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Strategic Engineering Gaming for Improved Design and Interoperation of Infrastructure Systems

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Abstract. *Large physical networks of interrelated infrastructure components support modern societies as a collaborative system with significant technical and social complexity. Design and evolution of infrastructure systems seeks to reduce wasted resources and maximize lifecycle value. Interdependencies between constituent systems call for an integrative approach to improve interoperation but many existing techniques rely on centralized development and emphasize technical aspects of design. This paper presents a simulation gaming approach to collaborative infrastructure system design leveraging the technical strengths of simulation models and the social strengths of multi-player engagement in a game execution. In a strategic engineering game, models representing each constituent infrastructure system share a common graph-theoretic modeling framework and are integrated using the HLA-Evolved standard for interoperable federated simulations. A prototype game instantiation based on a space-based resource economy supporting future space exploration is discussed with the objective of identifying how factors of game play influence insights to collaborative system design. Future work seeks to develop, execute, and evaluate the prototype game to further research the use of simulation games in supporting collaborative system design.*

Keywords. *Federated simulation, simulation gaming, infrastructure systems, collaborative systems, graph-theoretic model, engineering design*

1 Introduction

Infrastructure systems are the large physical networks of interrelated components which provide critical services for the function of modern societies. They produce and transport resources such as water, electricity, goods and people, and information between locations of supply and demand. Infrastructure systems are collaborative systems characterized by long life-cycles and high capital expenses. With growing concern over wasting increasingly scarce resources there are calls for “collaborative, systems-based approaches” with “recognition of the interdependencies among critical infrastructure systems” in creating a strategy for infrastructure renewal (National Research Council, 2009).

Strategic engineering is the process of architecting and designing complex systems in a way that deliberately accounts for future uncertainty to maximize lifecycle value.[1] Uncertainties are closely related to temporal processes, and methods such as integrated modeling and simulation can be used to expose system lifecycle properties in potential futures. Maximizing lifecycle value as an emergent system property can be approached using integrated methods such as multidisciplinary design optimization.

Purely technical simulation or optimization methods have difficulty in capturing the socio-technical design challenges of infrastructure systems. Unlike systems designed under a centralized design authority (such as systems engineering), infrastructure are fundamentally a collaborative system with operational and managerial independence of the constituent systems (Maier, 1998). Decision-makers across systems express differing and potentially competing objectives to shape their design and are also influenced by an institutional sphere of social policy.

Other domains such as military planning, business management, and policy analysis use gaming as a method to address social complexities that cannot be simplified to a mathematical form. Simulation games combine the technical strengths of computer-assisted simulation with the ability of human players to accommodate the social dimensions during “play.” Two recent applications to the domain of infrastructure systems include SimPort MV2, a simulation game to study a port expansion project in the Netherlands (Bekebrede, 2010) and SprintCity, a simulation game to study rail infrastructure development and land use in the Netherlands (Nefs et al., 2010).

The approach to strategic engineering design presented in this paper follows a similar approach of other infrastructure games by combining the strengths of integrated modeling and simulation with a collaborative and interactive gaming environment. The key difference in this application is the focus on decentralized engineering design by multiple players representing collaborative infrastructure system decision-makers.

The following sections introduce the motivation, a proposed structure, and an application of a strategic engineering gaming approach to infrastructure system design to fulfill research objectives. Section 2 introduces a federated simulation architecture used to simulate a collaborative space exploration system in the SISO Simulation Smackdown outreach event. Section 3 links the use of a graph-theoretic modeling framework and a federated simulation architecture to the development of strategic engineering games. Section 4 previews a potential instantiation of such a game in the context of space-based resource infrastructure. Finally, section 5 concludes by outlining the future work to develop and evaluate strategic engineering games.

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[1] Other projects approached from a strategic engineering perspective and supporting methods and tools can be found online at http://strategic.mit.edu.

