, but will also collaborate to address truly challenging problems.

### **RESEARCH AREAS**

Within the System of Systems Signature Area, four research areas have been identified as necessary to formulate and solve system of systems problems. These four areas may not have rigid boundaries, but they characterize the types of approaches and methods needed to formalize system of systems problems. These areas are 1) optimization, combinatorial problem solving and control; 2) non-deterministic assessment, and decision-making and design under uncertainty and; 3) game theory, economic/ competitive behavior; and 4) domain-specific modeling and simulation.

## **OPTIMIZATION, COMBINATORIAL PROBLEM SOLVING AND CONTROL**

The concepts of optimization have long been part of designing systems and vehicles. Over the past 20 years, advances in computation have allowed formalized optimization methods to become a part of design efforts for most single complex engineering systems, like aerospace vehicles. When addressing a single complex system, most design optimization strategies focus on minimizing or maximizing an objective while meeting several constraints. These objectives and constraints typically characterize the performance of the individual system for a typical design mission or missions. However, these design strategies rarely address the impact on the performance of a larger system of systems, nor do they usually address the dynamic, evolving environment in which the system of systems must act.

A great field of work exists that can address “organizing” a system of systems from existing single systems; resource allocation is currently used in any number of fields of engineering and business to improve the profit, throughput, or other system-level metric. However, these approaches make the assumption that the resources being allocated or assigned have known, static characteristics, while a system of systems problem would ask to not only allocate existing single system assets, but also define and allocate systems that have not yet been designed.

When designing new, single systems, there is often a great technology push to incorporate new technology onto the aircraft, spacecraft, etc. This generally has the impact of improving that system’s performance, but the impact of a new technology on the larger system of systems may not be as clear. If new technology choices could be formulated as discrete design parameters, it may be possible to incorporate these into a combinatorial optimization framework to help determine the appropriate use of advanced technologies for improves system of system performance.

Additionally, single complex systems designed today are typically designed for a specific, and generally static, design missions and operating environments. Because its constituent components are themselves independently operating systems, a system of systems can continually evolve. As new systems are produced, they must be integrated into the system of systems; similarly as current assets reach retirement, they must be removed from the system of systems. This implies that the system of systems would need to be designed to work in stages or phases following a set of strategies or policies. These concepts suggest applications of dynamic programming, in which decisions are made over time.

The optimization aspect not only is important for the design or architecting of a system of systems, but it is also important for the control of a system of systems to ensure optimal performance to complete the assigned tasks and missions. With multiple, independently operating systems in a system of systems, concepts of hybrid, hierarchical, and distributed / decentralized control may provide approaches to ensure that the system of systems maintains an optimal level of performance in real-time without information or computational bottlenecks and with limited conflicting commands.

## **NON-DETERMINISTIC ASSESSMENT, AND DECISION-MAKING AND DESIGN UNDER UNCERTAINTY**

A system of systems, like single, complex systems, will operate in “the real world”; however, the operating environment is non-deterministic. For instance, an air traffic management system of systems must operate in varying kinds of weather conditions, which can be predicted, but not with absolute certainty. Most engineering disciplines are beginning to address this type of uncertainty, and this focus must also be incorporated in system of systems problems.

A system of systems approach further extends the impact of non-deterministic assessment. Much of the motivation behind the move to a capability-based acquisition strategy requiring system of systems solutions is that the capabilities sought by the customer are driven by the desire to have high performance that is robust with respect to varying operating conditions and scenarios. As an example, consider one mission specified in the Coast Guard’s IDS program. Search and rescue is a high-visibility, high-priority mission for the Coast Guard. If one could assume that a distress call from a party in danger always contained exact locations of the party, it would be fairly easy to determine which assets should be used to retrieve the person(s) needing help. However, the distress calls do not always contain precise information, so the Coast Guard must often search for the person(s) and then retrieve the person(s). If the Coast Guard must cover a large search area, an aircraft asset may prove fastest to locate the missing

individual, but would not allow for retrieval of the person. For retrieval, a surface vessel or a helicopter could then be dispatched. Conversely, if the lost person is in a small area, or the sea is at a sea state too high for safe surface vessel operations, a helicopter may best perform both the search and rescue functions. Other variations in weather condition, search area size, location information, etc. could be posed as conditions within which the search and rescue mission is needed. The Coast Guard expects to successfully perform the mission regardless of these variations; hence, the Coast Guard maintains several different types of assets, capable of independent operation, to help perform this mission regardless of the operating conditions. When designing a system of systems, non-deterministic conditions must be addressed, and the system of systems must be architected to have the highest probability of success in spite of these probabilistic aspects of the design problem.

