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Simulating the Dynamic Marketplace: An Introduction to the Nodal Economic Space Commerce (NESC) Model

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The Nodal Economic Space Commerce (NESC) model is a dynamic, agent-based market simulation tool of the space marketplace. Each agent in the model is a representation of various entities within the space industry (consumers, producers, and the government) that provide or demand different products and services (Earth-to-orbit launch, habitats, resources, etc). Each agent has certain behaviors and interacts with other agents, such actions possibly resulting in competition between firms and entrance of new competitors. The NESC model contains various future space markets (duopoly, pure competition, etc.) and simulates the financial case of entities that undertake these projects. NESC is of higher fidelity than existing models utilizing more advanced financing, acquisition, and overall decision-making strategies throughout the full supply chain of space products and services (from vehicle developers to operators to consumers). Sample future markets that NESC will simulate include sub-orbital space tourism, orbital space tourism, commercial and government spacecraft, government exploration (ISS, moon) cargo/crew services, and future resources (mining, Space Solar Power, etc.). Agent-based modeling (ABM) allows one to simulate the impact of decisions before applying them in the real world. These choices include behaviors such as end-user price changes, product differentiation, insurance charges, and vehicle cost increases. Additionally, the impact of government actions can be incorporated (price elasticity, technology investment, anchor contracts, tax credits, regulation, etc.). The current model is still in development and this paper is designed to provide clarity as to the capabilities of the NESC model. An introduction is provided of the NESC model philosophy, the motivation behind the development, and potential applications to the aerospace industry. A general overview of agent-based modeling is provided. The theoretical framework and capabilities of a fully developed NESC model are discussed. Specific attention is given to the open-source agent-based software framework known as RePast, the components of the code, integration of the various algorithms, and general user operation. Basic functionality is demonstrated on a sub-orbital space tourism market case study consisting of multiple vehicle providers and a diverse pool of consumers. The future development path of NESC is also presented.

Nomenclature

ABM	=	agent-based modeling
AST	=	Administrator for Space Transportation
CEV	=	crew exploration vehicle
EDS	=	Economic Development of Space
ESMD	=	Exploration Systems Mission Directorate
ESAS	=	Exploration Systems Architecture Study
ESR&T	=	Exploration Systems Research and Technology
ETO	=	earth-to-orbit
FAA	=	Federal Aviation Administration
ISS	=	International Space Station
LEO	=	low earth orbit
MASON	=	Multi-Agent Simulator of Neighborhoods… or Networks… or something

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NESC	=	Nodal Economic Space Commerce
NPV	=	net present value
OTA	=	other transaction authority
RePast	=	REcursive Porous Agent Simulation Toolkit
VSE	=	Vision for Space Exploration

I. Introduction

The Ansari X-Prize, won in 2004 by the Mojave Aerospace Ventures (consisting of Burt Rutan's Scaled Composites and Paul Allen) may be viewed by future historians as a watershed event in the history of space commercialization. By actually providing evidence of the emerging commercial space community's capabilities to perform, it has opened the eyes of both the lay public and government space program managers to potential new markets and suppliers.

There are currently multiple start-up companies competing for the small-satellite launch market and or sub-orbital tourism market in a post X-Prize environment. For example, the emerging launch vehicle / space tourism companies currently include: Virgin Galactic (Richard Branson of Virgin), Scaled Composites, the SpaceShip Company, SpaceX (Elon Musk from Paypal), Blue Origin (Jeff Bezos of Amazon.com), SpaceDev, Xcor, Microcosm, Armadillo Aerospace (John Carmack of id Software), Rocketplane Limited, TGV Rockets, and the X-Prize Cup (X-Prize Foundation). Additionally, Bigelow Aerospace (Robert Bigelow) is in development of inflatable on-orbit modules based upon NASA-licensed technology. Orbital Recovery, Limited is a new company developing an on-orbit commercial satellite service based upon a stage-adapter from an Ariane-5 launch vehicle. There are also reduced gravity flights being offered by Zero Gravity Corporation. Robert Bigelow has also announced a new US$50M "America's Space Prize" requiring the following by 2010: a reusable spacecraft capable of taking a crew of no fewer than five people to an altitude of 400 kilometers and completing two orbits of the Earth at that altitude, repeating that accomplishment within 60 days, while demonstrating the ability to dock with Bigelow Aerospace's inflatable space habitat and be able to stay docked in orbit for up to six months. Separate from NASA's VSE and the traditional aerospace industrial base, there are innovative new groups pursuing multiple space services using a myriad of approaches seeking not only government but purely commercial customers (e.g. sub-orbital and orbital tourism).

Within the United States a major focus of future space policy has been the Vision for Space Exploration (VSE), announced by President George W. Bush on January 14, 2004. As stated in the VSE: "The fundamental goal of this vision is to advance U.S. scientific, security, and economic interest through a robust space exploration program."[1] The VSE has four major objectives:

1) Implement a sustained and affordable human and robotic program to explore the solar system and beyond.
2) Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
3) Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.
4) Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

The last objective of the VSE is interesting in its prominence, a top-level policy directive wherein NASA is tasked to seriously consider commercial involvement in space exploration. An important proponent of this thesis was the President's Commission on Implementation of United States Space Exploration Policy (June 2004), formed to examine the VSE itself. This commission stressed the imperative of commercial involvement as shown in their following recommendation[2]:

> NASA's relationship to the private sector, its organizational structure, business culture, and management processes – all largely inherited from the Apollo era – must be decisively transformed to implement the new, multi-decadal space exploration vision. The Commission recommends: NASA recognize and implement a far larger presence of private industry in space operations with the specific goal of allowing private industry to assume the primary role of providing services to NASA, and most immediately in accessing low-Earth orbit. In NASA decisions, the preferred choice for operational activities must be competitively awarded contracts with private and non-profit organizations and NASA's role must be limited to only those areas where there is irrefutable demonstration that only government can perform the proposed activity.

The Commission suggested multiple initiatives NASA should pursue in terms of involving the private sector including tax incentives, regulatory relief, and property rights in space. In the modern era there have been repeated calls from multiple areas within society for such change with only half-hearted initiatives eventually being proposed.