2 Federated Simulation and Outreach

Federated simulation was developed in the 1990s to support military training and simulation efforts by enabling simulation model interoperability and geographic distribution.[2] In spite of these benefits, federated and distributed simulation is seldom used in industry due to high perceived complexity (and thus, cost) and invisibility of benefits, leading to a low cost-benefit ratio (Boer et al., 2008). The issue of perceived complexity is addressed in this section while improving visibility of benefits of federated simulation is a larger objective of this research.

A concern in the broader modeling and simulation (M&S) community is a lack of university programs providing a strong educational background in M&S. From the authors' experience most university-level simulation classes focus on numerical methods corresponding to physics-based phenomena and the discrete styles of simulation coupled with deeper theory are not covered in as much detail.

In 2010 the Simulation Interoperability Standards Organization (SISO) introduced an outreach event called the "SISO Simulation Smackdown" to promote the concept of modeling and simulation as a discipline at the university level, leveraging a standard software architecture for federated simulation called the High Level Architecture (HLA) – Evolved (IEEE Std. 1516, 2010). The objective of the event is for university teams to build simulation models contributing to a collaborative space exploration system. Support and mentorship from a number of industrial partners including SISO, NASA, and AEgis and software vendors including Pitch, MÄK, and ForwardSim provide an opportunity for students to learn of the HLA software and interface.

The first SISO Simulation Smackdown took place on April 6, 2011 in Boston, Massachusetts in conjunction with the SISO Spring 2011 Simulation Interoperability Workshop (SIW). Student teams from the University of Alabama – Huntsville, Universities of Genoa and Bordeaux, NASA Johnson Space Center Internship Program, and MIT joined industry teams from NASA Johnson Space Center and ForwardSim in a federated simulation of a lunar exploration. Figure 1 illustrates the diversity of the simulation models participating in the event, ranging from ground-based lunar rovers to space-based satellites and transfer vehicles.

The 2011 Smackdown simulated exploration ran about 90 minutes at a real-time speed, though most federates illustrated the "most interesting" operational phase (e.g. the Lunar Shuttle landing sequence). Key interactions between federates included transmission of scouting reports identifying regions of high resource concentrations and the production and transportation of *in-situ* resources.

Following the success of the first SISO Simulation Smackdown, the second event is scheduled for March 26, 2012 in Orlando, Florida in conjunction with the SISO Spring 2012 SIW. At the time of writing, most participants from the 2010-2011 year are developing simulation models reaching for higher degrees of complexity and richer interaction between teams. Event-wide resources such as an online wiki have

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[2] Federated simulation is distinguished from distributed or parallel simulation as having heterogeneous simulation models (federates) executing across multiple logical processes.

been instrumental in improving collaboration between teams and reducing the learning curve in a domain where limited educational resources are available.

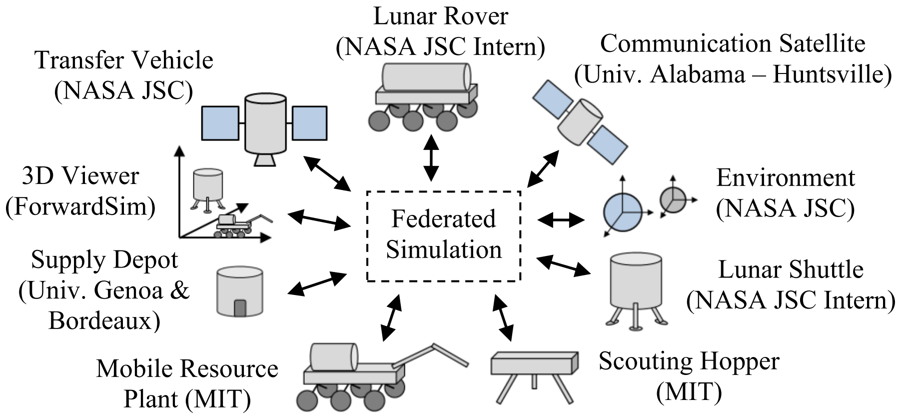

Fig. 1. The 2010-2011 SISO Simulation Smackdown included ground and space-based vehicle federates as well as visualization and environment federates in a collaborative lunar exploration system. Authority over federate design is distributed across student and industry teams.

