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EARTH TO ORBIT LOGISTICS AND SUPPLY CHAIN MODELING AND SIMULATION FOR NASA EXPLORATION SYSTEMS

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ABSTRACT

As exploration operations expand further into space, NASA must enhance its understanding and capability of the increasingly complex "supply chain" management of materials, people, information, and knowledge from sources (somewhere on Earth) to destinations (somewhere in space, e.g. LEO, GEO, Moon, Mars, etc.) and vice versa. Without the ability to understand, define, model, and simulate the supply chain to estimate, project, and affect decision making relevant to the supply chain performance, NASA will find it increasingly difficult to effectively manage this complex supply chain and to work as an informed collaborator with its supply chain partners in the planning, execution, and management of a successful space exploration mission. This paper describes an ongoing project on "the first ever application of 21st century space exploration supply chain modeling, simulation and analysis".

1 INTRODUCTION

A Supply Chain is a collection of several independent enterprises that have been partnered together to achieve specific goals by complementing each other. Each enterprise in the Supply Chain owns several elements including functional units or departments, processes, information, information resources, materials, and objects. Each enterprise, individually, manages these elements in addition to their flows, their interdependencies, and their complex interactions. Since the Supply Chain brings these individual enterprises together to complement each other, the elements in each enterprise have to complement each other and have to be managed together as one unit to achieve the partnership goals efficiently and ultimately customers' and stakeholders' requirements and goals (Fayez 2005). Supply Chain Management (SCM) is defined as 'the integration of key business processes from end-users through original suppliers (one or more tiers) that provide products, services, information and add value for customers and other stakeholders' (Tan 2001). Efficient and effective management of material, Information and financial flows across the Supply Chain is critical to its success and incurred costs. The National Aeronautics and Space Administration (NASA) is designing and building new space transportation systems. These systems will be used to explore the outer space (Lunar surface, Mars, and beyond) and to serve the already existing space functional units (ISS, Hubble Telescope, etc.). This will entail a flow of material, information, services, and finances across all NASA and Non-NASA involved parties on Earth and in space. The different parties involved will operate under a Supply Chain framework, i.e. The Space Exploration Supply Chain.

1.1 Space Exploration Supply Chain

The Space Exploration Supply Chain is defined as "The integration of NASA centers, facilities, third party enterprises, orbital entities, space locations, and space carriers that network/partner together to plan, execute, and enable an Exploration mission that will

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deliver an Exploration product (crew, supplies, data, information, knowledge, physical samples) and to provide the after delivery support, services, and returns that may be requested by the customer. The project described in this paper is aimed towards developing a Space Exploration Supply Chain modeling, simulation, and analysis capability. The tool will deliver a unique strategic analysis capability that will enable system operations analysts and decision makers to understand, estimate, and make informed decisions about the Supply Chain for Exploration and Space Transportation Systems early in the decision making. It is also anticipated to provide quantifiable and sustainable improvements in NASA operations, NASA Supply Chain and logistics operations directed towards Exploration performance goals and budgetary constraints. The Space Exploration Supply Chain is one of the largest chains known to man-kind. This complex Supply Chain brings together a space transportation system for which a usable payload is a small percent of extreme value. It starts on Earth, passes through different locations in space, reaches deep space, ends on a planet or lunar surface, collects samples and runs experiments, delivers back to Earth data and information through the deep space network, and later delivers physical samples back to Earth.

1.2 Paper Outline

In this paper, the methodology is described in section 2. The tool architecture is described in section 3. Finally, the conclusion of the work and the future work will be discussed in section 4.

2 METHODOLOGY

The objective of the project described in this paper is to develop an end-to-end Space Exploration Supply Chain modeling, simulation, and strategic analysis capability focusing on Earth-to-Orbit (ETO) operations. The methodology is delivered as a friendly, yet powerful, software tool that combines state-of-the-art research with innovation and agility, bridging the gap between applied research advances and practice. The methodology consist of an Ontology that imbeds the captured ETO Supply Chain knowledge, a simulation model generator, and a friendly Graphical User Interface (GUI) through which the user will be able to easily build and simulate "what if" operational scenarios. The methodology also includes the means to integrate the tool/model with other initiatives, including NASA Exploration Information Ontology Model (NExIOM). The methodology has been developed and prototyped during phase I; in phase II the tool will be implemented in full. The methodology adopted can be summarized as follows:

