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Developing Sustainable Space Exploration via a System-of-Systems Approach

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The purpose of this paper is to introduce a system-of-systems methodology and framework and its application for analyzing and designing space exploration architectures. Such architectures are comprised of various inter-connected, evolving networks, themselves comprised of heterogeneous systems. By employing the proposed framework, we aspire to discover the emerging patterns present across successful and unsuccessful architectures, thus, enabling informed decision-support for architecting. A system-of-systems model is being constructed to represent numerous possible objectives in the national space program. As part of this model, the analyses and results of various scenarios for Solar System Mobility Network are presented as a simple and partial implementation of the proposed methodology to explore possible architectures for multi-generational space endeavors. Results from these analyses indicate that there are observable performance merits in exploring the expansion of the physical infrastructure across the solar system using network theory metrics. More broadly, the application of network theory methods enables a better understanding of the structure and evolution of possible network topologies for system-of-systems problem like the national space program.

I. Introduction

Effective problem solving for decision-support in the national space program (NSP), beyond a systems engineering context, has remained elusive. While the percentage of individual US government space missions that accomplish their primary mission objectives has increased over the lifetime of the NSP, the overall space program stability and cost effectiveness are yet to be achieved. A developing system-of-systems engineering (SoSE) framework[1] has the potential to enable aerospace decision-makers to efficiently discern whether related infrastructure, policy and technology considerations together are effective, ineffective or indifferent over time for addressing the NSP's evolving requirements.[2] Consequently, the intent of developing a SoSE framework is to design and implement a long-term space program architecture that is both versatile and sustainable.[3] The unique qualities of the framework proposed in this paper are that a) it not only considers the evolving scientific/technical needs community but also accounts for political, social, economic, technological and operational factors, and b) quantitative methods for analysis and design of evolving networks of heterogeneous systems are developed. The primary objective of this method is to discover any emergent patterns that distinguish between successful or unsuccessful architectures. More generally, the research contributes towards an intellectual foundation for the study of system-of-systems (SoS) problems that enables stakeholders to successfully understand, abstract, model, analyze and implement complex, multi-generation space endeavors.

II. Background

A. Need for Improved Decision-Making

NASA's architecting methodology for the next decade is outlined in the Exploration Systems Architecture Study (ESAS).[4] Specifically, ESAS summarizes the technical and business processes by which NASA intends to carry out the transition from the Space Transportation System era into the Constellation era. The current technical methodology for architecting space missions consists of transporting complex engineered vehicles from Earth to perform specific exploration and science objectives throughout the solar system. This method is limited to the success of each individual mission and, thus, does not necessarily ensure overall program continuity and success. Therefore, despite the technical complexity of past and present missions, these missions boast relatively short life

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spans, and are incapable of responding to disruptions and discoveries efficiently. This is mainly a result of a lack of robust support infrastructure to perform maintenance, upgrades and re-supply of critical components and expendables after deployment.

While the individual space mission success rate has improved over the lifetime of the United States space program,[5] a lack of effective alignment of organizational and information infrastructure with physical infrastructure has resulted in recurring budget overruns, program delays and unachieved capabilities. Several recent reports, Ref.'s 6, 7, 8 and 9, concur that "NASA is being asked to accomplish too much with too little,"[9] under the current strategy for implementation of the *2004 Vision for Space Exploration*.[10] Successful implementation of the Vision will become even more difficult to accomplish as space activities progress from primarily a government based program to a mixture of multi-national and commercial ventures that may involve exploration, exploitation, planetary defense, tourism and colonization across the entire solar system. Since there is no shortage of demand for space missions from the scientific community or aerospace industry contractors to tackle the technical challenges, what is absent is a larger holistic approach, such as the proposed SoSE framework. This framework strives to maximize the benefit over several generations while minimizing the cost, risk and time required to achieve these benefits amidst continuous shifts in the NSP's drivers and disruptors. This framework is not meant to predict the future, rather it is meant to facilitate the exploration of various plausible scenarios for emergent patterns which can provide beneficial insights for making well-informed decisions. Consequently, this provides a means to bridge existing "information-gaps" between the aerospace analysts/engineers and decision-makers, in turn, merging multiple perspectives for collaborative design and operations.

B. System-of-Systems Traits and Behaviors

The history behind the term system-of-systems and a proper definition for it is the source of great debate in recent literature.[11,12,13,14] Our view is that a strict definition is not nearly as crucial as the traits of a class of problems that it represents. Following this perspective, eight traits are proposed to characterize SoS problems. The first five "principal characteristics" are attributed to Mark Maier,[15] while the last three were recently presented by DeLaurentis[1] as implications of Maier's traits on mathematical modeling of SoS problems. The description of these traits, in the context of the national space program, is presented in Table 1.

Table 1. System-of-systems traits and behaviors mapped to the national space program.

Traits	Description
Operational Independence	Each constituent system in the NSP can operate and serve a unique purpose, independently of other constituent systems.
Managerial Independence	Constituent systems of the national space program are independently acquired, integrated and operated (i.e., managed) by their respective owners/operators.
Geographical Distribution	Space program activities are distributed across the nation, the globe and the solar system; the primary link between these activities is exchange and pursuit of information, rather than mass or energy; the transportation of mass and exchange of energy required in operating space assets adds the high-level of technological complexity in this problem.
Evolutionary Development	NSP problem changes persistently, and is never fully formed or understood as new systems and capabilities are constantly added, removed and/or modified; measures of effectiveness for space program activities are evolutionary because of the dynamic of resources, stakeholder values, drivers, and disruptors.
Emergent Behavior	Emergence of patterns arises from the interaction of non-linear and dynamic constituent systems in the national space program; emergence cannot be observed completely by scrutinizing the constituents in isolation.
Heterogeneity	Constituent systems in the NSP vary in their fundamental nature per their own unique characteristics, dynamics and operational time-scales.
Trans-domain	The diversity of stakeholder values and resulting engineered systems in the NSP indicate the numerous domains that must be addressed: engineering $\cup$ economics $\cup$ policy $\cup$ operations $\cup$ culture, etc.
Networks	Constituent systems are found to be present in various, inter-linked, evolving networks in the physical, information and organizational topologies that define connectivity among the constituent systems.

The primary consequences of these eight traits are to serve in identifying and differentiating SoS problems, and to affect the means by which these problems are modeled and analyzed. Specifically, the characterization of a SoS problem is based on the notion that the "whole" is greater than the sum of the comprising pieces. Thus, effective architecting for a SoS problem seeks to understand emergent behaviors over the evolutionary development of this problem. In this context, emergence is the discovery of behaviors at the upper levels of hierarchy of SoS problems which arise from interactions between lower-level systems. Emergence is sought for both positive and negative results to enable decision-makers to implement robust architectures through uncovered opportunities, “jackpots,” while also maximizing the systems vulnerabilities, the “landmines.” One of the major obstacles associated with emergence in any SoS problem is system dynamics. Since the connectivity between the drivers, stakeholders, resources and disruptors change constantly, the design for architectures must be adaptable to the evolution of the SoS problem. This is in contrast to the present wide-spread practices in the national space program which emphasize short-term point predictions and optimization of the individual systems involved; this has resulted in a myopic sub-optimal implementation of the national space exploration program.[16]

C. Versatility and Sustainability as Objectives

Each SoS problem contains unique objectives based on the involved stakeholders and their respective values. While the specific scientific, commercial and military goals for the development of space perpetually evolve, two essential architectural objectives that are needed under any scenario are versatility and sustainability.[3]

Versatility is considered robustness in the presence of uncertain requirements. Presently, systems engineering is not set-up to achieve versatility due to the risks and costs involved in engineering adaptive systems. Future space architectures must posses versatility in order for the space missions to be “capable of long-term survival in uncertain, remote environments, and [to] converge on accomplishing the most relevant and useful mission, informed by intermediate results and experience in the operation environment.”[3] Therefore, it is critical that these missions possess an elevated commonality to share technical and procedural solutions across domains and temporal phases involved in the NSP.

Sustainable architectures accomplish their missions, remain relevant for long durations and show adequate investment planning; they must include “system effectiveness, reliability, safety, and affordability” as new technologies and discoveries emerge.[3] Therefore, the next class of missions should not only accomplish their intended objectives but must also be able to evolve along with their missions.[3] Limited resources and individual mission objectives frequently conflict with accomplishing “feed-forward” multi-generation space systems; thus, the problem remains: How do we optimize the use of available resources and minimize the impeding impact of changing space program objectives, when new discoveries are made and new disruptors come into play?

III. Proposed System-of-Systems Engineering Framework

A developing, three-phase system-of-systems engineering framework (illustrated in Table 2) is proposed for the investigation of the external factors and internal structure of an architecture as they evolve over time in an uncertain requirement space. In this framework, the *Definition* phase is used to understand and structure the NSP problem, the *Abstraction* phase is used to model the key descriptors, and the *Implementation* phase is used to model, analyze and explore solutions to the problem.