There may be potential in the VSE for involvement of non-traditional companies and development of commercially-applicable spin-offs. The challenge is to determine what components of the architecture required to go back to the Moon will be acquired directly from commercial providers versus developed in the traditional industry manner. NASA leadership has expressed concern of relying upon the emerging commercial community to develop architecture elements that are in the critical path of the exploration plan. Given this attitude, NASA may look to commercial companies to perform crew and cargo servicing of the ISS (after Shuttle retirement in 2010) as an alternative. Over the last few months, NASA Administrator Griffin has repeatedly made the argument for involvement of the commercial space community in this aspect of exploration. This can be seen in his remarks to the Space Transportation Association in Washington, D.C.[3]:

> So it is a real dilemma - it is a real dichotomy: how do we engage competition and position ourselves to take advantage of the successes and accept the failures which inevitable occur in that environment while, at the same time, meeting the goals and objectives that we have as managers? What I've come to, after considerable thinking (with some discussion and modifications to come) - for NASA: the best way to do that is to utilize the market that is offered by the International Space Station and its requirements to supply crew and cargo as the years unfold…So, there will - and there must - be a government-derived capability to service the space station even after the shuttle is retired. But because there must be such a capability does not imply to us that that is the way we would most prefer - to have cargo and crew logistics requirements for the station satisfied. What I would like to do is be able to buy those services from industry…There is a line in our budget called "ISS Crew and Cargo". It is not overly well-funded right now - a couple of hundred million dollars…We plan to use that to get us started on that process…[You can] expect to see the government looking to "make a deal" in a commercial sense. Again, rather than issuing a prime contract focused on process and on very detailed specifications on "how to do" things, [you should] look for a deal-making arrangement where we tell you what it is we want the requested services or good to be able to perform. For those of you that have spent any time in the world of communication satellites - look for that to be the model rather than the CEV procurement…[You should] look for us to conduct such a competitive procurement - and [you should] look for us to pick a "leader" with whom we will get started - and also to fund a couple of "followers" at the study level in case the leader falls off the track. Because, the leader is only going to continue to get his money if progress continues to be met. We will set up verifiable milestones, agreed upon in the deal, the way that any commercial deal would be done…[You should] look for us to conduct our contracting on a fixed price basis…In exchange for that [you should] look to be required to provide a commitment to sell at a specified price if I provide a commitment to buy - at a specified number…There won't be balloon payments at the end and there won't be "get well" arrangements if you screw up. On the other hand, there will be fairly substantial rewards for people who can deliver.

Additionally, he reaffirmed these points in his opening statement at a House Science Committee Hearing on "The Future of NASA" wherein he stated[4]:

> The loss of the Space Shuttle Columbia has made us acutely aware that one of the major impediments in fully utilizing the Space Station's capabilities is that we need a more robust logistics capability for crew and cargo than the United States or our international partners have readily available or on the drawing board. For this reason, we plan to leverage our nation's commercial space industry to meet NASA's needs for ISS cargo logistics and possibly crew support.

Thus there appears to be some genuine admission from NASA itself that the commercial community will be some portion, if perhaps not an integral part, of the implementation of the VSE. Chris Shank, Special Assistant to the Administrator stated at the Space Frontier Foundation's Return to the Moon Conference VI[5]:

> We've run the numbers, the budget numbers, and we can't afford this plan—we simply can't—if we follow the business-as-usual approach…NASA needs commercial ISS crew and cargo operations…If we assume CEV was the only vehicle, in a business-as-usual conservative costing approach, that if we didn't take a firm fixed-price approach towards our acquisition practices on how we're going to provide ISS crew and cargo, we could not afford to move on to the Moon.

One major new initiative just underway at NASA is the Innovative Programs Office in the Exploration Systems Mission Directorate (ESMD) at NASA Headquarters. This office contains the NASA program based upon and influenced by the commercial Ansari X-Prize model. Referred to as the Centennial Challenges program, four types of prize categories have been announced: Flagship (1-2/year at US$10-40M each, major private space mission), Keystone (3-5/year at US$250K-3M each, subsystem development), Alliance (2-4 / year at US$100-250K each, NASA provides prize purse, others administer prize), and Quest (up to US$1M/year, encourage science/technology/engineering/math careers). Current prizes include several US$10K space elevator prizes, a US$250K lunar stimulant ground-based oxygen processing prize, and US$250K astronaut glove challenge. Recently, it has been announced that this new office will also be examining non-traditional avenues for engaging the commercial community in exploration. The preliminary outlines of this office indicate that various contract instruments and activities will be utilized (see Table 1) including: service procurements (especially commercial services such as Federal Aviation Regulation Part 12), Other Transaction Authority (OTA) such as funded Space Act Agreements, and prize competitions (especially larger prize purses).

Table 1. Example Areas of Transaction by NASA Innovative Programs Office[6].

Mission	Government Transaction Type	Potential Application
1) Sub-orbital launch	Services	i. Micro-g experiments ii. Astronaut training
	Prizes	i. Altitude and reusability for science instruments ii. Vertical-Take-Off-Vertical-Landing (VTVL) and speed for lunar lander proxy
2) Low cost ETO launch	Services	i. Unflown payloads ii. Technology payloads
3) Proximity operations	Services	i. Unpressurized Space Station cargo delivery ii. Pressurized Space Station cargo delivery
4) Reentry	Services	i. Space Station cargo return
	OTA	i. Return vehicle development
	Prizes	i. Return vehicle flight
5) Crew transport	Services	i. Space Station crew transfer ii. CEV crew transfer
	OTA	i. Crew vehicle development
	Prizes	i. Crew vehicle flight
6) In-space propellant provisioning	Services	i. Lunar mission provisioning
	Prizes	i. In-space propellant storage and transfer demonstration
7) Small lunar transport	Services	i. Small missions ii. Surface payloads
	Prizes	i. Data/demo menu ii. Small soft lander

These initial examples of possible involvement through non-traditional means indicate a certain level of acceptance (or at least acknowledgment) of the commercial community and the products and services it may be able to provide.

Another important government action that will have a continuing effect is the Commercial Space Launch Amendments Act of 2004 (HR5382) passed by the United States Congress. This bipartisan law has been in work over the previous several years and amends the 1984 Space Launch Act which had no references to manned vehicles. The basic philosophy of the law is that as long as the uninvolved public is not threatened; allow the commercial industry freedom in their designs. Currently in the United States, space tourism vehicles are regulated by the Federal Aviation Administration (FAA) under the Administrator for Space Transportation (AST). This group is responsible for granting licenses and permits for both launch vehicles and launch sites. This new law specifically relates to the authority and duties of this body of the executive branch of government. A major aspect of the new law was to streamline the process for experimental permits to allow unlimited research and development flights (flights not for hire). For flights for hire, as in the case of sub-orbital space tourism operators, the FAA's regulation is limited to traditional informed consent procedures where participants are informed of the risks and waive their rights against the U.S. government. The AST has been given three years to pass regulation regarding these areas. Future issues that may need to be addressed include export control laws (currently affecting Virgin Galactic's purchase of Scaled Composite's sub-orbital space tourism vehicles), international landing laws, and international liability. However the nascent sub-orbital and orbital space tourism industry views this new law as a significant milestone that acts as a major step forward in clarifying the role of the government in terms of permitting, licensing, and general regulation.

