Agent-based Simulation of Shuttle Mission Operations

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Abstract

A human-centered work process modeling project at NASA's Mission Control Center is presented. The approach uses NASA's agent-based modeling and simulation tool called Brahms. Brahms is a multiagent BDI-like modeling language and simulation environment. The objective of the project is to show how detailed agent-based modeling and simulation can be used in the analysis and design of new mission operations work processes at NASA. MODAT is the work analysis and design decision-making tool developed as an integration of Brahms and Microsoft Excel for both model design input, and simulation statistics output.

1. INTRODUCTION

The Work Systems Design & Evaluation group at NASA Ames Research Center is engaged in modeling and simulating mission operations at NASA Johnson Space Center (JSC). The objective of the project is to show how detailed mission operations modeling and simulation can be used in the analysis and design of new mission operations at JSC. Our human-centered work systems design approach [1, 2] combines workplace observation (e.g., Luff, Hindmarsh, & Heath, 2000) and agent-based modeling and simulation of current and future work processes and practices. This paper reports on an application of human-centered work systems design[1], bringing agent-based computer simulation of a human-machine work system as a rigorous systems engineering tool in the design of NASA's mission operations.

1.1. Challenges to develop new Mission Operations

The Mission Operations Directorate (MOD) at JSC is currently supporting three programs, the Shuttle, the International Space Station (ISS) and Constellation[2].

These three programs are in different phases of their life cycle: Shuttle in the beginning of its phase out, ISS in the late build-out phase and Constellation in its early design phase. Although there are some common work functions between Shuttle and ISS, there is a need to distill the best practices out of both of these programs in order to lower the operational risk and cost of the Constellation program. MOD is committed to classical analysis and "lessons learned" to accomplish this, but has identified an opportunity to leverage an emerging technology—agent-based modeling and simulation of work processes.

Why is this an important initiative? In a single word, it is automation, a cornerstone in the Constellation program cost control. The Constellation program, starting with the Crew Launch Vehicle and Crew Exploration Vehicle (CLV/CEV)[3], is a technology infusion program for NASA. The work process modeling initiative provides the capability to judiciously consider automation of processes that traditionally took people to execute. The choice can now be made as to a function being in situ, on-board, or remote in a control center. However, there is a fundamental requirement for information that must be met to execute this initiative. That is the analytic understanding of the work and

[1] The BPM and BI communities are starting to call this "human-centric business process modeling." However, our approach is long founded in the Scandinavian tradition of participatory design, workplace observation and work practice [3].

[2] "Constellation is the combination of large and small systems that will provide humans the capabilities necessary to travel and explore the solar system" from http://exploration.nasa.gov/constellation, 10/26/2006.

[3] NASA renamed the CLV to Ares and the CEV to Orion.

associated work processes.

To be successful, work process analysis must be detailed beyond what is essential to complete the role of MOD in missions executed today. NASA as an agency is targeting a significant reduction in the processing, configuration for flight, and flight management systems as a means of achieving cost effective exploration systems, within acceptable risk boundaries that can continue to evolve as the mission of exploration unfolds.

Continual assessment and evaluation against metrics must be performed, if automation and significant movement of critical flight processes are integrated within the Constellation systems and vehicles. The required step is building a sufficiently detailed model that facilitates flight process redesign and assessment, while controlling risk. In an effort to avoid undue complexity and yet have an analytic model of the work process, MOD embarked on a prototype project that evaluated a potential tool referred to as MODAT, Mission Operations Design Analysis Tool. MODAT would enable MOD to continuously conduct assessments as shown in Figure 1 [4].

1.2. Intro to MODAT and its objective

At last year's ADS conference, we presented an environment for analyzing and designing mission operations called Mission Operations Design and Analysis Tool (MODAT) [5]. MODAT is an environment for simulating planetary surface missions end-to-end by integrating several simulation environments. In this paper we describe the use of the Brahms multiagent simulation environment [1, 6] to model and simulate JSC's MOD organization, and the work performed during the Shuttle pre-launch through docking phases with the International Space Station. The objective of this effort was to validate our Brahms simulation approach for analyzing the work of flight controllers in MOD in order to 1) understand their work, i.e. activities on console, communication over the voice loop4, interaction with systems and the Shuttle, and 2) to optimize the workload of flight controllers. This not only supports the Shuttle program in the near term, but addresses the focus of MOD in the Constellation program. The output of the simulation is a detailed time line of the flight controllers' activities and communication and metrics of different work activity and workload.