2.1 Obtaining an Understanding of Exploration /Space Transportation Supply Chain.

The Space Exploration Supply Chain has unique features and characteristics when compared to other government/commercial Supply Chains. In particular, NASA's Supply Chain is a low volume space transportation system, which delivers (from earth to space locations) human beings, life support items, and other goods using transportation systems that have been designed and integrated to order based on an exploration mission. Deliverables from space to earth include extremely high value information, data, knowledge, and physical samples. The Supply Chain locations are geographically dispersed on earth and in space (all space locations are remote). Locations can be millions of miles apart, which make the Supply Chain very complex with long delivery and transportation (non-value added) lead times. A summary of the features of the Space Exploration Supply Chain identified during Phase I is listed below.

- The "Largest" Supply Chain known to Mankind.
- Extends to locations: remote, no man has gone before, harsh, and uncertain.
- Low volume.
- Reusable and refurbished components.
- Long lead times.
- Mixed models: Engineer to Order (ETO), Make to Order (MTO), and Make to Stock (MTS).
- Supply Chain elements have different roles in different phases.
- The transportation system is ETO/MTO.
- The payload is a very small percent of extreme value.
- Different deliveries at different phases
- International vendor base.
- Long term phased implantation plan.
- Uncertain costs.

These features, and more will be explored in more depth to derive a better understanding of the Space Exploration Supply Chain which will enable the project team to draw conclusions and find commonalities between Space Exploration Supply Chain and other commercial/government Supply Chains. These commonalities can surface Supply Chain best-practices which can be applied to NASA's Supply Chains. A high level representation of the end-to-end Space Exploration Supply Chain is shown in Figure 1.

2.2 Obtaining a Structured and Explicit Definition of the Supply Chain

The first and arguably the most important step in modeling and analyzing a Supply Chain is to define the Supply Chain in such a way that would capture and define, generically, all the constituent parts. That involves a comprehensive definition of, at least, the following:

- ***Processes**:* An explicit definition of all the planning, execution, and enabling processes in the Supply Chain. These processes must span from customer requirements and orders to the receipt of the order to the after-delivery services. Standard processes such as the Supply Chain Operations Reference Model (SCOR Model) processes were used (SCC 2003).
- ***Performance Measures:*** All the necessary Key Performance Indicators (KPIs) that will enable NASA to measure and assess its Supply Chain performance. Standard metrics such as SCOR metrics will be used. In conjunction with the Figures of Merit (FOM) defined in the **Exploration Systems Architecture Study (**ESAS) study (NASA 2005).
- ***Material Flow:*** All the materials, their transitions, and their flows in the Supply Chain upstream to downstream that were used to realize the final deliverables. The material flow should span from suppliers' suppliers to customers' customers.
- ***Information and Information Flow:*** An explicit definition of all the information necessary to plan, execute, and enable the Supply Chain, the information to measure the performance of the Supply Chain, and the information necessary for the flow of the materials or other objects (e.g. Orders, requests, or Invoices) across the Supply Chain. The information, information flow, and information interdependencies should span from suppliers' suppliers to customers' customers.
- ***Information and Processes Interdependencies:*** The interdependencies between the information, interdependencies between the Supply Chain processes, and the interdependencies between the information and the processes. It should span from suppliers' suppliers to customers' customers.
- ***Objects Flow:*** An explicit definition of all the objects such as orders and invoices, their transitions, their flows, their interdependencies and interactions across the Supply Chain. It should span from suppliers' suppliers to customers' customers.
- ***Information Resources and Application Systems:*** An explicit definition of all the information resources and enterprise application systems that exist in the Supply Chain, the information that resides in these systems, the date structure or schemata of this information, and the information resources interactions with the Supply Chain processes. This should span from suppliers' suppliers to customers' customers.
- ***Decisions:*** The Supply Chain decisions that are necessary for the planning, execution, and management of the Supply Chain, the information required for these decisions, and the decision making processes.
- ***Complex Interactions:*** All the interactions between the Supply Chain partners, Supply Chain partners' functional units, Supply Chain processes, material, objects, information, decisions, information resources, enterprise application systems (e.g. SAP, IAM). The interaction should cover from suppliers' suppliers to customers' customers.
- ***Best Practices:*** The best practiced techniques, operational procedures, business models, or technology that might affect the performance of the Supply Chain processes and the effectiveness of managing it. Also the interdependence and prerequisites of these best practices has to be identified and defined.