II. Project Background

With exploration activities being guided by separate commercial and governmental motivations, it is important to be able to envision the properties of this future. Commercial industry is interested due to the competitive effects of the marketplace on the financial health of an enterprise. Governments are interested in the effects of their fiscal and regulatory power upon the development of a sustainable space industry.

A contribution by SpaceWorks Engineering, Inc. (SEI) in this area and generally to the implementation of the Vision for Space Exploration (VSE) is the project entitled: "Economic Development of Space (EDS): Examination and Simulation." This project, begun in April of 2005, is funded exclusively by NASA's Exploration Systems Mission Directorate (ESMD) Research & Technology program under a Broad Agency Announcement (BAA) for the Exploration Systems Research and Technology (ESR&T) office at NASA Headquarters.

The EDS project's aim is to examine and simulate potential future scenarios of the commercialization of space and identify how they relate to the national Vision for Space Exploration. This project will develop specific recommendations on how NASA can utilize other government and commercial products and services to meet the goals of the VSE. One component of this project are a series of workshops attended by relevant thought leaders to address what potential services can legitimately be provided by the commercial marketplace in these categories and also what spin-offs from government exploration missions would be utilized by the private sector. The EDS project team is led by SpaceWorks Engineering, Inc. (SEI) and involves a team of international space experts who have expertise in space commercialization, market forecasting and modeling.

The project is concerned with two general categories of future economic development of space: human/cargo access to space and space resources. The first category includes earth-to-orbit (ETO) transportation for crew and cargo, commercial and civil, domestic and international. This category includes the development of commercial infrastructure such as on-orbit recovery and space habitats. Specific examples of products and services in this category include space tourism, alternate access to space station, on-orbit satellite servicing, the use of the United States' EELV fleet, commercial habitat development, new commercial launch vehicles, foreign launch providers, European ATV development, and Air Force/DARPA space programs (ARES, FALCON, Orbital Express). The second category involves the use of materials available in space including In-Situ Resource Utilization (ISRU), Space Solar Power-(SSP), and asteroid mining.

A major component of the EDS project is the development and use of an economic and market simulation model referred to as the Nodal Economic Space Commerce (NESC) model. From sub-orbital space tourism, new small payload launch vehicles, and inflatable space habitats a myriad of companies and organizations are proposing innovative solutions to the space exploration problem. What is commercial industry doing that could be utilized for the return to the Moon and beyond? What specifically can NASA do to fully allow these innovations to help? What will future space commerce look like? These are the types of questions the EDS project seeks to answer through dialogue with the leading thought experts coupled with a high fidelity computer simulation of the future space marketplace. This paper provides an introduction to the NESC model as it is being developed during the EDS project. Capabilities of the NESC model are outlined as well as descriptions of sample applications. For more information on the EDS project, including results from workshops already conducted, see the companion paper entitled "Economic Development of Space (EDS) Project Update: Examining and Simulating the Space Marketplace."[7]

The qualitative and quantitative assessments of the EDS project will help develop a roadmap the government can use to plan the appropriate mix of commercial acquisition and government development required to meet the goals of the VSE. This will help NASA determine which technologies have the greatest potential contribution to the commercialization goals for space exploration. Phase I of the study includes examination of products and services related to human and cargo presence in space such as Earth-to-orbit (ETO) transportation for crew/cargo and commercial infrastructures such as space habitats. An eventual final report and results from the NESC quantitative model will be presented to managers at NASA Headquarters and other relevant policy makers.

III. Motivation for Development

Current conceptual level economic models do not fully capture the relevant interactions amongst all the players in a marketplace. From the diverse utility functions of each individual customer, to one's supply chain, to one's competitors, to the actions of the government; all these interactions are occurring simultaneously in the real marketplace. Spreadsheet-based modeling, used extensively throughout various industries in the conceptual design process, may not be appropriate to fully capture these effects. Other relevant market modeling techniques that have been used extensively in other industries can be applied to current and future space markets.

The level of sophistication of economic models used to value space capital projects seems to have stagnated at the current level of spreadsheets. Sophisticated economic models created and used by the authors can contain discrete variable inputs and can result in non-continuous jumps in the objective function (such as Net Present Value) resulting in the need for non-gradient based optimization schemes such as evolutionary algorithms. In addition, probabilistic methods may be required given the uncertainty in cost, market demand, etc.

As an example, current acquisition logic programmed in Visual Basic for Application (VBA) in Excel for reusable launch vehicle (RLV) economic analysis contains discrete vehicle purchasing algorithms that can require recalculation times of minutes per iteration on even the fastest of today's modern personal computers.[8] This has confined the models to computer processing limitations inherent within that environment making models infeasible for optimization or probabilistic data assessment in a conceptual design environment. Higher fidelity models, optimization routines, and probabilistic life cycle simulation requires faster model execution times than currently available in spreadsheet based formats. VBA coded functions and routines in Excel are typically much slower than similar coded routines in other programming languages such as C, C++, Java, or Python.

Current generations of models also are limited by the ability to only perform single price optimization (one single price is charged to all customers, public or private). This assumption is not valid given the different utility functions for space services of public and private entities. Normally the government has different requirements and will often pay more for similar space services than the private sector. The government market can even be divided up into unmanned space science payloads (more elastic pricing strategies) and manned payloads (less elastic pricing strategies). This divergence in pricing escalates into multiple pricing schemes for multiple markets.

Additionally, there are interactions between vehicle producers, operators, and consumers (the supply chain) that are not taken into account. Normally, differing models are used to evaluate each of these nodes in the supply chain separately. A more enlightened analysis would attempt to also model the interactions of these entities. Financial algorithms and models could then be applied to multiple entities resulting in more comparable output metrics. For example, a sub-orbital space tourism market may consist of the developer of the vehicle, the flight operator, and actual space flight participants. A future Space Solar Power (SSP) market may have the actual in-space hardware/power delivery company and a separate Earth-to-orbit (ETO) transportation company doing business with each other.

Given all the above limitations, new implementations of economic models have to be developed to both timely and accurately simulate the landscape of the future. The authors propose a new, agent-based dynamic market simulation and financial engineering tool entitled NESC (Nodal Economic Space Commerce) for commercial and government space entities. Such a capability can allow government planners to forecast the impact of their actions on commercial space development through the creation of a variety of options like technology investment, anchor contracts, tax credits, etc. The commercial sector should be able to analyze their business case taking into account the actions of consumers, suppliers, competitors, and the government.