[4] A voice loop is a method by which multiple people may listen or broadcast on multiple channels, thus allowing different roles to monitor and address different groups simultaneously [7].

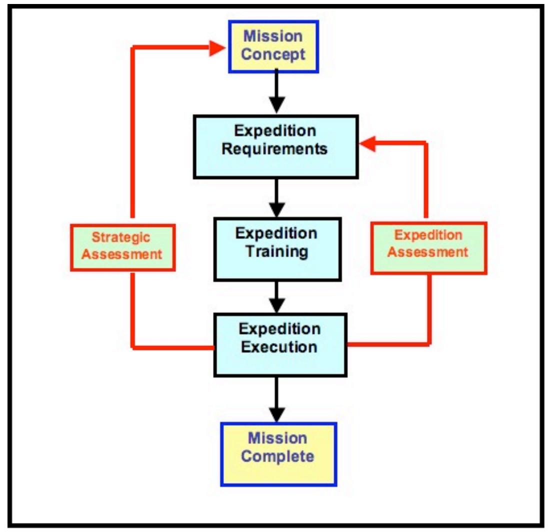

Figure 1. Mission Life-Cycle

This paper discusses the Brahms model and simulation, as well our method for model development. We start by describing the Shuttle launch to docking with ISS phases. We then describe the steps in our collaborative modeling effort and the results of a two-day modeling workshop with MCC Shuttle flight controllers. Next we describe the Brahms agent-based model and simulation output. We conclude with lessons learned.

2. OTHER RELEVANT WORK

Business process modeling (BPM) became "fashion" during the early nineties, with the advent of business process re-engineering (BPR) [8]. At that time different BPM tools were developed and used in business. Today, there are a fair number of BPM tools that are based on the rigorous theory of parallel or distributed communicating automata called Petri Nets [9]. Petri Nets are most often used to model workflow and implement workflow system engines [10]. Petri Nets are complex state transition diagrams and can model most imperative programming concepts, such as sequence of actions, conditional and loop statements. Since Petri Nets can easily model concurrent tasks, one could actually argue that any multi-agent model can also be modeled as parallel Petri Nets. Indeed, Petri Nets have been used extensively for parallel programming [11]. Brahms, however, is a different type of agent language. Brahms agents are BDI-like (Belief-Desire-Intention) agents [12]. BDI agents use a declarative programming paradigm. Most declarative programming paradigms are logic or rule-based, and so is Brahms. It is well known that a rule- and belief-based paradigm is more suited to model human behavior than an imperative paradigm [13]. Therefore modeling organizations of people in "human-centric" work processes is easier done with Brahms than with Petri Nets. This is key to the introduction of automation in the operations of space missions.

The Business Process Modeling Notation (BPMN) is a standard graphical notation for drawing business processes as workflows [14]. BPMN is based on a workflow paradigm. In [6], chapter 2.1 discusses the problems with modeling people's behavior with a workflow paradigm. Simply put, workflow models do not allow modeling how people really work. However, the BPMN notation can be used to model the tasks of different roles in an organization (using so called "pools" and "swim lanes") and is one of the modeling frameworks that could be used to statically represent a partial Brahms model. The BPMN modeling framework, however, does not allow for the representation of an agent's beliefs and the reasoning with these beliefs. BPMN models also cannot represent the locations and places where activities that people perform are taking place.

3. FROM LAUNCH TO DOCKING WITH ISS

In our discussions with JSC, we modeled the current mission operations for Shuttle flights, because such a model will be applicable for future designs of mission operations. In particular, we agreed to model mission operations activities of flight controllers within MOD during a Shuttle mission starting from the launch of the Shuttle from Kennedy Space Center (KSC) to its docking with the ISS.

During discussions with several flight controllers, we created definitions for several flight phases of the Shuttle. These flight phase definitions gave us a common understanding for developing a detailed model.

The following serves as background information on MOD operations for understanding the more detailed modeling descriptions that follow. Figure 2 depicts our definition of Shuttle flight phases, from pre-launch to docking with the ISS.

The *Pre-Launch Phase* involves all the preparation activities that the flight controllers perform prior to the Shuttle liftoff from the launch pad at KSC. Typical activities involve planning for the mission, checking all the equipment on-board the Shuttle, etc. This phase also includes the countdown where the Shuttle's rockets fire and the Shuttle is waiting to liftoff.