Table 2. SoSE framework for approaching system-of-systems problems.

Definition Phase		Abstraction Phase		Implementation Phase
Operational Contexts	⇄	Stakeholders	⇄	Objects
Status Quo		Drivers		Classes
Barriers		Resources		Methods
Scope Categories		Disruptors		Data
Levels		Networks		Measurers

A. System-of-Systems Engineering versus Existing Methodology

Before the details of the proposed SoSE framework are presented, an understanding of the common related terminology should be addressed. First, *systems engineering* provides the methodology for individual mission development which enables the ability to cope with some of the trans-domain characteristics inherent in SoS problems, but on its own is not sufficient to completely represent SoS problems. Second, *architecting* provides the methodology to identify a fundamental and unifying framework, and underlying essential structure to produce an arrangement of function and feature/form that maximizes the objectives of program development.[17] Thus, the proposed system-of-systems lexicon and SoSE methodology enable the quantitative analyses of architecting for SoS problems. They are intended to enable the exploration of the requirement space of SoS problems and provide the bridge between architecting and systems engineering processes. Distinctively, SoSE methodology strives to shift the performance curves to be more malleable in the temporal domain of the entire national space program.

B. Definition Phase

The development of effective analysis and solution methods can only transpire upon a widespread understanding of the problem among, and effective communication across, the majority of stakeholders involved. Foremost, the *Definition* phase consists of conceptualizing the operational context of the problem and characterizing the SoS problem as it currently exists (i.e., the status quo). This phase consists of establishing scope categories and levels, forces at play, and known barriers to preferred behavior. During the application of the SoSE framework, the *Definition* phase is revisited and remolded to pose the correct problem; the key questions may evolve as the observed emergent patterns develop. Hence, emergent phenomena that may occur by applying a SoSE framework to the NSP is a potential reevaluation of fundamental principles and assumptions, along with recommendations for long-term transformations in operations, economics, policy and resources.

1. Status Quo and Barriers of the Legacy National Space Program

There are numerous misconceptions about the NSP's effects on society, nature of NASA's projects and goals, cost to the taxpayers, and even the history of the program. Although, the NSP shapes our every-day life (e.g., medicine, economic stability, transportation, computing, communication, weather forecasting), most Americans are unaware of the program "spin-offs" and thus, view NASA's existence as a commodity rather than a necessity. If progress is to be made, one of the recommendations may involve a better public education about the importance and benefits of space exploration and exploitation endeavors.

Contrary to popular belief, at the height of the Space Race in the Cold War, the space program was not backed by high public support. Rather it was rather viewed by United States policy makers as a matter of "national priority."[18] Specifically, it was driven by a political crisis of the country's growing concern of the spread of communism and the Soviet success in being first to reach space.[18] Additionally, during the Apollo era of the space program, up to 13% of the annual US budget was allocated for space related activities (Figure 1), there were few clear goals, set timelines and committed budgets presented by Congress and the Presidents to the American public.[5] Furthermore, while the memory of President John F. Kennedy's vision for winning the race to the moon installed a matter of national importance to fulfill that goal; however, it did not provide a unified long-term vision for post Apollo program activities.[18] Hence, post the initial Space Race era of 1950's and 60's, the why or the how was not clear for continuing and spreading human presence in space. Consequently, since the Apollo program was not achieved in a "normal" political environment;[18] architecting for future space exploration missions cannot be based on the same assumptions and methods as before.

In the past two decades, Gallup polls repeatedly show that while a majority of the public have "a favorable impression" of the national space program and its benefits, it is still viewed as exploration for science, and thus, it comes second to priorities such as national defense, education, unemployment, healthcare and social security.[18] Additionally, from a recent study, most Americans believe that the US government spends about 20% of its annual budget on NASA, while in reality approximately half a percent (Figure 1) is allocated to NASA and only a portion of that is directed toward the NASA Space Budget.[5,18] Accordingly, there are simply too many projects that are competing for a smaller pot of national funds because there does not exist the capability to successfully implement one grand common Vision for this era that is also able to sustain the numerous objectives residing in today's scientific community. It is not necessarily that the US aerospace community and NASA are unable to accomplish technological innovations as was done in the Apollo era, but rather, it is that there is not a overarching structure in place that provides long-term stability in the NSP that is also supported by multiple administrations of governing bodies, scientific community and the public.

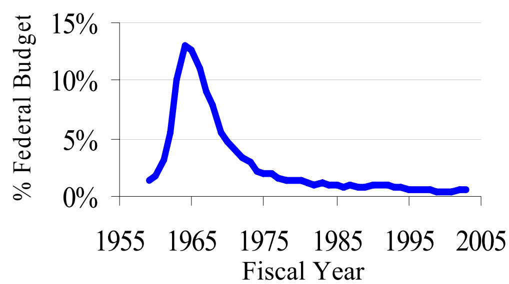
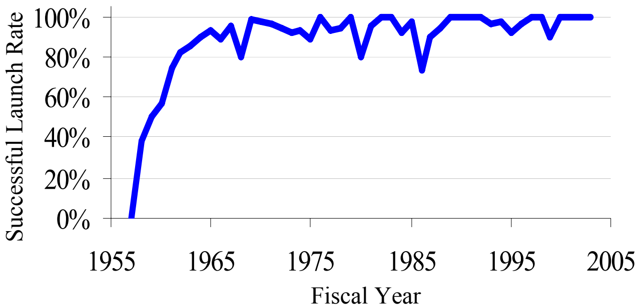


Figure 1. Annual percentage of federal budget spent on the space program.

There has been a clear disconnect between individual mission success and the overall program success in the NSP. Figure 2 demonstrates the increasing success, over time, of the US government to launch its payloads into low earth orbit (LEO). Contrary to the increased technical robustness observed in Figure 2, it has taken more of budgeted dollars (i.e., the increasing trend observed in Figure 3) per achieved successful launch of all US government robotic and human missions. Consequently, the NSP's failure to achieve overall lower cost for each mission success demonstrates the decreased capabilities and increased cost observed in large-scale NASA space projects like the Space Transportation System and the International Space Station. The primary cause for this behavior is the lack of efficiency and alignment of NASA's organizational and information network infrastructure (i.e., organizational culture and flow of information) with its physical (i.e., technical) network infrastructure.[19]



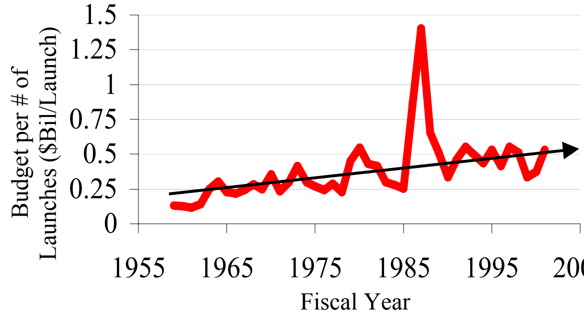


Figure 2. Mission performance: annual percentage of successful launches.

Figure 3. Program performance: annual US Space Budget per number of successful launches.

2. Unifying Lexicon for Problem Representation

Some aspects of the space program's operations relate to operational connectivity (e.g., network of communication systems), while others involve the economic utility of use (e.g., return on investment). Such constructs are commonly addressed independently, because a holistic analysis across hierarchical levels is perceived as too difficult to represent and analyze. Previously proposed system-of-systems lexicon addresses this by first identifying the trans-domain categories involved in this problem.[2] The benefit of employing the proposed lexicon is that it makes it easier for cross-disciplinary stakeholders to interact and share insights when all the stakeholders employ a standardized vocabulary. There is also an improved correlation between the analyses performed by the engineers/analysts with the resulting policy decisions made by the decision-makers. Table 3 provides the categories of the proposed lexicon.

Table 3. System-of-system unifying lexicon categories.[2]

Categories	Descriptions
Resources	The physical entities that give physical manifestation to the system-of-systems
Operations	The application of policies/procedures to direct the activity of physical entities
Economics	The non-physical, sentient systems that give a "living system" character to the operation of the physical entities in a market economy
Policies	The external forcing functions that impact the physical and non-physical entities

Within these categories are multiple levels of heterogeneous systems in networks, as illustrated in Figure 4. Certain situations are best represented in a network within a category while others must span categories. This latter type is often neglected because it is again believed to be too difficult to conceptualize. In order to mitigate this, the use of Greek letters to establish a multi-level hierarchy is recommended. Here, alpha (α) elements are the base level entities for which further decomposition does not take place, beta (β) elements are collections of α-level systems organized in a network, gamma (γ) elements are collections of β-level systems organized in a network, followed by the delta (δ) level and so on.[2]

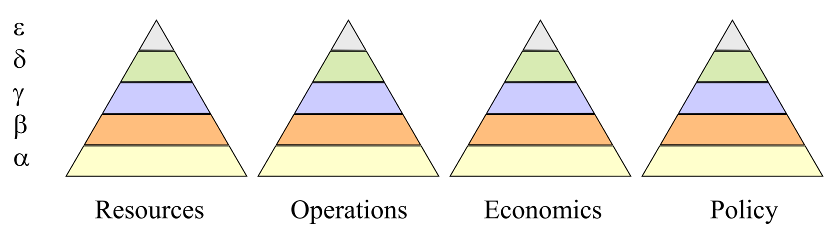


Figure 4. Unfolded pyramid of unifying SoS lexicon: scope categories and hierarchy of levels.