The NESC tool will model various future space markets (duopoly, pure competition, etc.) and simulate the financial case of entities that undertakes these projects. NESC will be of higher fidelity than existing models, developed in programming language, incorporated in a collaborative design environment, use credible financing toolkits (venture financing, equity financing, government effects, real options), use heuristic-based operations research methodologies to determine acquisition / manufacturing schedules, use genetic algorithm / heuristic / neural network optimizers to determine optimum market pricing strategies, and provide probabilistic output metrics. Obtaining clarity as to the shape of future space demand and impact of government actions can determine financial viability of space enterprises. Dynamic simulation models based upon such forecasts can provide guidance on market growth and evolution (ranging from current terrestrial telecommunication markets to future cis-lunar resource markets to Space Solar Power). NESC will be able to provide such clarity.

IV. Agent-Based Modeling (ABM)

The complex world consists of many interactions of multiple groups. These groups consist of simpler individual entities each with certain behaviors. As conditions around these entities change, so do their reactions based upon their behaviors. Multiple economic relationships exist between entities and need to be modeled. Typical, spreadsheet-based models strain to model the complexity both within these individual entities and their interaction with other entities. Additionally, spreadsheet models may also require more computation time for optimization and probabilistic analyses for very advanced models. Complex financial calculations for an adequate model require more processing than typically handled in such environments.

There are different philosophies of modeling. Some are equation-based as in a typical spreadsheet model. Other techniques are simulation-based where there are actual steps for the simulation, perhaps in a certain arranged temporal order. Some of these simulation-based techniques include discrete-event simulation (DES) and what could be referred to as subset of DES known as agent-based modeling (ABM). ABM can provide a solution to the previously mentioned issues in spreadsheet-based modeling by allowing the simulation of dynamic and higher fidelity interactions. ABM is not just chosen to replace a conventional spreadsheet-based simulation because of the capability of higher fidelity that could easily be accomplished by use of programming language. ABM also allows the dynamic interaction of multiple entities within the marketplace.

A. Overview of Agent-Based Modeling (ABM)

ABM involves the interaction of heterogeneous agents with varied and dynamic behavior. Simulation can represent plants and animals in ecosystems, vehicles in traffic, people in crowds, or autonomous characters in animation and games. These models typically consist of an environment or framework in which the interactions occur with some number of individuals that are defined in terms of their behaviors. Each individual can be perceived as an autonomous decision-making entity referred to as an "agent." The characteristics of each agent can be tracked through time. Each agent decides for itself which actions to perform at what time, based on external conditions and private internal aspects (current beliefs, desires, etc). General benefits of ABM include[9]:

1) ABM captures emergent phenomena: Emergent phenomena result from the interactions of individual entities. The whole is more than the sum of its parts because of the interactions between the parts. For example, a traffic jam, which results from the behavior of and interactions between individual vehicle drivers, may be moving in the direction opposite that of the cars that cause it
2) ABM provides a natural description of a system: The model seems closer to reality. For example, it is more natural to describe how shoppers move in a supermarket than to come up with the equations that govern the dynamics of the density of shoppers
3) ABM is flexible. It provides a framework for tuning the complexity of the agents: behavior, degree of rationality, ability to learn and evolve, and rules of interactions. There is an ability to change levels of description and aggregation (e.g. aggregate agents, subgroups of agents, and single agents, with different levels of description coexisting in a given model)

As some have stated ABM involves "Global consequences of local interactions of members of a population."[10] Another explanation of ABM includes[11]:

> The new models combine lessons from biology with a bottom-up analysis. The aim is to create a society-in-miniature inside a computer…the new models create virtual worlds with hundreds of miniprograms. Each miniprogram represents a real-world economic entity--such as a factory, store, bank, or household. These get tossed together in a silicon realm where they evolve as they interact with other entities, creating a dynamic economic model.

Through ABM one can better understand both the universe as a whole and the individual participants of that universe.

B. Examples of Agent-Based Modeling (ABM) Application

As complexity science has emerged as a field of inquiry, more investigation has been performed into the interactions of swarms, networks, biological evolution, etc. Coupled with more rigorous analysis of decision-making from the field of economics, techniques such as Agent-Based Modeling (ABM) have emerged. ABM has been used in multiple areas for analysis of dynamic interactions. Examples that can be found of previous investigations using ABM include:

1) School voucher programs
2) Decision making in closed regimes
3) Modeling the size of wars
4) Voting dynamics
5) Self-organizing computer networks
6) Multi-cellular tumors
7) Simulation for the everglades/big cypress region of south Florida

8) Growth of individual plants and interactions with individual insects
9) Social behavior in rat pups modeled by simple rules of individual behavior
10) Individual and collective actions of people in large temporary gatherings (crowds, mobs, etc.)
11) Modeling of prehistoric settlement systems in southwestern North America
12) Individual-based models of the music CD business
13) Electricity markets of how customers respond to different price patterns for electrical power
14) Movement of individuals across the transportation network (use of cars or buses by the second)
15) Seating in a theater, how the appropriate number of people decide to show up for an event
16) Micro-analytic model to simulate the U.S. economy (agents represent various decision-makers)

ABM has been used in the financial community to help evaluate decisions. One example comes from the world of retail[12]:

> "The client, Macy's group vice-president William M. Connell, is amused and oddly pleased, if only because he can see that the team is making some progress toward an incredibly ambitious goal: to harness the emerging science of complexity, the notion that complicated behavior emerges from the interaction of many components, and create a powerful new tool for top executives. Farrell's team [K. Winslow Farrell Jr. of PricewaterhouseCoopers Emergent Solutions Group] is creating artificial worlds of evolving, reactive software creatures. If all goes well, the actions of those "adaptive agents" will so closely mimic human behavior that managers for the first time will be able to use them to test the impact of their decisions before implementing them in the real world."