The Launch Phase begins once the Shuttle leaves the launch pad. As the Shuttle is ascending, the Solid Rocket Boosters (SRB) and Main Engines (ME) are firing and being monitored by flight controllers. After the fuel in the SRBs is consumed, flight controllers signal for them to separate from the Shuttle's External Tank (ET). Parachutes attached to the SRBs are opened and they plunge into the ocean. The Shuttle reaches "main engine cut-off" (MECO), eight minutes after lift-off, when it is in an orbit approximately 28 X 100 miles above the Earth's surface, ending the Launch Phase.

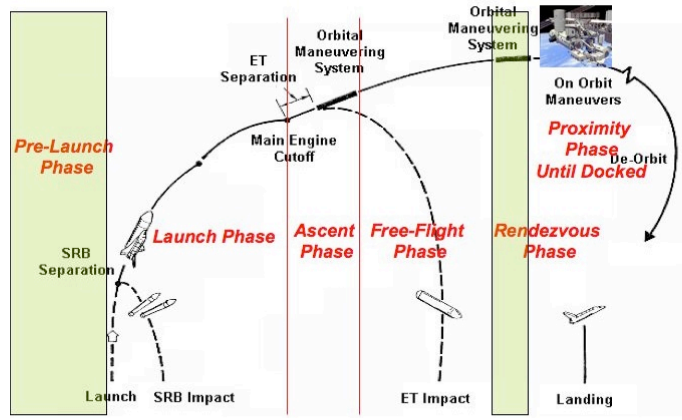

Figure 2 Flight Phases of Shuttle (based on Benton, 2006)

The Shuttle is in its *Ascent Phase* after MECO. The ET's fuel consumed, the General Purpose Computer (GPC) flight software gives the command to separates from the Shuttle. The ET enters the Earth's atmosphere and disintegrates. The crew / GPC use the Shuttle's Orbital Maneuvering System (OMS) engines to circularize the orbit, moving into an orbit close to the ISS

Once in a circular orbit, the crew opens Shuttle Cargo Bay Doors. The Shuttle is then in its Free-Flight Phase. The shuttle will continue in its flight trajectory, controlling its attitude with a series of carefully designed engine burns to "catch up" to the ISS. The Shuttle will continue to be in this phase for about 48 hours until it approaches the ISS.

When the Shuttle is several miles form the ISS, the Rendezvous Phase begins. Before the launch, the flight controllers nominally select the day of Rendezvous. During the Rendezvous Phase, flight controllers use precisely timed RCS (Reaction Control System) burns to steer the spacecraft toward specific "targets" so that the Shuttle is close enough to the ISS for the astronauts on-board to manually maneuver the spacecraft and dock with the ISS.

When the Proximity Phase begins, the astronauts on-board the Shuttle take over to manually maneuver the spacecraft. During this phase, the Shuttle is very close to the ISS and the astronauts have a visual sighting of the docking target of the ISS. Once the spacecraft is in contact with and secured to the ISS, it is in its Docking Phase.

4. MISSION OPERATIONS ANALYSIS

We held a two-day Work Process Modeling workshop at MOD. The workshop was part of a "knowledge acquisition" exercise of mission operations at JSC. The objective of the workshop was to learn as quickly as possible (in two days), as much as possible (talking to as many subject matter experts as possible) about the work process in the Space Shuttle Flight Control Room (FCR) at JSC.

We used the Compendium collaborative modeling approach [15]. This approach is based on a method and a tool for modeling work processes, together and interactively with subject matter experts (SME). The method is called conversational modeling [16]. In this method a group facilitator focuses the discussion with SME's on a particular scenario relevant to the work process. In this case we used a scenario of a Shuttle launching and docking with the ISS (see previous section). We limited the discussion around this scenario. The objective of the facilitated discussion was to model the work a SME is doing within the scenario. Compendium is essentially a multi-media hypertext database, specifically geared towards capturing and representing information for projects.

During the two days, several Shuttle flight controllers and some of their managers were interviewed. These were our SMEs. During a SME session, the first author facilitated a discussion about the SMEs work during the pre-launch-to-docking scenario. The sixth author in real-time, using Compendium displayed on a large LCD projection screen, modeled this discussion. The modeling approach followed a kind of question-and-answer format, in which detailed process and data flows were generated, as well as specific work activities, interaction with systems and communication with other flight controllers.