The levels and categories of the lexicon are intended to classify the constructs involved in order to better understand the multiple networks involved in SoS problems. Examples of α-elements proposed for the national space program would include spacecraft, launch vehicles, mission control centers, mission operational procedures and mission budgets. It is cautioned to initially avoid expanding these α-elements into networks of sub-elements (e.g., spacecraft subsystems) as to avoid limiting the performance of the entire system-of-systems by existing biases in the engineering of the α-level systems . This stems from the philosophy that the optimization of the entire SoS problem does not imply optimization of each constituent system. It is possible that performance penalties or compromises at the design of the α and β-level systems may actually increase the performance at the γ, δ, and ε-levels of the NSP.

Table 4 provides a basic mapping of current space activities into the SoS lexicon; the abstraction of the constituent entities in each level and category will change over time.

Table 4. Space program activities abstracted into the lexicon pyramid categories and levels.

Level	Resources	Operations	Economics	Policy
α	Vehicles, facilities, tools and infrastructure	Operations of a resource (mission control, project management, operator-user interaction)	Economics of building/operating/ buying/selling/leasing a single resource	Policies relating to single resource use (safety, cleanliness, launch/flight procedures)
β	Collection of resources for a common function (space centers, DSN, lunar human exploration)	Operating resource networks for common function (earth observation, planetary exploration, human space flight)	Economics of operating/buying/ selling /leasing resource networks	Policies relating to multiple resource use (space center, resource transportation management)
γ	Resources in a space program's sectors (commercial, government, military, private sectors)	Operating collection of resource networks (NASA centers, NSF activities)	Economics of a sector (exploration, defense, academic, commercial)	Policies relating to sectors using multiple vehicles. (research goals, safety, defense, commercial)
δ	Multiple, interwoven sectors (resources for a space system)	Operations of multiple business sectors (operators of total space exploration and exploitation program)	Economics of entire space program (national budget, commercial investment)	Policies relating national space program's activities (presidential Vision, FAA policies, space agency policy)
ε	Global space activities	Global operations in space	Global economics of space exploration	Policies relating to the global space activities (COSPAR)

Overall, the proposed lexicon framework is constructed with the hypothesis that preferred behavior of a system-of-systems is a function of structure and the organization at higher levels, in addition to the characteristics of the α-level entities. Implicit in this is a design perspective: to drive performance at higher level networks from the combination of their topologies and capabilities of the lower level systems that comprise them. Thus, the most consequential decisions arise at the upper levels of the proposed lexicon.[1]

C. Abstraction Phase

SoS concepts are neither technology nor network operational concepts, but rather a union of the two. These concepts, with the generic constituent systems, must exhibit scalable behavior in response to shifts in demand, goals, disruptors, and drivers. An *Abstraction* example for the NSP is where the Congress empowers NASA to employ aerospace contractors and research institutions to execute the national *Vision for Space Exploration* while addressing the nations' scientific, security, and economic interests.[6] Figure 5 provides an illustration of the four types of abstraction entities and their inter-connectivity in the *Abstraction* architecture field; the in-depth description of these entities was presented previously in Ref. 1; the summary of the description of these entities in the NSP context is provided in Table 5.

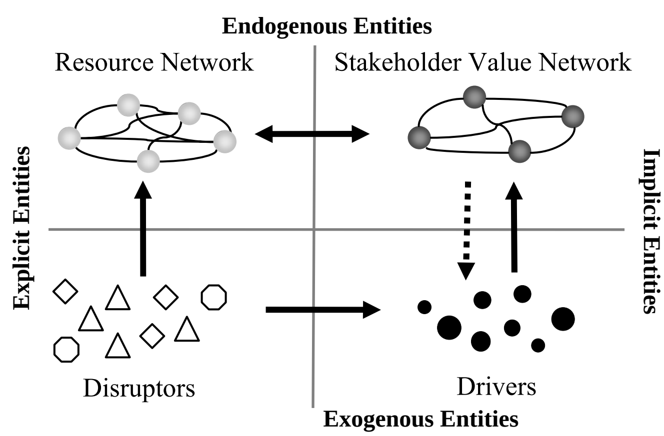


Figure 5. Space program abstraction architecture field.[20]

Table 5. Understanding the abstraction entities and their mapping to the national space program.

Entities	Descriptions	Abstraction Entities Mapped to NSP
Stakeholders	"players" of the SoS problems that populate the value network	policy-makers, NASA personnel, aerospace contractors, space research community, media and so on
Resources	physical entities in networks, that are used by the stakeholders	mixture of networks of human and robotic systems, centralized and distributed systems, and highly connected to seemingly unconnected systems
Drivers	circumstances that implicitly influence the stakeholder value network	demand for exploration, exploitation, colonization and planetary defense
Disruptors	circumstances that alter the resource network, and change the drivers which alter the value network	any unforeseen discoveries or events in the scientific, political, social, economic, technological and operational environments

D. Implementation Phase

Since accurate long-term performance prediction of any SoS problem is unrealistic, the proposed SoSE framework's *Implementation* phase carefully crafts the problem representation and abstraction to develop a SoS simulation that can uncover emergent patterns across multiple scenarios for the NSP. In other words, what combination of management, economic, technical and policy practices show robustness across a multitude of the scenarios being explored? The modeling within the simulation strives to employ quantitative and repeatable SoS formulations, tools and processes to accomplish this; it is also designed to "test-verify" policies and technologies for a multi-generation space program.

Using Agent-based Modeling (ABM) as a foundation, a national space program "virtual world" can be created, where we can test for the sensitivity of different architectures against emergence of values, technologies or discoveries and their effect on metrics such as risk, cost, schedule, social and environmental impacts. Versatility and sustainability can be sought under a collection of plausible operational and program scenarios; this is desired to enable the identification of disruptions that may be shown to severely impair an architecture (e.g., loss of the space shuttles as delivery vehicles for crew and cargo to LEO). Figure 6 illustrates the overarching foundation for a SoS simulation that is being constructed to evaluate various space program architectures.

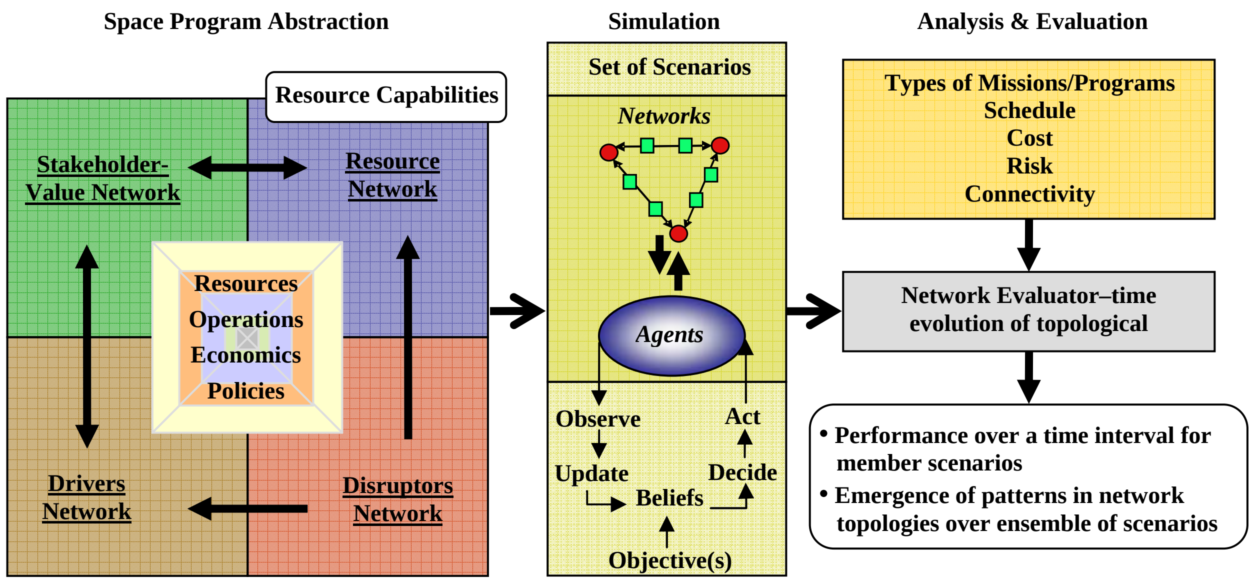


Figure 6. Hybrid modeling framework for design in a SoS context.