In order to define the supply chain as entailed above, different supply chain views/models were developed. A comprehensive review of available business modeling techniques and information modeling techniques was carried out during Phase I. The focus of this review was to find standardized models and modeling techniques able to capture and generate the required Supply Chain views. Two suites of models were found that cover most of the modeling require-

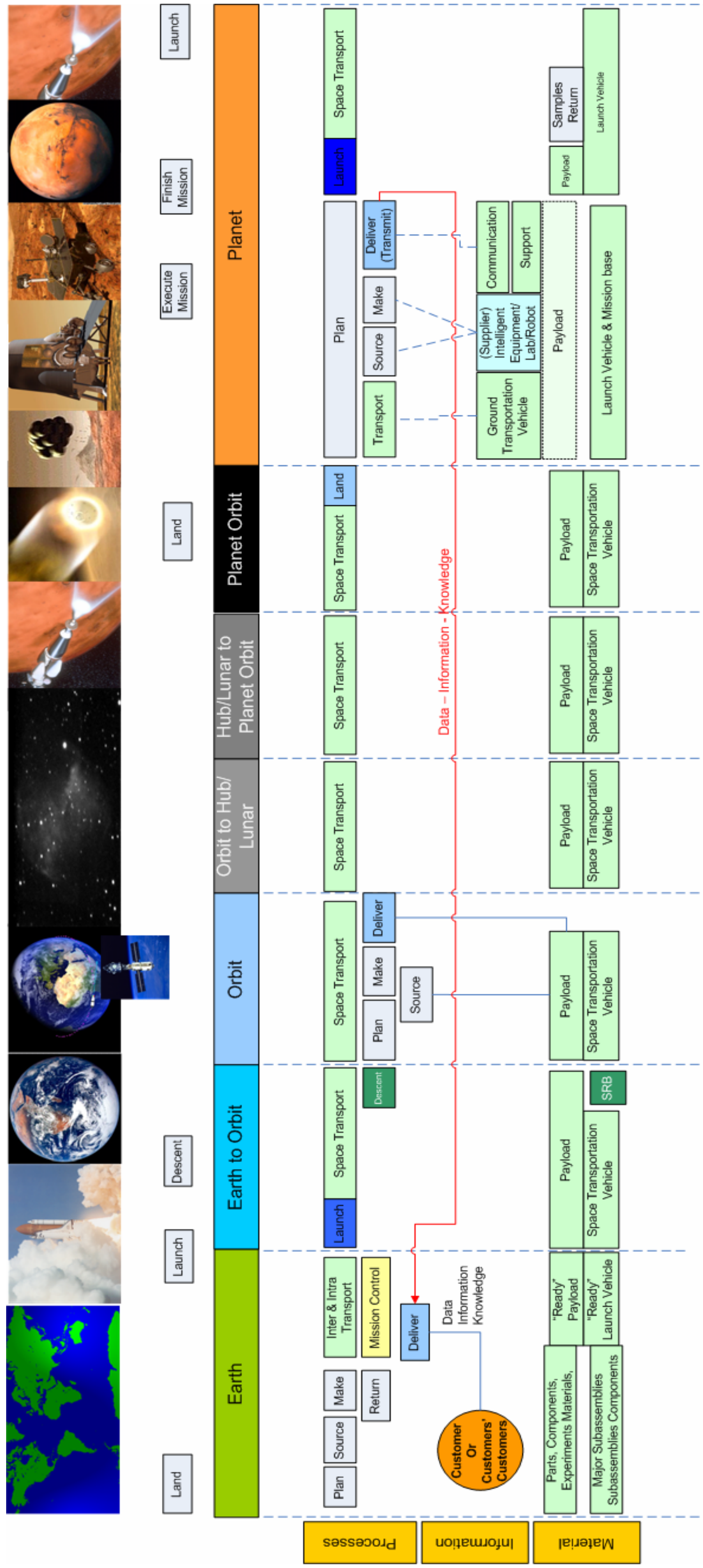

Figure 1. High Level End-To-End Space Exploration Supply Chain

ment. These two suites are the Integrated DEFinition (IDEF) family (KBSI 2003) and Unified Modeling Language (UML) family (OMG 2003). The review of the specifications of both suites concluded that both suites offer similar modeling capabilities.