There are a few key points to take away from the SISO Simulation Smackdown as an outreach event. First, interoperability of the simulations was critical as each team developed on the platform with which they were most comfortable. Federates were implemented in MATLAB, C++, and Java languages on both Linux and Windows physical and virtual machines. Second, design of simulation federates was a practical exposure to systems-level engineering for many students, providing a “hands-on” application not often possible in systems engineering education. Finally, the success of the SISO Simulation Smackdown is evidence that it is feasible for students to learn and use the HLA standard to produce a simulation federate within a few months provided there is mentorship and support from an inter-disciplinary team (usually at least one member with object-oriented programming experience and one with engineering experience). The learning curve and complexity of federated simulation do exist, however in this author’s opinion it is due to lack of accessible educational materials versus an infeasible barrier.

3 Technical Design of Engineering Games

While the SISO Simulation Smackdown simulates infrastructure elements in a real-time operational scenario, strategic design takes place over longer timeframes requiring more abstract modeling approaches. The technical design of engineering games addresses two aspects: 1) developing a modeling framework to represent the structure and behavior of infrastructure systems and 2) selecting a software architecture enabling decentralized model development and execution. These points are discussed in the following subsections.

3.1 Graph-theoretic Modeling Framework

A modeling framework provides a generalized form for model instantiations. In the case of infrastructure systems, the modeling framework must express the structure and behavior of infrastructure elements. Infrastructure systems are realized as large physical networks, suggesting a graph-theoretic approach for modeling structure. Past research in space exploration logistics and terrestrial city infrastructure also revealed an underlying network structure.

A generalized modeling framework used in the SpaceNet tool for space exploration logistics analysis defines nodes as locations on planetary bodies, stable orbits, or points in space and edges as physically-allowable trajectories or paths between nodes, illustrated in Fig. 2. During a space exploration simulation, infrastructure elements operate within the network of available locations. The abstracted network approach also enables optimization of resource transportation through a time-expanded network (Grogan et al. 2011).

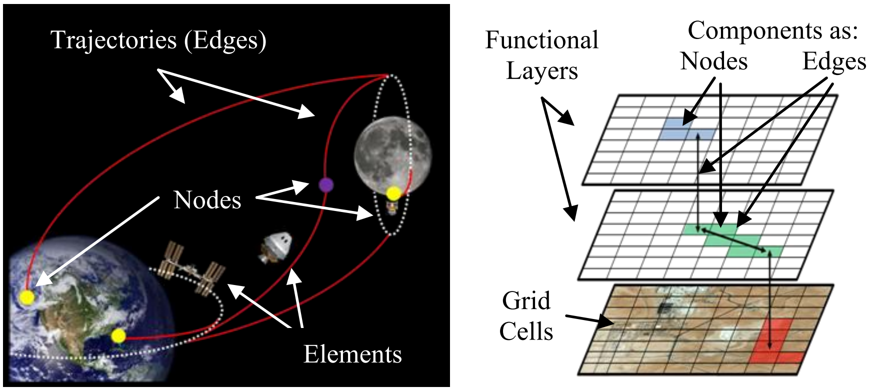

Fig. 2. Graph-theoretic models applied to space exploration using time-expanded networks (*left*) and city infrastructure components using layered networks (*right*).

A graph-theoretic approach is also applied in the City.Net tool for exploring interdependencies between components of city infrastructure (Adepetu et al., 2012). In this application, allowable nodes are based on a grid meshing of an urban area and components are represented as a node on a functional layer or edge linking nodes within or between layers, illustrated in Fig. 2. The City.Net modeling framework, however, does not include the time dimension and is not “executable” as a simulation.

Combining these two approaches, the structure of infrastructure systems can be modeled with nodes based on geography and edges representing infrastructure elements at or between nodes. With this approach every infrastructure element is an edge connecting two nodes provided some static infrastructure elements, such as plants or depots may connect a single node.