In this conceptual framework for abstracting, modeling and analyzing solutions for the NSP:

1. The abstraction segment represents the available infrastructure and the desired capabilities,
2. The simulation is driven by set of scenarios and the stakeholder agent rule set selected by the modeler,
3. The analysis and evolution of the resulting network topologies are evaluated for performance and emergence of patterns.

The evolution of the network topology representing the SoS's connectivity is determined by the actions of agents and not by pre-specified, simplistic growth models. Thus, rule models that represent real behaviors of stakeholders/agents in the problem are added to the arsenal of possible design and constraint parameters. Each agent pursues its objective(s) by using its beliefs to guide its decisions and actions. Subsequently, as the simulation progresses, the agent observes changes in the environment and responds accordingly. Finally, network evaluators are employed to compare the evolved networks to topologies that exhibit preferred behaviors.

Accordingly, as this model is implemented, network theory analysis methods can be used to measure performance of the various topologies. Also, while this model is being shaped by the existing national program as the baseline, it can be used to alter specific desired parameters to observe their overall impact on the architecture performance. For example, one can explore changes in export/import policies for space technology, address the projected shortfall in science and engineering workforce, evaluate the development of private LEO commercial capabilities, and compare the series of proposed space systems, communication scenarios, operations, multi-national cooperation, business practices, etc.[21]

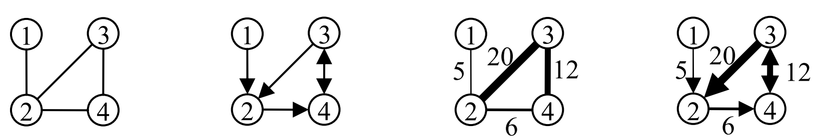
Verification and validation of any constructed model is desired to ensure that the simulation is an effective representation of the real world and to also understand the model's limitations. Verification can be performed by comparing the expected behaviors of the paper model (i.e., the conceptual representation of the expected model structure, behavior and outputs) with the performance of the actual simulation. Validation of analysis and simulation can be performed via historically exercised architectures in the NSP (e.g., the Apollo program).

1. Employing Network Science

Recent developments in Network Science (or network theory) offer a mathematical means to observe the performance of network topologies, and to also explore mechanisms of network evolution.[22] In this process, networks are defined by the connectivity (links) between a set of chosen entities (nodes).[23] For the national space program, we are not only interested in the study the physical network topologies (e.g., physical infrastructure and vehicle transportation) but also the temporal network topologies (e.g., information flow through the organizational structure). Entities in various context (e.g., physical vs. temporal) and varying types of connectivity (Table 6) can define very different network topologies. Examples of these are shown in Figure 7. While these have the same node and link placement, the varying link types form very different topologies; therefore, it can be shown through network analysis methods that the sample networks presented in Figure 7 will behave and perform very differently.

Table 6. Types of possible network links.

Type of link	Description	Examples in NSP
Undirected	Links form a unilateral connection between nodes	mutual relation between team members
Directed	Links are directional between nodes	planetary trajectories, information flow
Un-weighted	All links assumed to have the same cost value	existence of a communication link
Weighted	Each link is assigned a different cost value	difference in monetary cost, distance, time between nodes, energy between orbits



(a) un-directed, un-weighted **(b) directed, un-weighted** **(c) un-directed, weighted** **(d) directed, weighted**

Figure 7. Example of possible network types.

While current national space program topologies exist for the physical infrastructure, the information flow, and the business enterprises that operate them on Earth, future topologies may include much more distributed adaptive infrastructure facilities and human presence in multiple planetary systems with completely different business and information flow networks than what we have today. Thus, understanding the effect of network evolution is as important as understanding the effects of their structure; it will take progressive improvements to the structure and integration of these networks to enable a sustainable and versatile NSP.

2. Agent-Based Modeling

While network analysis methods determine network performance, it is also equally important to understand how the network is shaped by its constituents. Agent-Based Modeling is being employed to represent the collective behavior of autonomous, interacting and decision-making agents. Benefits of ABM include: the combination of actual resource models with simple stakeholder rules for the observation of emergent behaviors. Time-dependent activities can be then identified by examining when certain resources or strategies are adopted unintentionally, and disruptions can be interjected to test for versatility and sustainability in the respective architectures.[24]

IV. Application: Simulation of Solar System Mobility Network

A. Introduction

As part of larger exploration of future space program activities, a methodology was created to explore scenarios for networks of infrastructure systems strategically placed across the solar system. In contrast to the historical practice of a few large, single planet focused missions, the objective of constructing such networks is to maximize the future ability to explore, colonize and exploit the solar system over an extended period of time. The concept is termed a Solar System Mobility Network (SSMN) and is notionally depicted in Figure 8. Consideration of distributed network operations for future space exploration is certainly not new; one example of an existing study that is investigating the interplanetary supply chain network for the Earth-Moon-Mars network is the *Interplanetary Supply Chain Management and Logistics Architecture* project at MIT.[25,26]

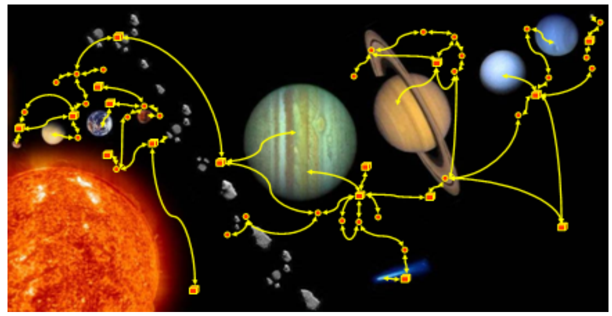


Figure 8. Solar System Mobility Network Example.

The SSMN consists of transport missions being transferred between planetary systems. The changes in drivers for these missions combine with the changes of the physical topology of the solar system to produce a mobility network. Particularly, the use of network analysis metrics explores the cost of velocity change (Δv in km/s) and time-of-flight (ToF in years) of relocating plausible future missions and resources from and to various locations across the solar system. This SSMN model consists of only nine planetary systems (nodes) and is limited to a 50 year timeframe. This network analysis of the SSMN model is intended to enable the basic study of α and β-level operations of resources driven by varying γ and δ-level policy and economic conditions.

The SSMN is the transition from abstraction to implementation on which the larger SoS simulation operates. Figure 9 provides a flowchart of how the SSMN and the evaluation of the network topology structure and evolution integrate into a larger SoS simulation being constructed for the in-depth analyses identified in Figure 6.

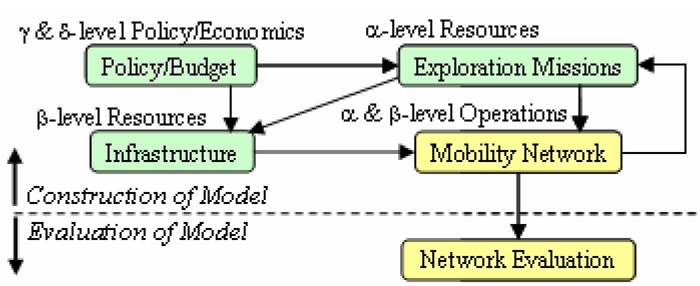


Figure 9. Flowchart of SSMN model and evaluation as part of a larger system-of-systems model of NSP.

B. Solar System Mobility Network

At the center of this study resides the mobility network; the fundamental structure upon which this simulation is built. The mobility network is defined as a network of all available trajectories from which network desire and demand (D&D) may be satisfied. This network is comprised of planetary systems (nodes) that are connected by routes (links) such that planetary resources may be reallocated and mission desire can be satisfied. While this study only examined a physical network connecting different planetary systems, it can be expanded to include additional networks within each planetary system or other desired destinations (e.g., comets and asteroids); in addition, it is desired to integrate the physical, organization and information networks involved in this problem. For the SSMN, links are created from planetary systems with excess resources to the planetary systems with a need for resources. Each link has a weight of $\Delta v \times \text{ToF}$ corresponding to the least costly available trajectory and is directed along the inter-planetary flight path. This performance metric was chosen arbitrarily to provide comparable importance of Δv and ToF. Hence, this weighted, directed network may be used in assessing which planet can provide the appropriate resource with the least amount of "cost" (i.e., weight).

1. *Network Theory Metrics for SSMN*

A set of network theory metrics and their application to the SSMN are introduced in Table 7 to explicate the structure and evolution of the selected network topology.

Table 7. Network metrics applied to the investigation of SSMN as a directed, un-weighted network.