The workshop resulted, collaboratively with the SME's, in a model of the work of six fight controller positions during the pre-launch to docking phase of a Shuttle mission5: the Booster Systems Engineer (BOOSTER), Flight Dynamics Officer (FDO), Proximity Engineer (PROX), Propulsion Engineer (PROP), Flight Activity Officer (FAO), and Data Processing Systems Engineer (DPS). These static Compendium hypertext models served as input for the development of a detailed agent-based work process simulation. For this we used NASA Ames' Brahms multi-agent modeling and simulation environment. One Brahms modeler developed this agent-based simulation over a three-months period, working about 75% of his time on the project. The simulation enabled us to generate relevant metrics about the current work process. After the simulation development phase, we held a SME workshop, to verify and validate the models., resulting in improvements in the simulation model.

In the following sections we discuss the Brahms agent-based model for the FDO and FAO flight controllers.

5. BRAHMS MODEL

Based on the mission operations analysis described in the previous section, we developed the Brahms model. The Brahms model can be subdivided into an Organization model, a Geography model6, an Object/Data model, an Activity model, and a Communication model.

5.1. Organization Model

MOD Flight Controllers are organizationally in the Mission Operations Directorate (MOD) organization of JSC. Flight Controller roles are subdivided into organizational groups. A number of groups together make up a MOD branch. Divisions within MOD are made up of a number of branches. The MOD organization is modeled using the Brahms concepts group and agent.

In Brahms, a group can be a member of other groups. An agent, similarly, can belong to one or more groups. These two modeling concepts, plus their inheritance rules are sufficient to model the various divisions, branches, groups, roles and activities of people within MOD.

Brahms agents—such as the Ascent Flight Dynamics Officer (FDO), Rendezvous Dynamics (DYN) and Launch Flight Activities Officer (FAO)—have roles and responsibilities during Shuttle flight mission operations for our scenario.

During Launch Phase, the FAO updates the timeline based on mission events, and provides attitude and pointing support to other flight controllers. The Ascent FDO is responsible for all trajectory processing, ensures that flight rules are satisfied, and updates the abort and contingency plans during the Ascent Phase. The Rendezvous DYN, provides support to the Rendezvous FDO, computes and evaluates both ground and on-board targeted burns, and evaluates contingency situations during Rendezvous Phase.

5.2. Activity Model

Based on what the flight controllers told us that regarding their time "on-console", we created a model of their activities. Our model is a work practice model, but is subject to the well-known problem that what people say they do may not be what they actually do. A validated work practice model would be created based on actual observed activities of the flight controllers during an actual mission or high-fidelity mission simulation. However, in this prototype project we did not have time to do work place observations. Nevertheless, Table 1 shows model input for the activities performed by the Rendezvous Flight Dynamics Officer (FDO). Each phase of the Shuttle flight from launch to docking with the ISS is modeled as a Timeline Activity. Within each Timeline Activity, a relative priority can be specified for each activity and also maximum and minimum durations to complete an activity.

5.3. Object/Data Model

We also modeled data that the flight controllers process and analyze when they perform their activities. For example, when the Rendezvous FDO performs the activity Calculate Burns mentioned in the activities model (Table 1), Rendezvous FDO needs the orbit length flight rule from the Rendezvous Constraint Table and then updates the Detailed Maneuver Table, etc.

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[5] For a description of flight controller positions see http://en.wikipedia.org/wiki/Flight_controller

[6] We cannot disclose details of the MCC geography model, which represents workstation layouts on rooms in buildings.

5.4. Communications Model

Another source of information that gave us a better understanding of the work processes of flight controllers during the Shuttle flight phases came from a recording of the voice loops between flight controllers [7]. We transcribed communications between flight controllers during the Shuttle rendezvous with the ISS of Shuttle mission STS-96. Table 2 shows an example of the voice communications that we modeled in Brahms.

6. BRAHMS SIMULATION

Brahms Agent Viewer is a visualization and analysis tool that allows a user to display the behavior of modeled agents and objects on a simulated timeline. In Figures 3 and 4 we show examples of what a user can visualize and analyze using this tool.