Reliability prediction of a large scale system generally requires constructing an aggregate probability distribution that describes the system's overall reliability. For a single complex system, the aggregate PDF can often be measured by sampling from the reliability distributions of the subsystems and components that make up the large scale system. In a system of systems sense, it is not clear that the system of systems level reliability assessment could be conducted in the same manner. Because a system of systems is comprised of multiple systems capable of independent operation, as one system entity begins to reach a degraded performance or a failure mode, other system entities can alter their independent operations to perform functions that the failed system no longer performs. This is not simply an "*m-out-of-n*" redundancy issue, because, if properly designed, the system of system does not necessarily include spare systems whose sole purpose is to fill-in for a failed system.

For instance, if a regional transportation network is viewed as a system of systems, whose constituent systems include busses, trains, and aircraft, and then as a train system becomes unavailable, no spare train may be present in the system of systems. One or more of the busses can be assigned to different or more frequent routes to replace the transportation capacity of the train. Or, when the train becomes unavailable, an aircraft may be assigned to different or more frequent routes. The more desirable option would be the one that maintains the highest system-of-system performance; yet, deciding upon this best option implies some sort of resource allocation is needed. In order to predict the reliability of the system of systems, the failure of the train system would need to be modeled, and then a series of conditional assessments are needed to determine the remaining reliability of the system of systems if one bus is used to replace the train system, if multiple busses are used to replace the train system, if an aircraft is used to replace the train system, etc. The approaches needed to perform this type of assessment are not readily apparent.

### **GAME THEORY, ECONOMIC AND COMPETITIVE BEHAVIOR**

A system of systems is comprised of individual systems capable of independent operation. As described in previous sections, using multiple systems in collaboration can provide capabilities well beyond those available from a single system. Further, the ability for each constituent system to operate independently can provide increased robustness for the overall system of systems. However, these aspects provide an additional level of complexity in determining which systems provide which contributions to the overall performance. The best operation for one system may compete with best operation of other systems. Decision making for the system of systems must resolve these issues, and determining an appropriate sharing of capabilities and resources will call upon applications and approaches from game theory and competitive behavior. In some circumstances, a system of system may itself compete against other systems of systems using strategies that allow less or non-competitive behavior in one aspect in order to provide overall system-of-systems level performance. The common adage "lose the battle, but win the war" will likely hold true, and game theory approaches may help to determine these systems of systems strategies.

### **DOMAIN-SPECIFIC MODELING AND SIMULATION**

With the focus of the System of Systems Signature Area centered upon problem formulation and solution strategies, it becomes apparent that much of the work needed to assist with these tasks is in the area of modeling and simulation. While this idea is likely no surprise, it also poses some interesting multidisciplinary issues for system of systems work. For example, the proposed Future Combat System involves manned ground vehicles, unmanned air vehicles, combat robots, soldier robots, communications systems, and the soldier him/herself. To successfully provide function evaluations for an optimization approach, or other decision making strategy, these components must be appropriately modeled. For example, modeling the aircraft systems requires expertise in aircraft, modeling the ground vehicles requires expertise in ground vehicles, etc. One important issue is that these systems be modeled at compatible levels of detail, which will require aircraft domain-experts to successfully communicate with ground

vehicle domain-experts. Further, nearly all systems of systems will have humans-in-the-loop, requiring the capability to model and simulate human behavior.

Simultaneously modeling all of the constituent systems in a system of systems is a daunting task. Emerging approaches like grid computing, where a central core or bus computational structure controls distributed, dissimilar simulations and modeling programs, appears to be a promising area for system of systems approaches. Modeling a large number of diverse systems capable of independent operation may see benefits from recent work in agent-based modeling. Some applications of agent-based modeling have included tens of thousands of independent agents and have also incorporated human behavior simulation as part of the modeling strategies. Concepts from collective intelligence may provide similar benefits for modeling very large systems of systems. A further challenge is how to use these modeling strategies in conjunction with optimal design and optimal control methods.