Network Metric	Measures
total-degree	sum of in-bound and out-bound links for a given node
average degree	average degree value of a selected number or all nodes in a network
degree distribution	probability that a selected node has a certain number of links
clustering coefficient	number of triangles centered on a node per number of triples centered on it
average clustering coefficient	the mean of clustering coefficients for all nodes in a network
shortest path	least costly (in number of links) directed path between two nodes
average shortest path	mean of all shortest paths in a network
network diameter	single largest value of the shortest paths in a network
betweeness centrality	importance of a node with respect to the number of total shortest paths that must pass through it in the entire network
assortativity	average degree of the nearest neighbors of a specific node

Some possible impacts of these metrics on network topologies are as follows:

- The degree of a node determines the connectivity of that node to the rest of the network. Nodes with relatively high degree are referred to as "hubs" and are more important to the overall network connectivity.
- The average clustering coefficient and average shortest path are employed to determine whether a network exhibits the "small world" effect: whether a majority of nodes in a network can be reached within a relatively short number of links. Networks with high average clustering coefficient and low average shortest path are considered well connected and exhibit the small world effect.[23]
- The degree distribution also helps to distinguish small-world versus random networks. The overall structure of a given network enables the study of the expected performance with respect to a disruption, as well as, quantifies the difficulty of moving from one node to another.

Armed with these tools for network analysis, various classes of experimental studies can be examined to determine the overall robustness as part of versatility, reachability as part of sustainability, and phase transitions as part of understanding network evolution of the SSMN within the larger NSP problem.

2. Trajectory Determination

The basis for determining the mobility network resides in developing a set of trajectories which effectively "map" the solar system. Since actual trajectory design and optimization is a complex process in itself, a simpler and quicker parameterization of interplanetary trajectories is required. This must be robust enough to characterize Δv and ToF as functions of both planetary combinations and date, as well as be accurate enough to provide results that generally represent interplanetary travel.

Trajectory analysis was performed using Mission Design and Analysis Software (MIDAS), a patched conic interplanetary trajectory optimization software package.[27,28] The objective of MIDAS is to minimize Δv and provide the corresponding ToF for a given pair of planets on a given desired departure date and is limited to the assumption of instantaneous velocity changes. MIDAS is also able to consider both powered and un-powered flybys of planets and deep-space maneuvers to aid in minimizing the required Δv. Before the trajectory can be optimized, MIDAS also requires an initial guess of the approximate dates for which each intermediate planetary encounter may occur. An example of using MIDAS to simulate and illustrate a mission trajectory flown on a NASA spacecraft is shown in Figure 10.

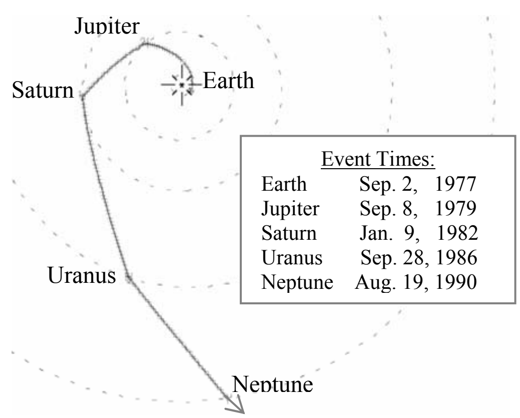


Figure 10. MIDAS application example: Voyager II Grand Tour.[28]

To successfully develop the mobility network for each combination of planets and at each specified date requires an approximate date for each flyby to be known a priori. While these initial dates can be "guessed," selecting inappropriate dates will not ultimately result in an absolute minimum for the given pair of planets, but a minimum which is closest to the initial guess (similar to a local, but not a global minimum). Thus, a genetic algorithm was used to determine the global optimum for a given pair of planets for a given date. This by no means establishes a true "optimum," but rather provides an "approximate optimum" from which generic, realistic trends may be established. This genetic algorithm minimizes Δv as a function of encounter date(s), where the number of encounter dates varies for each combination of planets. A date for each planet between the destination and departure planets is considered for a flyby (i.e., the encounter date), as well as the rendezvous date at the destination planet. Thus, using the MIDAS software and a genetic algorithm optimization method, trajectories for each combination of planets at every desired launch date, over the course of 50 years, were developed. This provided a database of Δv and ToF for each scenario assuming a minimum Δv trajectory. This database was then utilized to determine the weight of each link in the mobility network, and the appropriate trajectory for each mission. Figure 11 shows the relative magnitude of the best scenario (minimum Δv over a prescribed time period) for each planet pair.

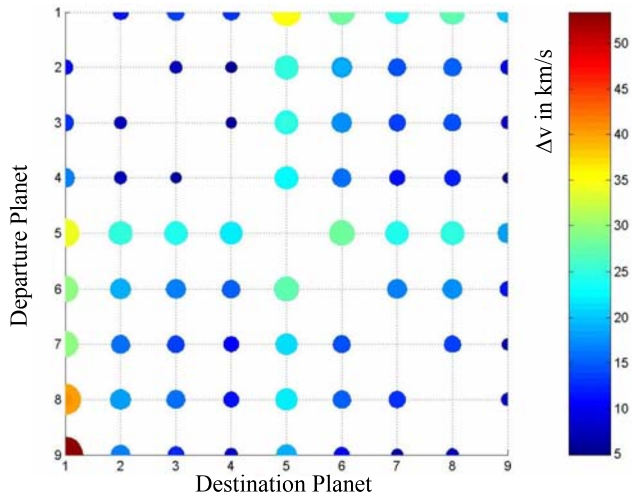


Figure 11. Minimum Δv from MIDAS data for a 50 year time span.

Mission availability is further refined by establishing mission constraints on both Δv and ToF. For this study, only missions with a $\Delta v \leq 50$ km/s and a $ToF \leq 25$ yrs are considered. This adds more realism to the network design, and removes missions that require larger ToF's and Δv's that lead to vehicle mass/cost increases. The effect of employing these constraints is discussed in the subsequent sections.

3. Interplanetary Demand Structure

Interplanetary desire and demand must also be established as a function of time. Interplanetary Desire and Demand (D&D) is broken into two sections, mission desire (i.e., political motivation for interplanetary travel) and infrastructure demand (i.e., the reallocation of planetary system resources to satiate infrastructure demand). In this model, infrastructure resources establish the Net Requirements and Resources (NR&R) for each planetary system and are then scaled with population.

Mission desire is considered separately since political mission desire is population invariant. Interplanetary D&D is created via six different state variables: current population, air, water, energy, raw materials, and political mission desire. These state variables are specified for each planetary system at a given time. NR&R is defined by the imports and exports of a particular planetary system, and it is assumed that each planetary system will not be (initially) self-sustaining; thus, resources must be sent between planetary systems. This interplanetary demand creates an infrastructure network that is independent of any political desire, and is only reliant on the needs of each particular system.

Each state variable is a measure of the existing planetary system infrastructure's ability to produce or manufacture a particular resource. These are presented on a per "population" basis, where a negative value represents a requirement (import), a positive value represents an excess (export) and value of zero demonstrates the planetary system is self-sufficient. To develop demand and relate it between planetary systems, the per "population" demand is multiplied by its current "population" such that the demand is now in a set of absolute units. Resources are reallocated in such a way as to eliminate any need for importing a resource (thus, making the planetary system's demand equal to zero).

The SSMN is setup linking planetary systems via their ability to successfully export the required resource to the planet of need. This establishes links between all available planets with an excess of a given resource and the planet for which it is required. The mission path (again governed by minimum $\Delta v \times ToF$) is chosen for the actual mission. The particular resource is then removed from the exporting planet and added to the importing planet. This also allows planets of greater need to receive resources from more than one planet, as well as suffer a loss if there is a lack of a certain resource. A noteworthy caveat in the network explored is the availability of a certain resource may decrease, not by a reduction or insufficient production, but due to their inaccessibility. Due to the dynamic nature of the solar system, certain planetary systems at certain times become inaccessible via the constraints imposed. While this generally is not problematic for the inner planets, access to the outer planets may become limited, and thus, they are more difficult to establish resource dependent infrastructure.

Political mission desire allows for the establishment of links for reasons other than pure infrastructure demand. Initially, as planetary systems are explored, preexisting infrastructure will not be available; this provides a means to establish links to unvisited planetary systems. As with infrastructure demand, a negative value determines a desired destination, a positive value determines a possible departure planet, and a value of zero issues no desire. Also, the number of missions a planetary system is able to support can also be fixed. This can force missions to originate from different planetary systems, some from less desirable systems than others. For example: while in some time-frame the best planet (in terms of available cost in trajectory weight) to deliver resources to Jupiter is from Mars, if Mars does not have those resources available, the resources may be shipped from Earth instead.