6.1. Shuttle Flight Phases

Figure 3 shows a Brahms Agent Viewer screen showing a timeline view of the Shuttle on the launch pad at KSC during its Pre-Launch Phase, then its lift-off at Launch Phase ascending to an Earth Orbit 28 X 100 miles high, and changing to its Ascent Phase when it reaches an Earth Elliptical Orbit (120 X 85 miles). At the same time, two agents, namely, Ascent FDO and Launch FAO are performing activities as the spacecraft passes through its different phases over time. For example, during the Ascent Phase the Ascent FDO is working on Calculate Available OMS Gas while the Launch FAO is just Monitoring Ascent. Similarly, at Pre-Launch Phase, Launch FAO is Checking Orbital Communications Adapter.

Timeline Activity	Activity Name	Priority	Min Duration	Max Duration
Free Flight Phase	Rendezvous Plan Refinement	50	1800	3600
Rendezvous Phase	Monitor Station Health	100	900	1800
Rendezvous Phase	Monitor Shuttle Health	100	900	1800
Rendezvous Phase	Process Ground Nav Data	80	900	1800
Rendezvous Phase	Process On Board Sensor Data	80	900	1800
Rendezvous Phase	Calculate Burns	60	900	1800
Rendezvous Phase	Execute Burns	50	900	1800
Rendezvous Phase	Monitor For Breakouts	20	1800	3600
Proximity Phase	Monitor Crew Relative To Nominal Trajectory	500	1200	1300
Proximity Phase	Monitor On Board Sensor Data	400	1200	1300
Proximity Phase	Monitor Station Health Prox Phase	300	1200	1300
Proximity Phase	Monitor Shuttle Health Prox Phase	200	1200	1300
Proximity Phase	Monitor For Breakouts Prox Phase	100	1200	1300

Table 1. Rendezvous Flight Dynamics Officer Activities Model Input (time in seconds)

Recording Time	Communications	Which Voice Loop?	From	Communicate With	Communicated To Location
11:20:41 PM	Ask For Orbit Flight Rule	Flight Dynamics Front-to-Back Support Loop	Rendezvous FDO	DYN	MPSR
11:21:38 PM	Provide Orbit Length Flight Rule	Flight Dynamics Front-to-Back Support Loop	DYN	Rendezvous FDO	FCR
11:39:11 PM	Configure Orbit Length	Flight Dynamics Front-to-Back Support Loop	Rendezvous FDO	DYN	MPSR