The suites provide process flow models, functional models, material and objects flow models, information and information flow models, and schema models. Other modeling techniques that were used to develop the other views are the Supply Chain network diagram, geographical maps, the thread diagram, cross-functional diagram, product structure, and objects structure. Finally, the interdependence modeling requirement is fulfilled by the Design Structure Matrix (DSM) which has been used successfully in information intensive projects (Fayez *et al* 2003). The various views generated signify a formal representation of a specific aspect of the Supply Chain where his ultimate use of any of these views is to *answer* specific questions, where the answers will collectively build the comprehensive definition of the Supply Chain. Geographical maps and Supply Chain networks capture the Supply Chain. The Supply Chain network is formed of connected nodes, where each node represents a Supply Chain partner. The network is constructed around a focus enterprise.

2.3 Obtaining a Coherent Integration of the Different Views Defined.

The different Supply Chain views were developed separately, one view at a time. The views were then used to derive the ten elements enabling the comprehensive definition and model of the Supply Chain at the four levels (Supply Chain, Enterprise, Functional Unit, and Element). Since each view is explicitly defining specific aspects of the Supply Chain, a comprehensive definition is realized by integrating these views. The Supply Chain Ontology provides the capability to integrate the SCOR model and the different Supply Chain views in a coherent representation. The Ontology is constructed to enable the user to extract a specific Supply Chain view or knowledge, such as information view. It also provides the capability to extract a specific Supply Chain knowledge that spans over different views, such as the information required for a specific Supply Chain process. Supply Chain Ontology enables the Supply Chain definition to be machine understandable regardless of the machine platform or technology. Finally, Supply Chain Ontology enables the reusability of specific concepts in a restricted way, such as reusing the Supply Chain Ontology or part of it for a specific Supply Chain scenario, e.g. ETO Supply Chains.

2.4 Defining and using Supply Chain Key Performance Indicators.

All the necessary Key Performance Indicators (KPIs) enabling NASA to measure and assess its Supply Chain performance are defined. The definition of the KPIs utilizes the 250 metrics defined in the SCOR-model. Also the KPIs are integrated with NASA Figures of Merit (FOMs), described in the ESAS) Study. The SCOR-model has categorized the Supply Chain performance measures into five categories. These five categories are Reliability, Responsiveness, Flexibility, Cost, and Asset Management. The SCOR model considers each category as a performance attribute that can be used individually to evaluate any Supply Chain performance that lies within this attribute. These performance attributes are supply chain delivery reliability, responsiveness, flexibility, costs, and asset management efficiency. he Figures of Merit (FOMs) are categorized into five categories. These five categories are **Safety and Mission Success**, **Effectiveness/Performance**, **Extensibility/Flexibility**, **Programmatic Risk**, and **Affordability**. These FOMs are integrated with SCOR level one metrics and are modeled in the ontology and the simulation, in such a way to be aggregated from the model generated statistics and reported side-by-side with the KPIs.

2.5 Obtaining an end-to-end Supply Chain Simulation and analysis Capability.

We have developed a capability to build a simulation model that represents an end-to-end Space Exploration Supply Chain operational scenario. The users interact with a graphical user interface to define the Supply Chain at a high level utilizing the knowledge/information in the Ontology. This triggers the generation of session files developed in Arena® simulation language. The baseline session file represents the "as is" simulation model of the Supply Chain. The user can also generate "what-if" scenarios by modifying the baseline session file through the user interface. The what-if session files represent the "to be" simulation models of the Supply Chain. Also at this point, the required data is extracted from their perspective sources, and the user is prompted for any input modeling preferences. The user is also prompted for the output required and the structure of the report. The current state "as is" base model is the first simulation model to be generated and executed, the output of the simulation run represents the base line or the current Supply Chain (financial and non-financial) performance. The model information and the simulation output are saved in an XML session file. The simulation models are verified and validated according to

NASA's V&V procedures. The complete (logic and V&V) simulation and analysis capability enables the operational analysts to analyze what-if cases of priority Constellation program as per the agency or strategic management requests.

2.6 Obtaining a Flexible Report Generation System.

A capability is built in the GUI to select the KPIs and FOMs to be computed and reported in the final report. The user has the capability to select any combination of KPIs and FOMs to be computed during/after the simulation run and reported in the final report. The report is generated for one simulation scenario or multiple scenarios where they can be compared side by side against the pre-selected KPIs and/or FOMs. The report includes text, tables, and graphics, which the user selects after the simulation run. The user is able to change the final representation of the report without the need to re-run the simulation model.