In addition to structure, infrastructure systems behavior must also be accommodated in a modeling framework. de Weck, Magee, and Roos (2011) discuss a functional classification for complex systems consisting of a 5x5 matrix of operands and operations shown in Table 1. The rows of the table – transform, store, transport, exchange, and control – are believed to be a complete classification and capture the behavior of infrastructure systems at a high level of abstraction.

Table 1. Functional classification of complex systems with operations and operands.

	Matter	Energy	Information	Currency	People
Transform	*Plants, Factories, and Processors*				
Store	*Depots, Tanks, and Accumulators*				
Transport	*Pipes, Lines, Grids, and Networks*				
Exchange	*Markets and Trading Systems*				
Control	*Governmental Agencies and Organizations*				

The combined structure and behavior modeling framework models infrastructure systems as edges on a physical network of nodes. Edges, as infrastructure system components, are classified as having one or more functional operations acting on one or more of the operands.

3.2 Federated Simulation Architecture

While the modeling framework generalizes model instantiations, the simulation architecture guides their integration and interoperation in an execution. In particular the architecture should capture the decentralized authority of collaborative infrastructure systems and their model instantiations. To accommodate decentralized model development, the software architecture follows the SISO Simulation Smackdown event and uses the HLA-Evolved standard for federated simulation.

Each federate in a federated architecture executes independently on separate logical processes (often on separate computers) with interdependencies communicated through message-passing over a network connection. Maintaining synchronization between federates and enforcing local causality due to asynchronous messages is a challenge in distributed simulation, though the HLA-Evolved standard mitigates some of these challenges with a runtime infrastructure (RTI). The RTI is a software layer that implements synchronization algorithms and aids with data exchange and acts as the interface between federates.

In the context of interrelated infrastructure systems, the main interactions between federates are the communication of resource demands and supply. In a non-integrated analysis these interactions may be considered exogenous variables and model state or output variables. Using the modeling framework discussed in the previous section, interactions between federates can be generalized as a transfer of resources at a node. Figure 3 illustrates two infrastructure federates passing messages to coordinate demand and supply of electricity at a node.

The implementation of each federate can be determined independently as long as agreement is reached at the interactions at the interfaces, i.e. resource transfer at the nodes. This architecture provides a decentralized approach for developing large or complex simulation models.

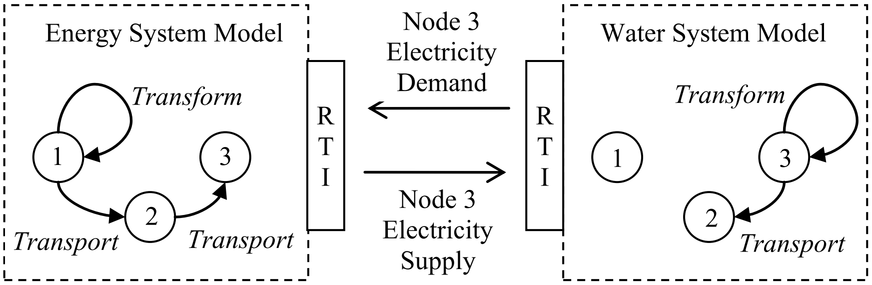

Fig. 3. Diagram of two infrastructure system models in a federated simulation. The energy system (*left*) transforms and transports electricity from a power plant. The water system (*right*) transforms electricity into potable water (e.g. desalination) for transport.

4 Prototype Game Instantiation

This section discusses how the modeling framework and software architecture may be used to implement a prototype game instantiation. As a prototype, the focus of the game is not on the ultimate design of a collaborative infrastructure system, but rather in researching the use of simulation games in collaborative system design. The outline presented in the subsections below follows the distributed simulation engineering and execution process (DSEEP) recommendation (IEEE Std. 1730, 2010).