Table 2. Voice Loop Communications Model Input

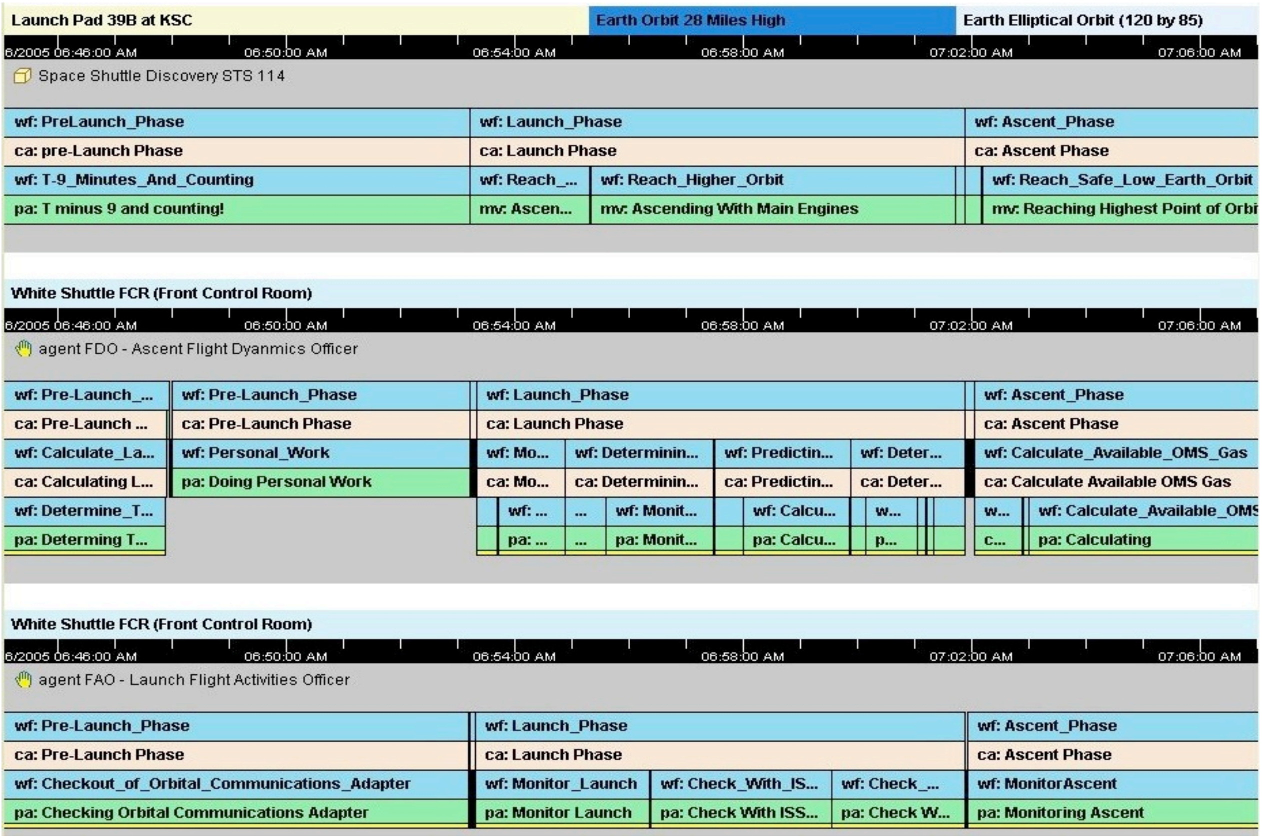

Figure 3. Brahms Activity Timeline Output for Shuttle Discovery STS 114, Ascent FDO and FAO

6.2. Data Communications

As mentioned in a previous section, we modeled data that flight controllers use in performing their activities. The data FDO needs to perform a single activity of calculating the "length of launch window" prior to launch of Shuttle is simulated as FDO "reading" the information from the different data objects. The Agent Viewer shows communication as arrows that indicate the direction of the communications (i.e., who originated the communications). For example, the FDO "reads" from the Paperless Mass Props (PMP) object the Shuttle and ISS mass properties, the Vector Admin Table object provides Shuttle's state vector and the Weather Data object gives the weather conditions at KSC.

6.3. Voice Communications

As mentioned, we also modeled the voice communications between flight controllers talking on voice loops, similar to ham radios. Figure 4 (corresponding with Table 2) shows the activity output from simulating voice loop communications during the Rendezvous Phase of flight, which is when the spacecraft is very close and approaching the ISS. The Rendezvous FDO and Rendezvous Dynamics Officer (DYN) are located in different rooms. Rendezvous FDO is located in the Flight Control Room (FCR) and DYN is located in the Multi-Purpose Support Room (MPSR). Rendezvous FDO is asking DYN for the Orbit Length Flight Rule via the Flight Dynamics Front-To-Back voice loop. DYN answers to FDO, on the same voice loop, and gives the requested flight rule requested.

6.4. Analysis of Simulation

Besides viewing the output of the simulation using the Agent Viewer, the output of a Brahms simulation is stored in a database, which can be queried to perform statistical analysis.

For example, we asked, "What is the Ascent FDO doing 3 hours before launch?" To answer this question, we first assigned a category to each activity. For example, all activities that involve analyzing spacecraft sensor data, performing calculations to derive spacecraft orbits, flight paths, etc. were categorized as Analysis. Activities that FDO performed that involved checking spacecraft components, validating software functions, etc. were categorized as Checking. We then ran a simulation, queried the data from the database into a spreadsheet and plotted a pie chart. The pie chart in Figure 5 shows that the Ascent FDO spends the majority of the time (64%) performing activities that involves Analysis during Pre-Launch Phase. Conversely, the Ascent FDO spends the least amount of time (2%) performing activities that involve Planning.