This process develops the links into a weighted, directed network, and then creates the appropriate adjacency and chosen path matrices as a function of time. The adjacency matrix illustrates all of the possible trajectories between planets, whereas the chosen shortest path matrix illustrates the best possible trajectory via link weight. Care is also taken to allow for link "delays" due to ToF. This need arises because interplanetary travel is not instantaneous, but requires a substantial amount of time to travel between planets. Thus, a link between planetary systems must exist for the duration of the mission (i.e., the ToF).

4. *Verification and Validation*

Upon completion of a simulation, steps must be taken to insure that verifiable results are produced. This was accomplished using a two-step process; model verification and model validation. Model verification compares both the paper and implementation models together. This was achieved by investigating how the implementation model compared to the desired performance via the paper model. Also, scenarios were investigated for any occurrence of anomalous activity in the implementation model. Model validation involves a comparison between model output and raw data. Strong validation is inherently difficult to achieve for SoS models due to the relative unavailability of empirical data and the uncertainty involved in SoS problems. This is especially apparent for this scenario, given the nature of what is being modeled and since no existing raw data exists on such a subject. Thus, a weak validation was sought with hopes of further reinforcing model veracity. Existing programs were utilized for the majority of the more complex calculations. It was assumed that both the MIDAS software and the genetic algorithm code were previously distributed, tested and verified, and thus can be used in confidence for this analysis.

C. Faux Exploration Initiative Scenario

The main impetus for creating the SSMN is to understand exploration of the solar system from the standpoint of Earth decentralized development; where Earth is no longer a primary infrastructure hub—the baseline scenario for this will be referred to as Faux Exploration Initiative (FEI). The mobility network as a whole represents an infrastructure with no real motivation (e.g., a network of roads and cars, without any reason to travel from point A to point B). Thus, a "dummy entity" was envisioned to provide the required stimulus above the β level such that solar system exploration might be properly imagined. This incorporates a Deterministic Decision-Maker (DDM) Agent, which provides a means to drive solar system exploration, albeit in a predetermined fashion.

1. *Deterministic Decision-Maker (DDM) Agent*

The created DDM is governed by a simple set of rules and a predetermined exploration agenda. This agenda schedules exploration (link establishment) every five years, and proceeds through the planets in the following order:

Mars ➔ Jupiter ➔ Mercury ➔ Saturn ➔ Venus ➔ Uranus ➔ Neptune ➔ Pluto

This scenario begins as infrastructure is created on Mars, and proceeds with the exploration agenda. This process takes 35 years to theoretically establish infrastructure in every planetary system, while the investigation continues for another 15 years until the specified 50 year time-frame is reached. The exploration agenda is driven purely by political demand; therefore, it can be specified a priori.

Infrastructure demand is created via a static NR&R structure that specifies interplanetary demand per population and is time invariant. Since no true units are utilized with NR&R, each planetary demand was arbitrarily created via an educated guess. An example of this would be establishing a demand for air in the majority of the planetary systems, excluding planets with the possibility of in situ air production. This procedure establishes the NR&R for each planetary system which governs interplanetary demand as a function of population. Certain planetary resources were also adjusted to provide more robust network development as well as to encourage emergent behavior. Table 8 discusses the NR&R values used in this study; the values were chosen to enable demand of resources across all planets.

Table 8. Planetary system NR&R (per population).

Resources	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Air	-1	3	10	3	-1	-1	-1	-1	-1
Food	0	-1	10	0	-1	-1	-1	-1	-1
Water	-1	-1	10	0	0	1	-1	-1	-1
Energy	10	-1	1	-1	0	3	-1	-1	-1
Raw Materials	1	-1	-10	1	5	5	-1	-1	0

The progression of infrastructure development is governed by the population of the planetary system. Planetary system population is defined as the number of "units" available to consume or produce resources. This includes both human and robotic missions together as a single unit. Planetary systems also contain a maximum sustainable population which constrains planetary growth to reasonable levels for comparison with Earth. This prevents the population of Mars from unrealistically surging past Earth's population in 50 years.

Population is also governed by a simple set of rules. First, if a desired mission is successful and a link is established, the population of the planet, where infrastructure is created, increases by 1. If infrastructure exists in a planetary system for more than 5 years, the population also increases by 1. If any demand is not met (for any resource) for a given (time-step) year, the population decreases by 1. The governing rules for population are summarized below:

- Initial link establishment: +1
- Infrastructure exists for 5 years: +1
- Planetary demand for resources is not satisfied: -1

These rules are established to provide more realism to the model. This allows for the possibility of establishing infrastructure on a planet that is accessible for a limited duration, and would show either the planet must be abandoned at a given time (i.e., the infrastructure is lost). It is worthwhile to note that for this study, Uranus is accessible for only a short fraction of time through Saturn. Thus, if infrastructure was lost at Saturn or Uranus became naturally inaccessible, infrastructure would slowly be lost on Uranus. These rules also provide a simple means of expanding infrastructure in each planetary system. Simply increasing the population increases both the planetary demand and the production ability of the system.

Mission desire is also governed by a set of simple rules. These guide the expansion of the network via political desires and make sure the infrastructure attempts to develop in the desired direction. The first rule reestablishes a desire for links that previously failed to be created. If infrastructure development is desired on Uranus at the given time, but it is inaccessible, the mission desire remains until infrastructure is established at a later date. Also, if a planet's infrastructure is completely lost (population reaches zero), mission desire is reestablished. While this may not be the best of ideas since something caused the loss of infrastructure in the first place, infrastructure reestablishment was given priority to continue developing infrastructure for academic reasons. The governing rules for mission desire reestablishment are summarized below:

- Initial Link Establishment Fails
- Total Infrastructure Failure (i.e., population=0)

A final caveat of the DDM resides in the fact that Earth is always an active node. While certain circumstances may cause the infrastructure of Earth to fail, these are beyond the scope of this study. It is assumed that the infrastructure of Earth is orders of magnitude greater than that of any other planetary system which could be developed within a 50 year time period. Furthermore, it is assumed that the desire and demand are always present.

2. FEI Results

Network analysis of the FEI simulation resulted in a view of its evolution with time. The network progression, (degree distribution as a

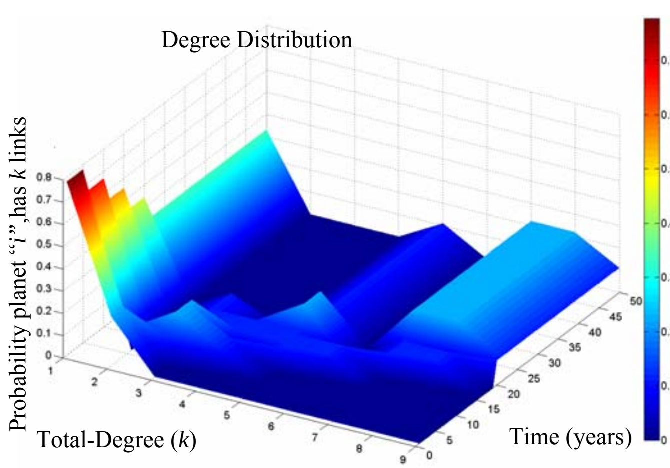


Figure 12. Network progression: time history of total-degree distribution for the FEI.

function of time), shown in Figure 12, generally indicates a transition toward a random network-high number of direct connections between all nodes. Initially, the network consists of Earth and Mars as the only nodes with in-bound and out-bound links to each other. The final network, which is achieved when every planet reaches its maximum sustainable infrastructure (occurs in the 21st year of the simulation) has high number of planets with high number of direct links. A comparison of the initial and final network degree distributions are provided in Figure 13; the physical representation of these two networks is illustrated in Figure 14. The dashed lines represent possible trajectories (via the adjacency matrix), whereas the solid lines represent the best available trajectory (via chosen shortest path matrix). The thickness of the solid lines is directly representative of resources being transported on those links; thus, the bigger the width of a link the more resources are being transported on it.

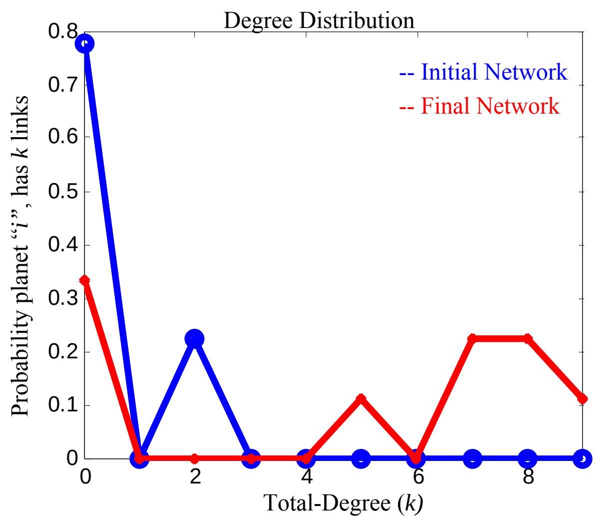


Figure 13. Initial and final network comparison.