C. Various Agent-Based Modeling (ABM) Computational Programs

Agent-based software (and Object-oriented programming) provides the framework for creating an agent-based model. A wide range of agent-based modeling software tools are available to assist in building such models. The advantage provided by agent-based toolkits is the availability of standardized libraries for building simulation environments, collecting data, and creating user interfaces[13]. Over 20 agent-based software toolkits were evaluated by the authors as potential NESC frameworks including NetLogo, Ascape, Ptolemy II, AgentSheets, TNG/SimBioSys, XRaptor, Aspen, JASA, ModuleCo, SDML, Vensim, Z-Tree, EcoLab, Quicksilver, VSEit. The list was narrowed to three finalists: RePast, Swarm, and MASON. The basic functionality of all three finalists is similar, and all are free and open-source. The provided frameworks are sufficient to support and assist with the creation of agent-based models while maintaining the flexibility to develop advanced customized models. The similarity in basic functionality is perhaps due to the fact that Swarm was one of the first agent-based software toolkits, and both RePast and MASON were designed based on Swarm. Simulations within all of these toolkits are driven by a discrete event scheduler and all have the capability to log and graph results. A brief summary of the finalist software programs follows:

1) Swarm was created by the Santa Fe Institute and is currently maintained by the Swarm Development Group (www.swarm.org). Swarm has a large base of users, a large support base available online (including via the Swarm wikipedia and mailing list), and the largest collection of applications of all frameworks examined. An Objective C and a Java version of Swarm are available.
2) MASON (Multi-Agent Simulator of Neighborhoods... or Networks... or something...) was created by the Evolutionary Computation Laboratory and the Center for Social Complexity at George Mason University (cs.gmu.edu/~eclab/projects/mason/). MASON is easy to use with good support including tutorials and a searchable mailing list. However, it does not have as large a library as RePast or Swarm nor some of the more powerful tools available with RePast. MASON is implemented in Java.
3) RePast (Recursive Porous Agent Simulation Toolkit) was created at the University of Chicago and is now maintained by the non-profit RePast Organization for Architecture and Development (RePast.sourceforge.net/). A large support base is available for RePast including tutorials and a searchable mailing list. Its libraries are well suited for economic and social modeling, and it features additional libraries for regression, Monte Carlo simulation, Genetic Algorithms, Neural Networks, and basic Game Theory. Version 3.0 of RePast is available for three different model development languages: RePast for Java (RePast J), RePast for the Microsoft.Net framework (RePast.Net), and RePast for Python Scripting (RePast Py)

Selection of the agent-based software toolkit for NESC from among the three finalists was accomplished by qualitatively evaluating development maturity, available modeling libraries and options, applicability to NESC modeling, support and documentation, the graphical user interface, future viability, and ease of installation. Each of these criteria were evaluated through independent testing and supplemented by software reviews[13, 14]. Ultimately RePast was selected for the applicability of its available libraries, ease of use and installation, and quality of documentation. Given the three language implementations of RePast, the Java implementation (RePast J) was chosen because of the availability of Java, flexibility of the language, and familiarity to the authors.

V. Goal of the NESC Project

A. Theoretical Framework of NESC

The Nodal Economic Space Commerce (NESC) model is a dynamic, agent-based market simulation tool for the space marketplace. Each agent in the model is a representation of an entity within the space industry (consumers, producers, and the government) that provides or demands different products and services (Earth-to-orbit launch, habitats, resources, etc). Each agent has certain behaviors and interacts with other agents, such actions possibly resulting in competition between firms and entrance of new competitors. The NESC model contains various future space markets (duopoly, pure competition, etc.) and simulates the financial case of entities that undertake these projects. NESC is of higher fidelity than existing models, and utilizes more advanced financing, acquisition, and overall decision-making strategies throughout the full supply chain of space products and services (from vehicle developers to operators to consumers). Sample future markets that NESC will simulate include sub-orbital space tourism, orbital space tourism, commercial and government spacecraft, government exploration (ISS, moon) cargo/crew services, and future resources (mining, Space Solar Power, etc.). Agent-based modeling (ABM) allows one to simulate the impact of decisions before applying them in the real world. These choices include behaviors such as end-user price changes, product differentiation, insurance charges, and vehicle cost increases. Additionally, the impact of government actions can be incorporated (price elasticity, technology investment, anchor contracts, tax credits, regulation, etc.). The current model is still in development (currently at version 0.3) and this paper is designed to provide clarity as to the capabilities of the NESC model. The NESC philosophy allows for a more realistic and dynamic simulation of traditional and emerging space markets.

The proposed NESC model will be modular to accommodate new concepts and methodologies. NESC will include logic for dynamic modeling of interactions within marketplaces that include:

1) Consumer, operator, and supplier relationships throughout the supply chain
2) Interaction between competitors, includes current and future competitors (expendable and reusable)
3) Entrance of new competitors within established and new markets, collusion of established entities against new entrants
4) Different types of markets and sub-markets (duopoly, monopoly, etc.)

NESC will use the concept of a trade route or supply chain that consists of the specific interactions in the marketplace. Infrastructure nodes and transportation links can be fashioned for any particular space architecture being examined by the user. Examples could include an Earth-Mars cargo delivery system or a sub-orbital space tourism supplier-operator-consumer chain.

B. Capabilities in a Fully Developed NESC Model

It is anticipated the final NESC model will:

1) Provide a market model that reflects the interaction of consumers, producers/operators (including competitors), and the government
2) Allow commercial companies to model their financial metrics of interest
3) Be able to accurately reflect the impact of government activities upon the private development of space activities, namely the impact of separate government pricing, government cost sharing, technology risk reduction, tax credits, loan guarantees, tax holidays, etc. upon the valuation to private companies of large scale capital projects
4) Incorporate various market demand projections including relevant and available market models such as those from Teal Group, Futron, Tauri Group, FAA COMSTAC, CSTS, NASA Mission Market models, NASA JSC exploration overlays, DoD studies, and international studies

5) Calculate not just Net Present Value (NPV) based upon a qualitatively derived discount rate as in current models, but actually apply Weighted Average Cost of Capital (WACC) measurements to determine the discount rate
6) Use more elaborate financing models than those currently employed in space transportation and architecture models, namely apply venture/mezzanine financing toolsets with calculation of warrants/stock valuations for commercial entities
7) Have the capability to determine the option value of investments to companies using methodologies from real options analysis; real options allow managers to examine the flexibility inherent in an investment decision using Black-Sholes derived methods (for a commercial entity waiting for technological maturity can help increase the value of a project, traditional discounted free cash flow methods using metrics like Net Present Value (NPV) do not account for the utility of such flexibility); real options theory has been applied in oil exploration, pharmaceutical drug development, and most recently in the telecommunications field
8) Have the breadth and depth to model the economics of both space transportation and infrastructure using inputs from cost, operations, safety, and market models
9) Simulate the space products and services supply chain, for example in the case of Space Solar Power, one company provides both the ETO and in-space transportation service as well as develops the orbital infrastructure and Solar Power Satellites) or there are many companies each providing a different service (i.e. in the case of Space Solar Power, three companies interact to provide ETO transportation, in-space transportation, and orbital infrastructure while charging different prices to each other)
10) Probabilistically simulate behaviors and agent input parameters such as cost
11) Have heuristic-based acquisition/manufacturing logic using inputs of life, reusability, turn-around time, etc.
12) Contain evolutionary based optimizers such as genetic algorithms and neural networks formulations
13) Be integrated within the Phoenix Integration's ModelCenter© collaborative design environment framework (compatible with other computational codes)
14) Eventually be ported to the web for use by remote users

Most of the above capabilities are projected to be available in the NESC model at the end of the first project year, with full capabilities and additional markets available by the end of the second project year.