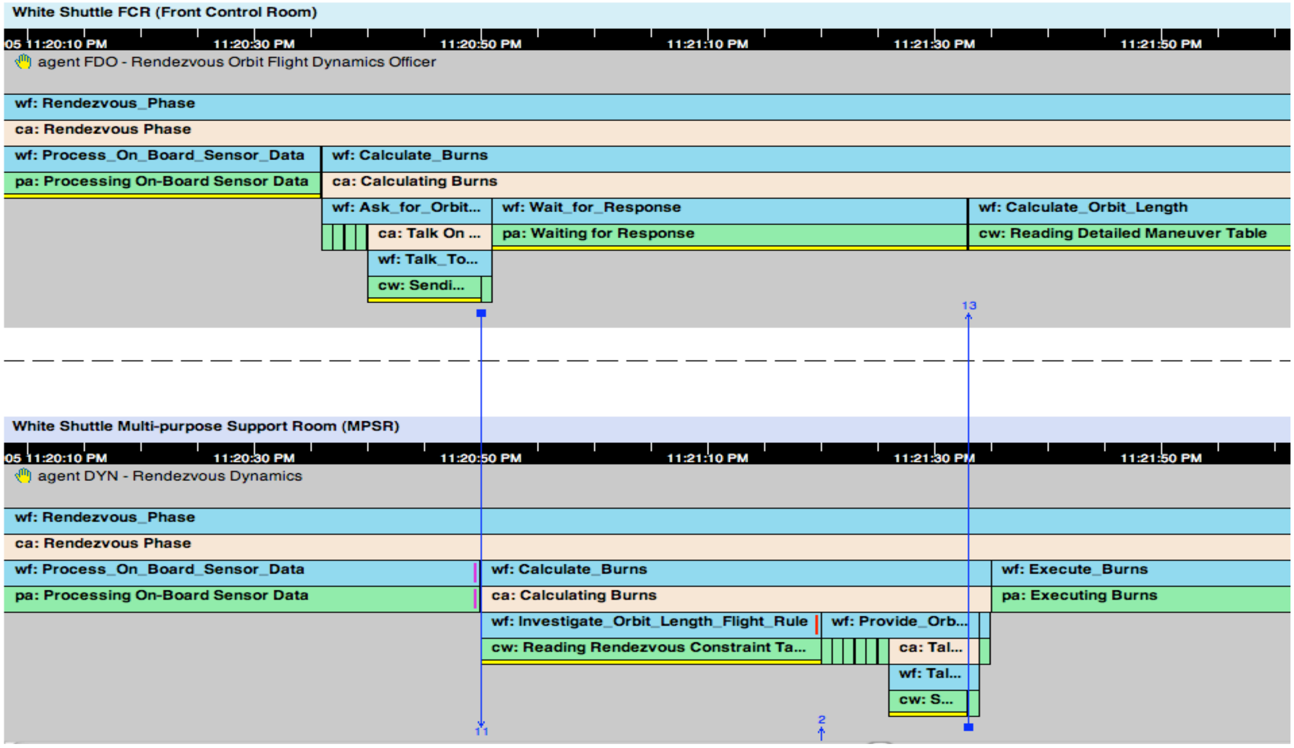

Figure 4. Brahms Activity Timeline Output of Voice Loop Communication between Rendezvous FDO and DYN

We also wanted to see what flight controllers were doing during Launch Phase. We again picked the Ascent FDO but we also chose the Booster Officer (BOOST), Data Processing Systems Officer (DPS) and the Flight Activities Officer (FAO). Once again, we tagged each of their activities with the categories we defined. Then we queried the data from the simulation database and plotted a bar chart.

In Figure 6 we see that the Ascent FDO is spending the majority of time on Analysis activities. We can see that both BOOST and DPS are performing Monitoring activities while the FAO is performing activities categorized as Checking.

7. CONCLUSIONS

We have presented an example of how detailed mission operations modeling and simulation can be created using the Brahms simulation tool. The Agent Viewer enables visualizing the parallel work and communications of multiple people and systems. Statistical analysis of the simulation enables measuring duration and frequency of processes. The example illustrates present operations, a first step in analysis and design of new mission operations at JSC.

Our experience suggests that future work simulations might be scoped by first determining what questions need to be answered (e.g., how many flight controllers might be sufficient for routine ISS operations after the Station is complete?).

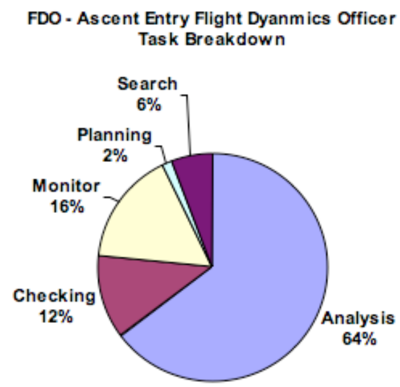

Figure 5. Ascent FDO Activities

Metrics could be developed that would provide information about design tradeoffs (e.g., does a reduced night shift increase daytime workload?), and the scenario's choice of detail would be driven by what is necessary to derive the chosen metrics.