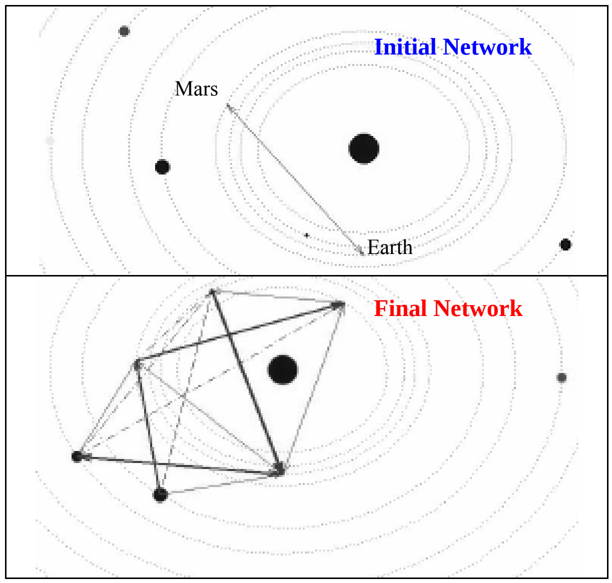


Figure 14. Illustration of Initial vs. Final SSMN's

It was also found that the progression of this network shows a low preferential attachment; each node develops at about the same pace, and nodes of higher degree do not receive preferential attachment as new connections can be established; this is shown in Figure 15. It is also interesting to observe that the with provided D&D, each planet exhibits phase transition toward higher degree to create a high level of connectivity, but because of the physical network dynamics and fixed demand and supply of resources, we do not observe unlimited growth; the network finds a steady level of connectivity to meet its objectives under the prescribed rules of interactions and set performance constraints.

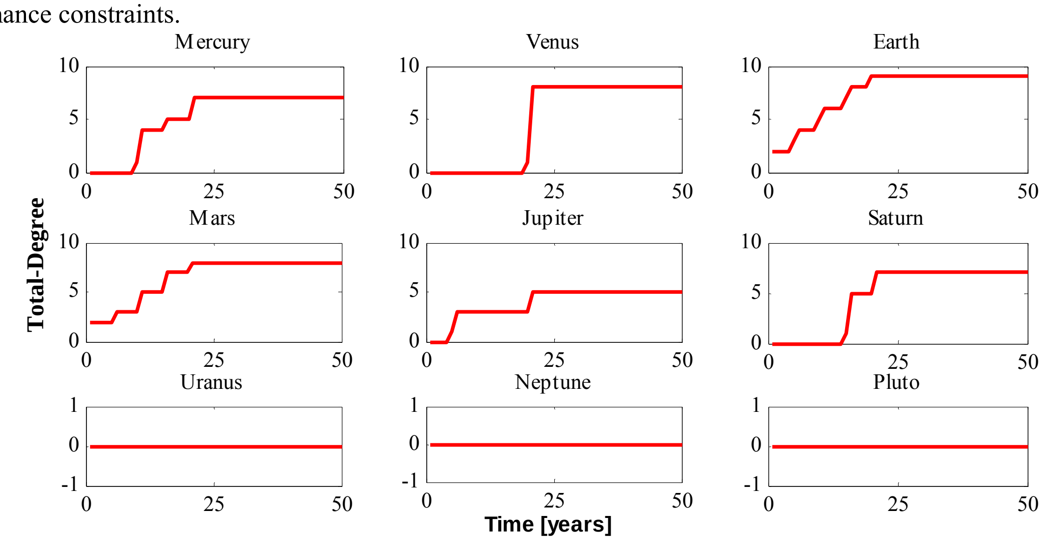


Figure 15. Planetary degree as a function of time.

As shown in Figure 15, the first six nodes, representing the 6 closest planets to the sun, begin with an un-weighted total-degree of zero or a small value and then these values progressively increased over time. The last 3 nodes, representing, Uranus, Neptune and Pluto, never establish links because all possible trajectories obtained from MIDAS exceed the Δv and/or the ToF constraints. Furthermore, it is surprising that Jupiter ends with a lower degree than Saturn; it was found that this behavior is caused by trajectory availability coupled with the prescribed planetary demand structure. The overall increase in average degree coupled with an increase in clustering coefficient depicts the network's tendency to become better connected over time (shown in Figure 16). This increase in clustering coefficient, relatively uniform degree increase, and visual comparison of the progression of the network topology also shows the network's tendency to become more assortative with time. Moreover, as the network develops, it becomes more interconnected instead of creating isolated hubs. The slight drop observed in Figure 16 is caused by loss of some of the connections due to loss of capability to establish certain links at that time.

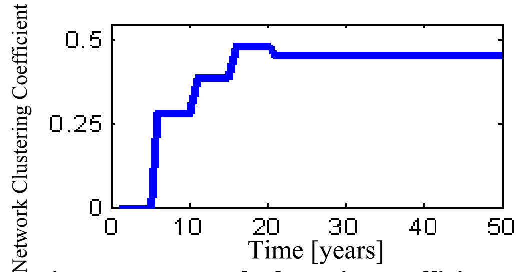


Figure 16. Network clustering coefficient time history.

The history of the geodesic network diameter was also examined. For every year over the course of the entire simulation, the network diameter, and thus the largest shortest path, is 1, with the exception of years 10, 15 and 20; which correspond with the initial settlement of Mercury, Saturn and Venus. It is of note that the initial settlement of Jupiter is not included in this set, which when compared with the relatively low degree Jupiter acquires upon reaching 50 years, shows Jupiter is not of much importance with respect to network performance in the FEI simulation.

Certain dates were found to be more significant throughout this simulation; these are years: 1, 10, 15, 20, and 50. These correspond to the initial network, when Mercury, Saturn and Venus were settled respectively, and then the final network. From a network analysis perspective, these dates are noteworthy for the various reasons described in Table 9.

Table 9. Noteworthy dates observed in simulation.

Year	Event	Attributed
1	Initial Network	---
10	Settlement of Mercury	Network Diameter: 2, Earth Betweeness Centrality: 1
15	Settlement of Saturn	Network Diameter: 3
20	Settlement of Venus	Network Diameter: 3
50	Final Network	Same Network Structure Since Year 21

In addition, the only time the Earth betweeness centrality is non-zero is the year Mercury is settled. This occurs because at this point there is a directional link from Earth to Mercury, and thus all the other planets can link to Mercury only through Earth. This disappears in the next time-step when links are established directly between Mercury and the other planets. Likewise, the non-unity geodesic network diameters exist for a similar reason. Once in-bound links with these planets are established, their respective shortest paths are increased until links are established directly between the planets.

3. Network Characterization: Scenarios

Several other scenarios were explored in evaluating the effects and performance of constructed SSMN model. The common element to all these models is variation of the demand structure and constraints on the overall system. The following list describes the scenarios explored for analysis of network structure, evolution and performance:

1. Baseline scenario for geo-centric infrastructure.
2. A completely connected, distributed infrastructure; each planet is connected to every other planet.
3. Random link failure with probabilities of failure at 1%, 10% and 30% for the baseline scenario.
4. Relaxed constraints: ToF relaxed to 50 years, instead of 25 years.
5. Removal of constraints for Δv and ToF.
6. Additional infrastructure constructed at a second planetary system, in addition to the existing one at Earth.
7. Purely random networks, with uniform and normally distributed links.
8. Earth centered, normally distributed random network

Most of the scenarios resulted in expected behavior; however, the outcome of scenario 6 proved particularly interesting in the sustainability and versatility context. Because Neptune and Pluto failed to establish any links and

Uranus only establish in-bound links for a limited time is evident of a lack of sustainability in the system under the prescribed set of constraints. This is visually illustrated in Figure 17, where hubs at Earth and Uranus (case 7), hubs at Earth and Neptune (case 8), and hubs at Earth and Pluto failed to show any link establishment in addition to the ones created from earth (i.e., the case with Earth as the only infrastructure hub). Thus, under the current rule set and abstraction of the network, there is an artificial limit on the size of the network and thus its ability to grow due to a lack of reachability of the outer planets.

It was also observed that the establishment of planetary infrastructure hubs, in addition to the one at Earth, created more network links, which allows for accelerated response to changes in demand and drivers. One example of this is shown in case 7 of Figure 17, where one infrastructure hub at Earth and one at Saturn, provided the highest average degree in the entire simulation, but that particular capability only existed for a limited time. This is an example of network evolution toward versatility, but does not provide sustainability. It also is an example of how this process can be used to guide well-informed technical and policy decisions for future space exploration activities; in this example it would allow the decision-makers to understand and compare the long-term performance effects of adding various infrastructure hubs.