4.1 Objectives and Scenario

In addition to serving as an illustrative example, the purpose of the prototype game is to empirically study how game play contributes to decisions in collaborative system design. In particular, we seek to address how a simulation game leads to insights of socio-technical complexities and recognition of and decisions leading to lifecycle value of the collaborative system. It is hypothesized that interpersonal interaction and problem engagement elicited by simulation games contribute to these goals. A game focusing on these research goals should model a complex collaborative system, but one having relatively closed boundaries and well-defined interactions to ease development, execution, and evaluation. For this purpose, the prototype game models the design of a collaborative space-based resource economy.

Future space exploration will not be limited to a single national space agency. Even today, multi-national collaboration on the International Space Station (ISS) will soon be joined by commercial partners for resupply missions. A future exploration to the moon or Mars will likely be a collaborative system of multiple national space agencies and commercial partners managing launch vehicles and/or resource production processes.

The scenario under development focuses on an exploration in the vicinity of the moon, which may serve as an *in-situ* source of key resources including water and oxygen. Constituent systems collaborate to produce, transport, and consume resources to support exploration demands. Some of the key constituent systems include:

- Launch vehicles (commercial and heavy-lift)
- In-space transportation vehicles and resource depots
- Surface transportation vehicles, habitats, and resource depots
- Transformation plants for key resources (e.g. water, oxygen, electricity)

Players exert design authority over a portion of the collaborative system. The objective of the game is to design and operate infrastructure across a network of nodes between Earth and the moon to maximize the capability of exploration.

4.2 Simulation Environment

The simulation environment includes the member applications participating in the federated simulation, interfaces between the member applications, and any other data shared across the federation. The member applications include simulation models of the infrastructure systems and a graphical user interface (GUI). The GUI allows participants to interact with the simulation models during a simulation execution.

A partial GUI mock-up is illustrated in Fig. 4 for a player designing surface infrastructure components near the Lunar South Pole. It includes a network view showing the location of infrastructure systems in the network. The user also has a panel to select the design and operation of their infrastructure elements during a simulation execution. A schedule component also helps to coordinate and execute decisions during periods of automatic simulation. During a simulation game execution, players have the opportunity to make changes to their schedule at regular intervals (turns), between which decisions are played out automatically.

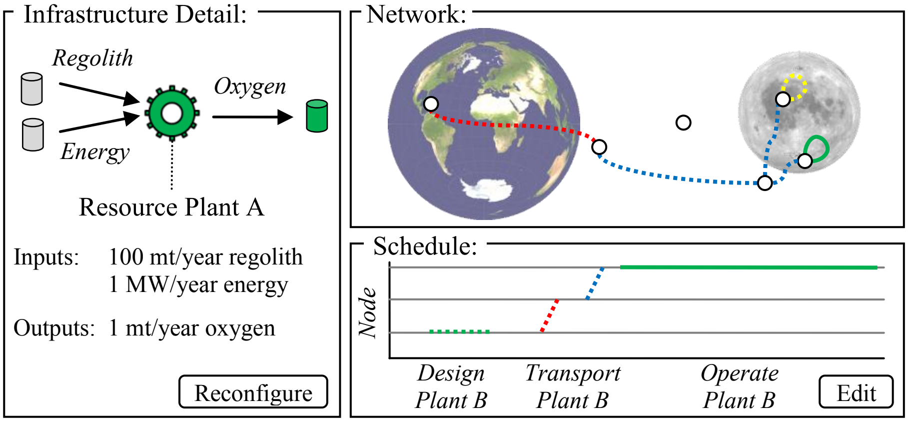

Fig. 4. A user interface mock-up includes a network view of the collaborative system, detailed control over the constituent infrastructure system components, and scheduling capabilities.

Interactions between member applications are described in two documents: a federation object model (FOM) and a federation agreement. The FOM defines the structure of data potentially shared between federates during a simulation, including attributes of persistent objects and transient interactions. The most general FOM contains one object class to represent infrastructure elements and one interaction class to represent the transfer of resources between infrastructure systems.

The federation agreement identifies the operational requirements of each federate with respect to the simulation execution and is unique for each scenario being simulated. One of the key components of the federation agreement is identifying the network in which the federates operate. In the lunar exploration scenario, the network includes locations on the Earth's surface and in Earth orbit, on the moon's surface and in lunar orbit, and at the second Earth-moon Lagrange point (location where gravitational attraction cancels between the Earth and the moon).