Financial models of companies in NESC will be composed of core modules that can be used to model an entire company and the subsequent interactions with other agents in the marketplace. The modules that make up a typical space company in the NESC model include the following:

1) Main Inputs and Outputs Module (MIOM): User inputs including those defining the program (start year, end year, etc.) including government effects upon the market
2) Space Market Module (SMM): Static and dynamic market simulation based upon input market forecasts/elasticities, models competitors and determine output pricing
3) Acquisition and Manufacturing Module (AMM): How to acquire and manufacture the assets required to supply the market demand (just-in-time, etc.); heuristics to determine the optimum method to create, maintain, and operate system to meet programmatic objectives given inputs from operations, safety, and mission models
4) Cost Schedule Module (CSM): Determining overall Life Cycle Cost (LCC) schedule, develop a schedule of non-recurring and recurring costs based upon an acquisition schedule and input DDT&E costs, TFU costs, and associated learning / rate / manufacturing effects
5) Financial Module (FM): Business case analysis to determine financial engineering metrics of interest, contains balance sheets, debt financing, depreciation, venture / equity toolsets, real options formulations, Net Present Value (NPV), Internal Rate of Return (IRR) calculations

These common sub-modules for company agents result in determination of acquisition schedules, cost flows, and cash flows for each type of agent in the system.

C. Pathways for Implementation

The NESC model's initial component to be developed in Phase I will consist of a dynamic market model to simulate the interaction between various markets (ETO, in-space, infrastructure, etc) and the business case simulation process. These analyses will be performed deterministically (Phase II will involve probabilistic analysis).

The NESC model will examine both short term and long term market projections with logic for market transition from one to another. Future market demand projections can originate from various sources.

VI. Current Implementation

The first market that was modeled in NESC was a sub-orbital space tourism market with companies competing for customers with the goal of maximizing revenues. In this version of NESC v0.3 (version 0.3) for the sub-orbital space tourism market, each company autonomously decides its pricing strategy given its unique capacity, costs, and vehicle characteristics. NESC outputs the financial health of each company (cash flows, Net Present Value, market share, etc.) and can be used to explore various scenarios including supply vs. demand effects, customer preferences, and company strategies (including product differentiation and cost leadership). Interviews were conducted at the first workshop of the EDS project of selected executives from multiple companies to help ascertain important variables in modeling commercial firms in NESC. A preliminary overview of the NESC model was presented at the second EDS workshop. Specific profiles of potential future space companies that could be modeled in NESC were also discussed at this workshop.

A. Program Overview

NESC v0.3 demonstrates agent-based modeling as a tool for analysis of the commercial space environment by simulating a suborbital space tourism market. Suborbital tourism is a nascent industry pioneered by companies such as Virgin Galactic, RocketPlane Limited, and Blue Origin. The typical suborbital experience will feature a small craft which carries passengers vertically up out of the atmosphere to around 150km. Near the top of their climb passengers will experience several minutes of weightlessness and observe the black sky and curved horizon before descending back to the surface of the Earth.

In NESC v0.3, suborbital tourism companies seek to maximize profits while competing with one another for sales in a market composed of individual customers. The product offered by each suborbital tourism company can be differentiated in terms of the suborbital vehicle characteristics and customer experience. Companies autonomously decide the price they will charge for a flight aboard their vehicle and customers independently evaluate the products offered by the companies according to their individual price sensitivity, tastes, and preferences. Each customer may choose to purchase from among the company offerings or not at all.

The RePast framework simplifies the output of any variable values, calculations, and results of the simulation. NESC v0.3 features four key outputs in the form of three line graphs and a text output window. The three line graphs track company price, market share, and cumulative discounted cash flow over time. The text output window displays statistics such as total number of customers in the market, total number of customers purchasing from any company, and the number of sales and flights sold by each company. Diagnostic outputs such as key calculations for the pricing process of companies are also sent to the text output window.

The simulation makes use of the RePast discrete event simulation engine to execute company, market, and customer actions as depicted in Figure 1. A single time step in the simulation represents one year. Thus, companies can only change their price once a year and purchases by customers represent yearly revenues for the companies. In the first year, companies set their price to achieve a desired return on investment. Once all the companies have set their price, information on the spaceflight experience offered by the company, including the price and vehicle characteristics, is passed to the market and the sales process begins.

The process by which companies make sales is the same in every time step. The market collects the price offerings and vehicle characteristics from each company and then iterates through all the customers. In this loop, the company offers are passed to each customer where they are evaluated on the basis of price and the degree to which they meet the needs of the customer. Each customer has an initial probability of purchasing a ticket for suborbital spaceflight that is increased or decreased depending on that customer's own preference for the product offered by each company. Whether or not the customer actually will buy from each company is determined by evaluating the purchase probability and the customer's willingness to pay the asked price. The customer agent returns its buying preferences to the market where supply is matched to demand by distributing customers to the companies according to the buying preferences of the customers. When company supply or customer demand is exhausted, the market returns the number of sales to each company. The companies calculate their financial health and use profit information to evaluate future pricing.

After the first year, the return from different price settings is estimated by the companies. The companies then charge the price which they believe will maximize their future cash flows. Companies evaluate pricing options by probing the market. In probing the market, the company receives an approximation of the sales it would make by changing its price. This estimate is accomplished in the same manner as that described for sales except that only a portion of the total customers are evaluated. This approach simulates limited intelligence about the market.