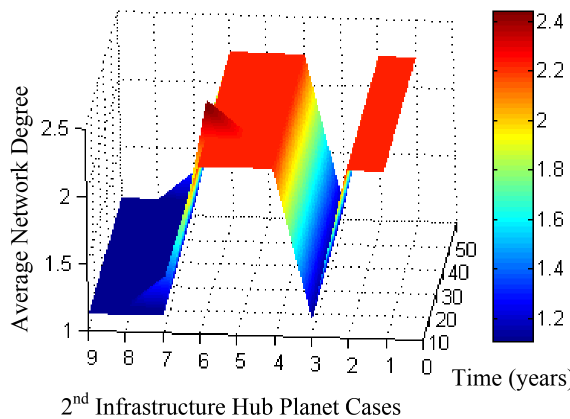


Figure 17. Results of a secondary planet infrastructure hub addition (network scenario 6).

V. Future Work

Future developments of the Solar System Mobility Network model include adding complexity to the available trajectory data set; this includes refining Δv and ToF values to provide data at constant date intervals (eliminate synodic period scaling), include possibilities of indirect fly-by trajectories (e.g., Earth-Venus-Jupiter tour) and include alternate methods for obtaining trajectories that allow us to reach the outer planets under the specified constraints; this involves trajectories with long-duration spiral burns or more complex trajectory design. Additional future work includes expanding from consideration of just planets to other points of interest across the solar system (e.g., comets, asteroids, moons, Lagrangian points), and integrating of the SSMN model and an agent-based model for decision-making into a larger SoS based simulation. The larger system-of-systems model, outlined in Figure 6, is being constructed to encompass the whole SoS methodology for the NSP, which includes: uncertainty in forms of random loss of resources and capabilities and changes in drivers, address the organization and information networks, and address other near term challenges of implementing a sustainable NSP.

VI. Conclusion

This paper introduced a nascent system-of-systems methodology and framework for modeling multi-level and multi-domain space exploration activities. It established the feasibility of using the methodology for analysis and design to investigate the evolving network of heterogeneous systems involved in space exploration. This enables the identification of emergent patterns across successful and unsuccessful architectures to assist in guiding effective decision-making. A Solar System Mobility Network was created to explore the feasibility of constructing infrastructure nodes across the solar system that can produce and transport resources from one planet to another; the SSMN dynamics were driven by the availability of cost-effective trajectories from planets that can supply the resources to the planets with resource demand. In exploring the constructed SSMN model through the use of network theory metrics, the outcomes provide a quantifiable means to determine the lifetime performance of the various scenarios explored. It was found that while the exploration of the SSMN can provide meaningful insights into potential future scenarios for ventures across the solar system, the performance of this network was limited by the data set obtained for the possible trajectories. While a larger SoS model is being constructed to represent possible objectives and activities of the national space program, a SSMN model and accompanying analyses and results were presented as a simple, introductory implementation of the proposed system-of-systems methodology.

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References

[1] DeLaurentis, D.A., “Understanding Transportation as a System-of-Systems Design, Problem,” 43rd AIAA Aerospace Sciences Meeting and Exhibit, 10-13 Jan. 2005.

[2] DeLaurentis, D.A., Callaway, R.K., “A System-of-Systems Perspective for Future Public Policy,” *Review of Policy Research*, Vol. 21, Issue 6, Nov. 2004.

[3] Cornelius, C., Doyle, R., “Architecture Design Strategies for the Evolutionary Development of Networked Human and Robotic Planetary Exploration Systems,” *1st AIAA Intelligent Systems Technical Conference*, 20-22 Sep. 2004.

[4] National Aeronautics & Space Administration, “NASA’s Exploration Systems Architecture Study,” NASA-TM-2005-214062, Washington D.C., Nov. 2005, URL: http://www.nasa.gov/pdf/140649main_ESAS_full.pdf

[5] National Aeronautics & Space Administration, “Aeronautics and Space Report of the President, Fiscal Year 2004 Activities,” 2004, URL: http://history.nasa.gov/presrep2004.pdf

[6] Camhi, E.J., “Editorial: Keeping the Science in Space,” *Aerospace American*, AIAA, April 2006. p.3.

[7] Boehlert, S., Gordon, G., et al., “NASA: Long-Term Commitment to and Investment in Space Exploration Program Requires More Knowledge,” GAO Code 120515, Report Number GAO-06—817R, United States Government Accountability Office, Washington D.C., 17 July 2006, URL: http://www.gao.gov/new.items/d06817r.pdf

[8] Space Frontier Foundation, “Unaffordable and Unsustainable? Signs of Failure in NASA’s Earth-to-orbit Transportation Strategy,” *A Policy White Paper*, Nyack, NY, 25 July 2006, URL: http://www.space-frontier.org/Presentations/UnaffordableUnsustainable.pdf

[9] National Research Council of the National Academes, “An Assessment of Balance in NASA’S Science Programs,” The National Academies Press, Washington D.C., 4 May 2006.

[10] National Aeronautics & Space Administration, “The Vision for Space Exploration,” Feb. 2004, URL: http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf

[11] Jamshidi, M., “System-of-Systems Engineering—A Definition,” IEEE SMC 2005 Conference, 10-12 October 2005, URL: http://ieeesmc2005.unm.edu/SoSE_Defn.htm

[12] Popper, S. W., Bankes, S. C., Callaway, R., DeLaurentis D. A., “System-of-Systems Symposium: Report on a Summer Conversation,” Potomac Institute for Policy Studies, July 2004, URL: http://www.potomacinstitue.org/academiccen/sos.htm.

[13] Keating, C., Rogers, R., Unal, R., Dryer, D., Sousa-Poza, A., Safford, R., Perterson, W., Rabadi, G., “System of Systems Engineering,” *Engineering Management Journal*, Vol. 15, No. 3, Sep. 2003, pp. 35-45.

[14] Bar-Yam, Y., et al., “The Characteristics and Emerging Behaviors of System of Systems,” New England Complex Systems Institute, Cambridge, Massachusetts, January 7, 2004.

[15] Maier, M. W., “Architecting Principles for System-of-Systems,” Systems Engineering, Vol.1, No.4, 1998, pp.267-284.

[16] Cowing, K., “Canceling NASA’s Terrestrial Planet Finder: The White House’s Increasingly Nearsighted ‘Vision’ for Space Exploration,” *NASA Watch*, February 6, 2006, URL: http://www.spaceref.com/news/viewnews.html?id=1092

[17] Martin, J. N., “An Introduction to Systems Engineering,” Tutorial presented at the INCOSE Crossroads of American Chapter, Indianapolis, Indiana, 25 Feb. 2005.

[18] Launius, R. D., “Public Opinion Polls and Perceptions of US Human Spaceflight,” *Space Policy 19*, pp. 163-175, 2003.

[19] National Aeronautics & Space Administration, “Columbia Accident Investigation Board Report,” Washington D.C., August 2003, URL: http://www.nasa.gov/columbia/home/CAIB_Vol1.html

[20] Lewe, J-H., DeLaurentis, D. A., Mavris, D. N., “Foundation for Study of Future Transportation Systems through Agent-Based Simulation,” 24th International Congress of the Aeronautical Sciences, 2004.

[21] Abbey G., Lane N., “United States Space Policy; Challenges and Opportunities,” *American Academy of Arts and Sciences*, Cambridge, MA, 2005, URL: http://bakerinstitute.org/Pubs/wp_aaas_spacePolicy.pdf.

[22] Barabasi, A. L., Albert, R., “Emergence of Scaling in Random Networks,” *Science*, Vol. 286, No. 5439, Oct. 1999, pp. 509-512.

[23] Newman, M. E. J., “The Structure and Function of Complex Networks,” Vol.1, 25 March 2003, URL: http://arxiv.org/PS_cache/cond-mat/pdf/0303/0303516.pdf

[24] Bonabeau, E., “Agent-based Modeling: Methods and Techniques for Simulating Human Systems,” *Proceeding of the National Academy of Sciences of the Unites States of America,* Vol. 99, Suppl. 2, 14 May 2002, pp. 7280-7287, URL: www.pnas.org/cgi/doi/10.1073/pnas.082080899

[25] Taylor, C., Song, M., Klabjan, D., de Weck, O. L., Smichi-Levi, D., “Modeling Interplanetary Logistics,” *SpaceOps 2006*, 19-23 Jun. 2006.

[26] “MIT Space Logistics Project; Interplanetary Supply Chain Management and Logistics Architecture,” Massachusetts Institute of Technology, Cambridge, MA, accessed May 19, 2006, URL: http://spacelogistics.mit.edu/

[27] Sauar, C., “Preliminary Draft of Users Guide to MIDAS,” Purdue University, West Lafayette, Indiana, 1991.

[28] Longuski, J. M., *AAE508-Optimiazation in Aerospace Engineering Lectures and Course Handouts*, Purdue University, West Lafayette, Indiana, 2006.