## **CURRENT STATUS AND NEAR-TERM PLANS**

Like all Signature Areas within the Schools of Engineering at Purdue, System of Systems is at first a research initiative. Currently, the System of Systems Signature Area is searching for new faculty members who are interested in collaborating with current Purdue Engineering faculty members on system of systems relevant research. To emphasize the multidisciplinary nature of the field, senior faculty members joining Purdue University through the system of systems area will have a joint appointment in two (or more) engineering schools; for instance, a full professor may receive a joint appointment in the School of Aeronautics and Astronautics and in the School of Industrial Engineering. Junior faculty members will join one of the established schools as a home department, with a courtesy appointment in another school.

Each signature area has an associated search committee of professors from across the Schools of Engineering to facilitate hiring new faculty members, and from the interactions among committee members, new collaborations are beginning. System of Systems committee members now serve on thesis advisory committees of students in other engineering departments. A recent Science and Technology Center proposal to the National Science Foundation was prepared that combines system of systems with prognosis; many of the Purdue participants in this effort participate in the System of Systems and Intelligent Infrastructure Systems Signature Areas.

Research in system of systems should lead promptly and directly into education. There will be high demand for students who have even primitive knowledge in this emerging area, and Purdue plans to be a preferred supplier of graduates with this knowledge. Because of the high relevance to many major engineering companies, the system-of-systems cluster area will provide several opportunities for engagement of Purdue University faculty and students with engineers from these companies.

The signature areas are currently research initiatives, so students enroll in one of the established schools of engineering (e.g. Aeronautics and Astronautics, Civil Engineering, etc.) and earn a degree from that school. The students will work with an advisor in the home school, but will likely have committee members from across the Schools of Engineering, or even across Purdue University as appropriate, who are interested in and have expertise in system of systems topics. As new faculty members are hired, a “critical mass” will be attained that allows for the introduction of new courses in system of systems topics, both from faculty joining Purdue and from current faculty members who did not previously have the impetus to develop such courses. As the multidisciplinary learning and discovery work in system of systems develops, an academic concentration, graduate certificate, or possibly degrees in system of systems engineering may develop.

## **SOME EXAMPLE PROBLEMS**

In an effort to begin a dialog with others about system of systems efforts and to investigate some of the challenges posed by system of systems design problems, the author of this paper has proposed a set of three very simple problems that contain some of the features of systems of systems. These example problems by no means represent the range of system of systems activities planned at Purdue; rather they are simply a starting point for one participant’s efforts. These are motivated by the author’s experience working in aerospace system design in industry and teaching aerospace systems design to university students.

Based upon the author’s interaction with industry colleagues, the approaches currently applied for system of system design problems are often ad-hoc; one colleague refers to this as “design by heroics”. In this “design by

heroics”, one or two engineers generate an idea about the system of systems, and a larger group of engineers rallies around this concept and works to make it perform the desired mission(s). However, this approach is not always rigorous and the innovation needed to begin the process cannot always be scheduled. There would be significant advantage if a formalized process could address system of systems design problems, so that designers would have an assist in developing the system of systems concept. Additional help for the designers would be provided if the approach could allow for new systems to be designed with the goals of improving the system of systems’ global performance; this is different from the traditional practice of working to improve the individual system’s performance.

To begin investigating potential system of system design approaches, three simple problems are posed. These example problems all have some characteristics of assignment or resource allocation problems. However, these are not classical assignment problems that can be solved via traditional linear or integer programming methods. To incorporate the design of new systems in the system of systems context, these problems become resource allocation problems in which the resources have variable attributes, i.e. they are variables themselves. Therefore, the resulting problems become mixed integer non-linear problems. Although non-linear programming is well established and some approaches for MINLP exist, the structure of variable allocation problems suggests that specific, tailored techniques could solve these problems more efficiently than general-purpose optimization techniques. One of the test problems includes uncertainty, which leads to probabilistic objective and constraint functions. At present, none of the problems have dynamic features, although this is an important consideration.