B. Program Components

The Java classes comprising NESC v0.3 are shown in Table 2 below. All RePast models have a model class and at least one agent class. The NESC Model class extends the RePast 'SimModelImpl' class providing the necessary automatic setup and access to methods necessary to run RePast models. In addition to setup and control of the

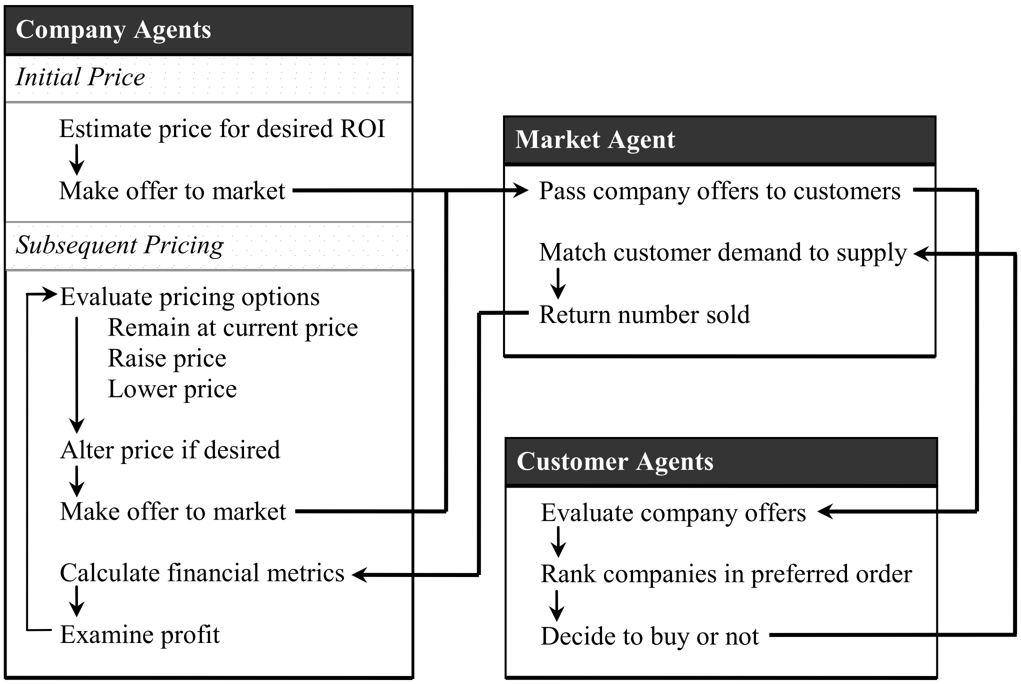

Figure 1. NESC v0.3 Formulation (Suborbital Space Tourism Market Simulation)

discrete event simulator, the Model class contains methods to create and update charts. A main method is also defined in the Model class to make the Model class executable. The NESC 'Space' class simply contains some methods for showing the market and company agents on the display by making use of the RePast 'Object2DGrid'. The NESC Agent class serves as the base class for all agents in the model. It contains a few methods used by all agents and also implements several RePast interfaces for drawing and graphic display.

The Company, the Market, and the Customer classes all extend the base Agent class. The Company and Customer agent classes define the attributes and behaviors of the individual companies and customers. When running the model, the number of companies and customers is specified by the user, resulting in the creation of several instances of the company agent and possibly many thousand instances of the customer agent.

Table 2. Components of NESC v0.3

Class └ Subclass	Description
SimModelImpl	RePast interface for all models
└ Model	Set-up and control of discrete event scheduler
Space	Defines the display
Agent	Imports and methods common to all agents
├ Company	Vehicle definition, price setting, and financials
├ Customer	Algorithm for customer buying decisions
└ Market	Matches customer purchases to company offers

C. Firm Modeling

The simulation assumes the suborbital tourism market is underway with companies already operating. Each company has spent a certain amount of money on development and production of a fleet of suborbital vehicles with certain characteristics. Variables defining these costs and other characteristics of each company and its fleet of vehicles are defined by the user in text input files. Table 3 summarizes the types of variables that define companies in NESC v0.3.

Cost and vehicle variables are fixed in NESC v0.3. Companies have autonomous control over their own price with no knowledge of the price their competitors will charge. As previously discussed, the first year price offered by each company is the price it believes it must charge to achieve its desired return on investment in the specified number of years taking all costs into account. In subsequent years, the decision to raise, lower, or remain at the current price is determined by probing the market whereby the companies receive limited information about the returns for their pricing options.

Table 3. Firm Variables in NESC v0.3

Variable Type	Examples
Development	Development cost, years of operation
Financial	Discount rate, desired return on investment, desired years to breakeven
Operations	Fixed operating cost, operating cost per flight, flights per year
Vehicle	Capacity, reliability, qualitative appeal to customers
Customer Experience	Ability for passengers to leave seat to experience weightlessness, length of training

D. Consumer Modeling

For NESC v0.3 to provide meaningful insight into the suborbital space tourism industry, the customer population must be accurately represented. Three factors are of concern: the size of the potential market as represented by the total number of customers in the model, the willingness of customers to purchase a suborbital flight experience, and the different preferences of each customer. The last two factors are closely related in that a customer's willingness to pay is likely greatly affected by their perception of the product offered in relation to their preferences. In the NESC model, whether a customer will purchase or not is determined by considering these two factors in combination.

Since suborbital space tourism is a new industry, little data is available from actual sales. Data on customer characteristics and behaviors must be determined from market surveys, inferred from other industries, or deduced using intelligent assumptions. One such source is the Space Tourism Market Study conducted by Futron Corporation in cooperation with Zogby International.[15] The market study involved telephone interviews of 450 people with household income of at least US $250,000 annually or net worth greater than US $1 million to examine the size, growth potential, and customer characteristics of the suborbital and orbital tourism markets.

The size of the customer population in NESC v0.3 is a user input. In setting this variable, the user might consider the number of high wealth individuals in the United States or the world. The population can be further limited by considering vacation spending habits, health qualifications, and general interest in suborbital spaceflight in a manner similar to that outlined in the Futron Space Tourism Market Study.

To achieve the increased fidelity that agent-based modeling affords, the characteristics of the individuals that make up the customer population are just as important as the size of that population. Price is certainly one important criteria considered by customers. When customers are created, their price sensitivity is randomly assigned from distributions of the Space Tourism Market Study survey responses. A customer will only purchase from a company if the customer is willing to pay the price charged.

In addition to a customer's willingness to pay, whether or not a customer purchases from a given company is determined by a purchase probability. An individual customer's purchase probability is increased or decreased due to that customer's preferences. For example, one customer may desire the freedom to remove his or her seatbelt at the peak of the flight to better experience weightlessness, whereas another customer may be indifferent to this aspect of the experience. The Space Tourism Market Study survey responses provide insight into the preferences of actual potential customers, and are used in conjunction with other data to define customer preferences in the model.

E. Market Clearing Process

The market agent completes the sales process matching supply to demand by distributing customers to the companies according to their buying preferences. The customers buying preferences are fulfilled in random order on a first-come first-served basis. In some cases a customer may prefer to buy from one company, but also be willing to purchase from a second company. In these cases, if the most preferred company does not have enough capacity, the customer purchases from the second company.