2.7 Interface and Integrate with other models, projects, and initiatives

An important part of the project and the software underdevelopment is the interface and integration with existing models and other Supply Chain Initiatives, such as GEM-FLO (Mollaghasemi *et al* 2002) and Analysis area 11B described in ESAS study (NASA 2005). The integration is done using the already existing integration Platform, i.e. NExIOM.

3 ARCHITECTURE

A simplified architecture of the tool that automates the methodology is shown in Figure 2:

The major parts of the architecture are the Ontology, the graphical user interface (GUI), and the simulation model generator. The first part is the ontology, which consists of classes, properties, and instances. The classes and their properties were developed during Phase I.

The main purpose of the Ontology is to facilitate the knowledge capture from the geographically distributed Supply Chain and logistics network. It captures the widest view of the system, logically divided into different representative views. The ontology is developed using XML (eXtensible Markup Language), as the semantic web standard languages (W3C 2003).

The second major part is the Graphical User Interface (GUI), which is the interface between the user and the decision support system. The user uses the interface to

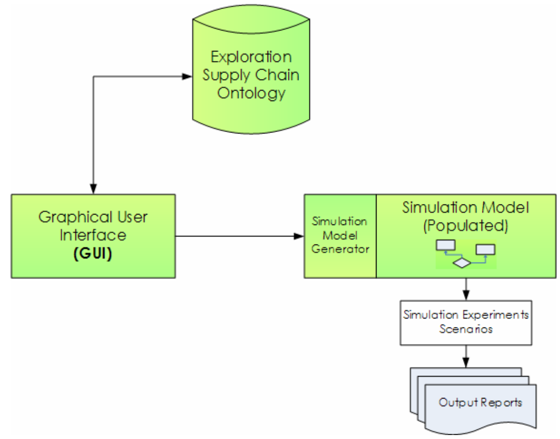

Figure 2. Simplified Software Architecture

define a Supply Chain operational scenario or access an existing pre-generated session file. The user defines at a high level, and then the details (relationships, interactions, etc.) are automatically extracted from the knowledge imbedded in the ontology. The interface is also used to select the KPIs/FOMs to be computed in the simulation model and the output report settings. The defined scenarios trigger the creation of the logic and the structure required for the creation of the current system simulation model, i.e. "base-line or as is" model and each new operational alternative defined triggers the generation of a new scenario.

The third major part is the simulation model generator, where the settings defined in the GUI at a high level trigger the generation of the simulation models, including baseline scenario and what-if scenarios. Generation of simulation models involve the development of the structure and the logic of the simulation model automatically from the pre-captured knowledge in the Ontology. The Simulation model can be modified to generate several scenarios. The user is able to make changes to the baseline model through the GUI and to save these changes in a different session file. The user is then able to output the session file information and run the simulation scenarios.

4 CONCLUSION

The first phase of the project has been completed successfully. As a result, prototypes for the ontology, the graphical user interface, and the simulation model have been developed. A scenario was generated using the Solid Rocket Booster (SRB) Supply Chain as a proof of concept. The continuation of the project has been awarded by NASA.

REFERENCES

Fayez, M. 2005. An automated methodology for a comprehensive definition of the supply chains using generic ontological components, *Dissertation*, University of Central Florida.

Fayez, M., P. Axelsson, and Y. Hosni 2003. Information intensive projects: planning and optimizing using the Design Structure Matrix (DSM),. *Paper presented at the 2003 Industrial Engineering annual conference,* Portland, Oregon.

KBSI. 2003. Integrated DEFinition methods IDEF. Available via <http://www.kbsi.com> [accessed March 11, 2006]

Mollaghasemi, M., M. Steele, G Rabadi, and G. Cates. 2002. A Generic Environment for Modeling Future Launch Operations (GEM-FLO). World Automation Congress, June 2002, Orlando, Florida.

NASA. 2005. NASA's Exploration Systems Architecture Study, from <http://www.nasa.gov/mission_pages/exploration/news/ESAS_report.html> [accessed May 15, 2006]

OMG. 2003. Unified Modeling Language (UML). <http://www.uml.org> [accessed December 20, 2005]

SCC. 2003. Supply Chain Operations Reference (SCOR) Model V.6.0.

Tan, K. 2001. A framework of supply chain management literature. European Journal of Purchasing & Supply Management, 7, 39-48.

W3C. 2003. *World Wide Web Consortium- Semantic Web*. Retrieved 2003 <http://www.w3c.org> [accessed January 10, 2006

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