**EXTENDED AIRLINE ALLOCATION PROBLEM**

Today, airlines assign aircraft to various routes in their system to meet expected passenger demand, with the intent of maximizing the profit for the airline. For this example, the airline serves as the system of systems; there are available aircraft capable of independent operation that, when working in coordination, will fulfill passenger demand at the lowest cost for the airline. If the airline is choosing aircraft from its present fleet to fill the routes, the problem is an optimization problem whose design variables include the number of flights and the type of aircraft used for each flight. Posed this way, the problem is a traditional assignment or resource allocation problem. This is often addressed using integer programming. In fact, one of the first presentations of an airline allocation problem can be found in Dantzig’s textbook from 1963.<sup>15</sup>

By including new, yet-to-be-designed aircraft as an option for this airline, a problem emerges in the context of system of systems (Figure 3). Aircraft design variables such as wing loading, aspect ratio, thrust-to-weight ratio, and payload capacity, are continuous and describe the geometry of a new aircraft. From these variables, the new aircraft’s size, weight and performance – which determine the cost coefficient of the new resource – can be estimated. Incorporating the aircraft design variables, the resulting problem becomes a resource allocation problem in which at least one of the resources has variable properties; this is a mixed-integer non-linear problem.



**Figure 3 United Airlines’ fleet, with a yet-to-be-designed aircraft.**

The solution to this extended problem would indicate both features of and the number of new aircraft that would best fit the airline. Solving the problem is, however, non-trivial. Some approaches exist for mixed integer non-linear programming, but these are often computationally expensive and are generally without proof of optimality. To determine appropriate techniques to solve this type of problem, concepts from resource allocation must be combined with concepts from aircraft design.

## EXTENDED CARGO DELIVERY PROBLEM

The second example problem has features of a traditional transportation or network flow problem. To begin, consider a distribution network connecting several cities, like that shown in Figure 4. Items are produced in certain cities and are in demand in other cities. There are costs associated with transporting goods from one city to another. The problem of matching the supply to demand at minimum cost fits the traditional definition of a transportation or minimum cost flow problem. If several items are produced, or if the items produced in one city are produced to satisfy the demand of another specific city, the problem becomes a multi-commodity network flow problem.

Package delivery companies closely fit this description: certain packages originate at a specific city and must arrive at another city, according to the wishes of the delivery service customer. A cost is associated with delivery of a package between two cities, and the goal of the problem is to minimize the total transportation cost. Generally, packages need to be delivered within a certain time period, which varies depending on their priority (high-priority or low-priority cargo). While this problem loses features of a simple transportation problem, it is still a linear programming problem for which solution approaches exist. By allowing the cargo to travel via one of several different aircraft or ground vehicles from the current fleet of the package delivery service, the cost and time of transit between destinations become variables in the problem. Now, the problem is a combination of a multi-commodity transportation problem and an assignment problem, which is more complex and non-linear than the simple multi-commodity problem.

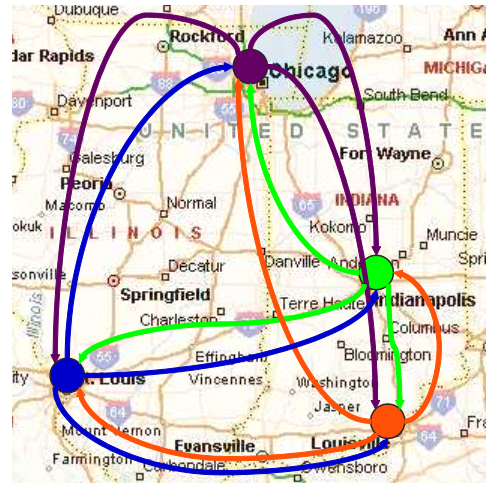


Figure 4 A notional four-city delivery network.

Like the previously described airline allocation problem, the problem becomes a system of systems problem by including features of yet-to-be-designed transportation systems (the aircraft or truck). The routes between cities could be served by ground or by air transportation. Potentially, new ground vehicles or new aircraft could be introduced to the delivery service's fleet to cover the routes. An approach to solve this type of problem can help a package delivery service, an airframe manufacturer, and / or a truck manufacturer decide if new transportation vehicles are needed to provide service. Further, the solution will indicate the features of the new vehicle system. A formalized approach, or even general guidelines, to formulate and solve this type of problem appears to be lacking; however, such an approach would be of great assistance in the decision-making process for all entities in the cargo delivery system of systems. This problem shares features with the military problem of delivering weapons to various targets, in which there are several means of delivery, several types of weapons, and targets of relative priority.