F. Program Operation

NESC v0.3 is archived in a Java JAR executable file for ease of portability and execution. Since RePast and NESC are programmed entirely in Java, NESC will run on nearly all computer platforms and operating systems including Windows PC, Macintosh, and Linux. When opened, the standard RePast toolbar appears. The user can change the values for model parameters such as number of years to run the simulation. The RePast toolbar contains buttons for initialization of the model (Initialize button), advancing a single time step (Step button), and continuously advancing time steps (Start button). When initialized, the display appears along with the output charts. In the display, the user can click on the boxes representing the market and each company to adjust the initial variable values. As the user advances time with the step or start buttons, outputs are displayed in the charts for each time

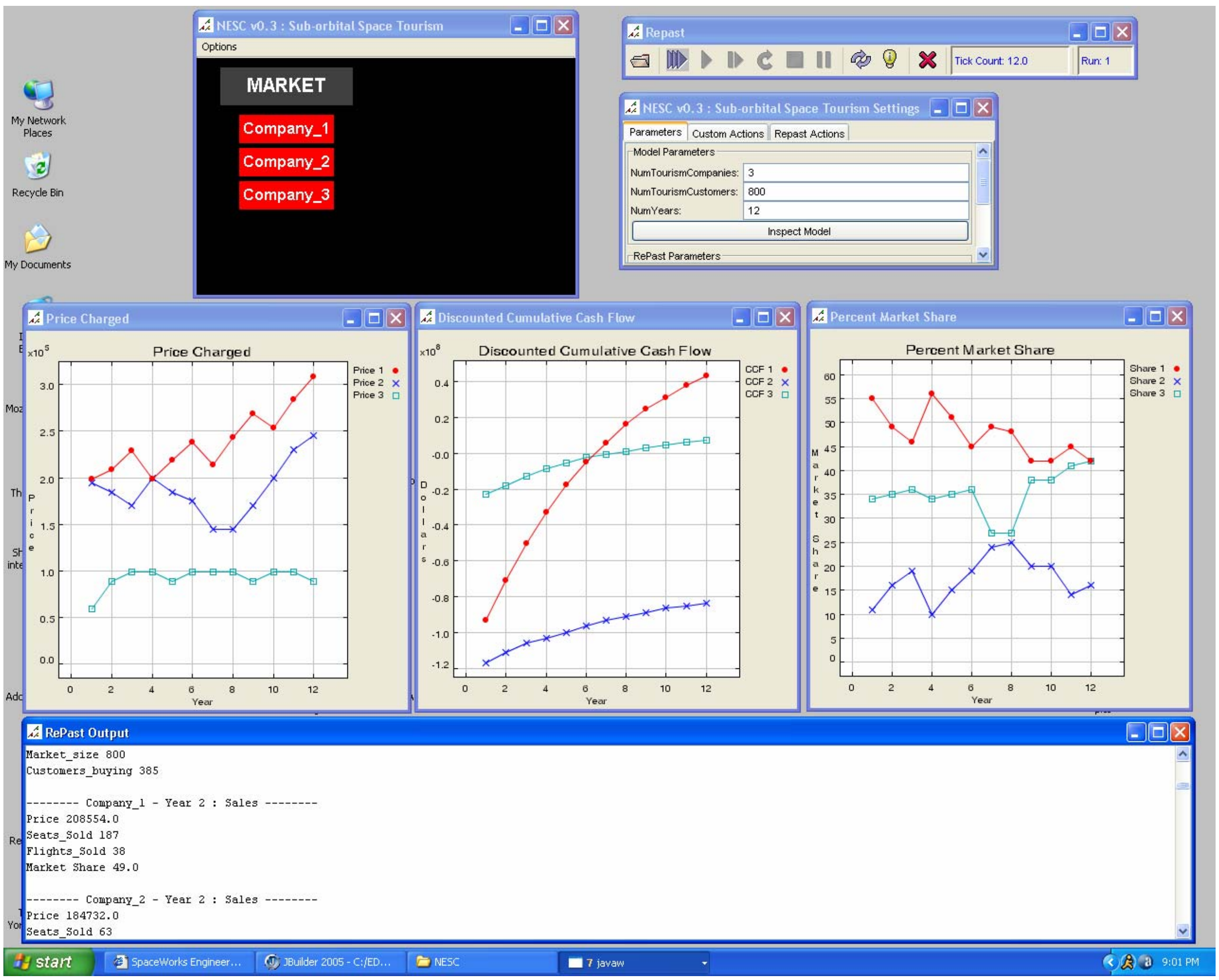

Figure 2. NESC v0.3 (Sub-orbital space tourism market) in RePast Framework on PC Desktop

step. Pause and stop buttons are available for the user to further control the simulation. Figure 2 below is a screen capture of NESC v0.3 on a PC desktop showing the RePast toolbar, NESC display, and major output windows.

VII. Future Development

After the initial space tourism market, the next major case to be examined will be ISS cargo/crew re-supply with agents representing demand (NASA, commercial space) and supply (NASA CEV, European ATV, Japanese H-II, Soyuz, Progress, emerging alternate U.S. providers). This market has been chosen because of recent government policy to allow commercial companies to provide ISS re-supply services in anticipation of a reduction in Space Shuttle availability.

Additional future markets to be modeled in NESC include orbital space tourism, space activities, space solar power, lunar/asteroid resources, etc. Additional financial methods to be implemented in NESC will allow for more insightful determination of company initial price points, allowing companies to enter and exit the market, and allow companies to use higher fidelity financing tools (stocks, warrants, debt financing). The strategies available to company agents will also be expanded to allow company agents to estimate the actions of their opponents, make production decisions to increase fleet size. New agents will also be added to the model, including expressing demand through individual customer agents or groups of customers with unique desires and behaviors (beyond simple market elasticity curves), vehicle production agents, and government agents (with the power to provide tax incentives, anchor tenancy, etc.). NESC has the potential for dynamically modeling the space marketplace in an agent-based software framework. In such an environment there is autonomous decision making by agents, communication between agents, and various price setting strategies. Case studies and expert interviews provide inputs to define company behaviors.

VIII. Conclusions

The Nodal Economic Space Commerce (NESC) model is a dynamic, agent-based market simulation tool of the space marketplace. NESC is of higher fidelity than existing models utilizing more advanced financing, acquisition, and overall decision-making strategies throughout the full supply chain of space products and services (from vehicle developers to operators to consumers). Multiple lessons have been learned from initial development of the NESC model that will help guide future development. Limited exposure of the model to commercial and government viewers has generated genuine interest on the part of the potential of this activity. The timeliness of this activity cannot be understated given the initiatives from commercial industry (e.g sub-orbital space tourism) and new programs within the government to utilize this community (e.g NASA's new Innovative Programs office and the a potential NASA ISS re-supply Broad Agency Announcement). The NESC philosophy allows for a more realistic and dynamic simulation of traditional and emerging space markets. The NESC model is proposed to help determine the shape of future space sustainability that will be reliant on both government actions and commercial competition.

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