4.3 Execution and Analysis

Executions of the space-based resource economy game will take place over the span of a few hours. During the execution participants have the opportunity to run through a scenario multiple times making design decisions within their constituent systems. The specifics of execution, including number of scenario repetitions, player roles, simulation duration, and implementation of uncertainties will be clarified with future development and iteration of the prototype game.

Analysis of the space-based resource economy game will take the form of human subject experimentation with both student subjects in a classroom setting and professionals during conference workshops. Simulation logs coupled with observations, interviews, and survey instruments will be used to gather data on the simulation executions. The analysis approach targets a theory-based evaluation technique (Kriz and Hense, 2006). This method of evaluating simulation games takes a process-oriented approach to uncover the relationships between variables to uncover "how" or "why" an intervention presents the results, directly relating to the objectives of the research.

5 Conclusion and Future Work

This paper takes a perspective of using simulation gaming as a supporting method for strategic engineering of collaborative infrastructure systems. The approach combines the technical strengths of simulation models with the social strengths of human interaction and gaming. The technical design of simulation games uses a graph-theoretic modeling framework to represent the large physical networks of infrastructure components and a federated simulation architecture to accommodate decentralized design authority.

The next phase of research seeks to develop an instantiation of a prototype game to identify the processes by which participants learn of interdependencies between constituent systems. The prototype game will implement a scenario based on a space-based resource economy supporting future exploration missions. The game development plans to follow the IEEE Std. 1730 DSEEP process for developing and executing a distributed simulation, culminating with an empirical evaluation of learning based on existing literature in the simulation and gaming field.

Future extensions of the modeling framework and simulation game architecture include investigating infrastructure investment in diverse environments such as on the

Arabian Peninsula where there is a tight coupling between water and energy infrastructure systems.

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References

Adepetu, A., Grogan, P., Alfaris, A., Svetinovic, D., and de Weck, O. (2012), City.Net IES: A Sustainability-Oriented Energy Decision Support System. IEEE Systems Conference.

Bekebrede, G. (2010). *Experiencing complexity: a gaming approach for understanding infrastructure systems.* PhD Thesis, Delft Technical University.

Boer, C.A., de Bruin, A., and Verbraeck, A., (2008), Distributed simulation in industry – a survey part 3 – the HLA standard in industry. *Proceedings of the 2008 Winter Simulation Conference*, 1094-1102.

de Weck O.L., Magee, C., and Roos, D. (2011), *Engineering Systems: Meeting Human Needs in a Complex Technological World*, MIT Press, Cambridge, MA, 39-43.

Grogan, P.T., Siddiqi, A., and de Weck O.L. (2011), Matrix methods for optimal manifesting of multi-node space exploration systems. *Journal of Spacecraft and Rockets*, 48 (4), 679-690.

IEEE Std. 1516 (2010), *IEEE standard for modeling and simulation (M&S) high level architecture (HLA) – framework and rules.*

IEEE Std. 1730 (2010), *IEEE recommended practice for distributed simulation engineering and execution process (DSEEP)*.

Kriz, W.C. and Hense, J.U., (2006), Theory-oriented evaluation for the design of and research in gaming and simulation. *Simulation & Gaming*, 37 (2), 268-283.

Maier, M.W. (1998), Architecting principles for systems-of-systems, *Systems Engineering,* 1(4), 267-284.

National Research Council (2009), *Sustainable critical infrastructure systems: a framework for meeting 21st century imperatives*. The National Academies Press, Washington, D.C.

Nefs, M., Gerretsen, P., Dooghe, D., Mayer, I.S., and Meijer, S., (2010), Gaming the interrelation between rail infrastructure and station are development: part 1 – modeling the serious game 'SprintCity.' *Proceedings from the 2010 Third International Conference on Next Generation Infrastructure Systems for Eco-Cities (INFRA 2010)*.