## PROBABILISTIC SEARCH AND RESCUE ASSIGNMENT PROBLEM

The third problem introduces uncertainty to the allocation of variable resources problem. The Coast Guard's search and rescue mission, included in the Integrated Deepwater System program, inspired this problem. Assume that a person is lost at sea; the lost person's precise location is not known, but general bounds on the search area are known. To find this lost person, the search and rescue team can deploy one or more aircraft; each type of aircraft has an associated capability (sensor footprint and flight speed) and cost of operation. If the lost person's location were fixed within the search area, then the aircraft(s) will eventually find its target given an appropriate coverage search, even if the location of the person was uncertain. The objective could be to minimize the time required for the search with appropriate constraints on the cost of the search. This problem has many features of the allocation problem discussed above. It is converted to the context of system of systems by treating the features of a new aircraft as variables in this problem.

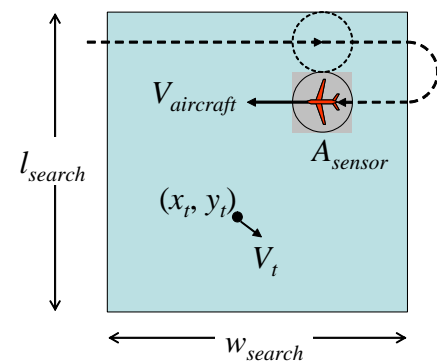


Figure 5 Search and rescue allocation problem concept

Uncertainty will be introduced into this problem by allowing the lost person to have a velocity, as if the person were adrift on ocean currents or blown by wind. Figure 5 displays this problem concept. With this uncertainty, it is possible that the aircraft(s) may not find the target within the search space. Now, the objective would be to maximize the probability of locating the lost person. With the inclusion of uncertainty, the standard linear programming approaches are no longer appropriate. Additional, relevant uncertainties include the sensor effectiveness (for example, visual or radar attenuation due to weather) and the direction and magnitude of the lost person's velocity. Addressing all of these in a problem formulation and solution provides a challenge. This third problem also has a military analog of locating and engaging a mobile target.

### **CONCLUDING REMARKS**

The System of Systems Signature Area within Purdue University's Schools of Engineering is an exciting opportunity for multidisciplinary, collaborative research into engineering systems. The idea of system of systems originated from faculty awareness that the acquisition approach for new engineering systems is evolving from customers asking for a specific system to meet a set of requirements to customers asking for broad capability with very few restrictions on the type of solution. With this evolution, the idea of combining multiple, but independent, systems into a system of systems becomes crucial to providing the requested capabilities. Purdue Engineering faculty members also recognized the opportunity for academic endeavors into the problem formulation and solution strategies for designing and controlling these systems of systems.

The Schools of Engineering have made a commitment to the System of Systems Signature Area by providing new faculty positions above the current number of core faculty positions within Engineering; a search for these new faculty members is currently underway. The committee in place to help coordinate the System of Systems search has already begun new cross-disciplinary collaborations. New faculty will also join these collaborations and lead new efforts. This will bring a strong emphasis for learning and discovery about interdisciplinary engineering systems to Purdue. Purdue Engineering students graduating with a subset of the skills needed for system of systems work will be in high demand by government agencies, aerospace and other similarly oriented companies.

While the efforts in system of systems at Purdue are still in their infancy, there are several endeavors underway, including research to address the three example problems listed above. Purdue University's Schools of Engineering has several faculty members who are world-class leaders in areas relevant to system of systems, and the Schools look to add to this through the new signature area. There is also strong support from industry partners. Although specific problems will always require domain-specific expertise, the premise of the System of Systems Signature Area is that common characteristics of all of these large, complex problems can lead to general tools and methodologies that support all of them. Hence, the time seems ripe for academic endeavors and leadership in this area.

### **ACKNOWLEDGEMENTS**

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This paper is intended to accurately introduce the System of Systems Signature Area; however, it is the work of the author and may not necessarily reflect official policy of the Purdue University Schools of Engineering.

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