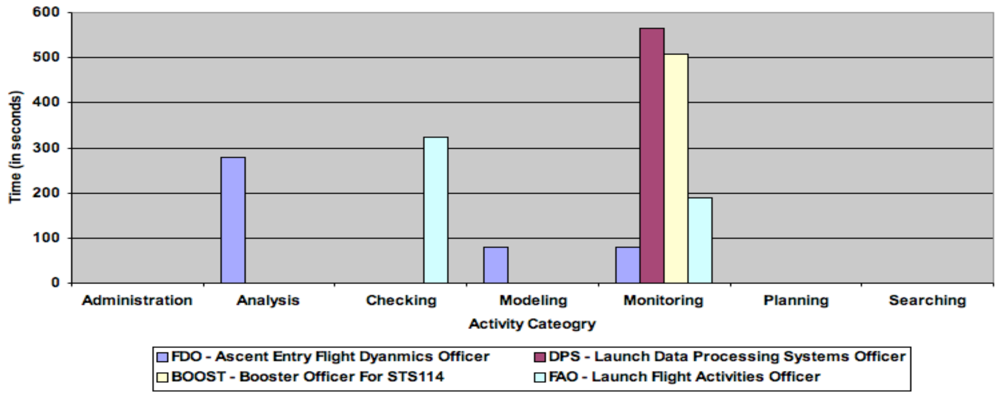

Figure 6. Launch Phase Activities Breakdown by Role

The method of interviewing and sketching a model in Compendium was demonstrated to be efficient. Mission transcripts provided a way to verify this information, and provided timing data, as well as realistic scenarios.

This relatively small modeling and simulation task demonstrated the use of Brahms in existing space programs. This task also demonstrated a method for designing mission operations work processes for future space programs, such as Constellation. Efficiency and risk management receive adequate review through the predictive model and metrics assessment techniques.

The work reported here is part of a long-term effort we began over a decade ago. The maturity of the tool, plus requirements and resources at JSC, suggests that trials in well-chosen problem areas of interest to MOD are now warranted.

8. REFERENCES

1. Clancey, W.J., et al., *Brahms: Simulating practice for work systems design.* International Journal on Human-Computer Studies, 1998. **49**: p. 831-865.
2. Sierhuis, M. and W.J. Clancey, *Modeling and Simulating Work Practice: A human-centered method for work systems design*. IEEE Intelligent Systems, 2002. **Volume 17(5)**(Special Issue on Human-Centered Computing).
3. Greenbaum, J. and M. Kyng, eds. *Design at Work: Cooperative design of computer systems*. 1991, Lawrence Erlbaum: Hillsdale, NJ.
4. Diegelman, T.E., R.E. Eckelkamp, and D.J. Korsmeyer, *Efficient, Affordable Explorations Operations: Crew Centered Control via Operations Infrastructure*, in *Beyond Earth: The Future of Humans In Space*, B. Krone, Editor. 2006, Apogee Press.
5. Sierhuis, M., et al. *Agent-based Mission Modeling and Simulation*. in *Agent Directed Simulation, 2006 Spring Simulation Multiconference (SpringSim 2006)*. 2006. Huntsville, AL: The Society for Modeling and Simulation International.
6. Sierhuis, M., *Modeling and Simulating Work Practice; Brahms: A multiagent modeling and simulation language for work system analysis and design*, in *Social Science Informatics (SWI)*. 2001, University of Amsterdam, SIKS Dissertation Series No. 2001-10: Amsterdam, The Netherlands. p. 350.
7. Patterson, E.S., J. Watts-Perotti, and D.D. Woods, *Voice Loops as Coordination Aids in Space ShuttleMission Control.* Comput. Supported Coop. Work, 1999. **8**(4): p. 353-371.
8. Hammer, M. and J. Champy, *Re-engineering the Corporation*. 1993, New York, NY: Harper Collins Publishers, Inc.
9. Petri, C.A., *Kommunikation mit Automaten*. 1962, University of Bonn: Bonn, Germay.
10. Aalst, W.v.d., *Putting Petri Nets to Work in the Workflow Arena*, in *Petri Net Approaches for Modelling and Validation*, J.M.C. W. van der Aalst, F. Kordon, G. Kotsis and D. Moldt, Editor. 2003, Lincom Europa: Munich. p. 125-143.
11. Cherry, G.W., *Parallel Programming in ANSI Standard Ada*. 1984, Reston, VA, USA: George W. Cherry.
12. Wooldridge, M., *An Introduction to MultiAgent Systems*. 2002: John Wiley & Sons Ltd. 366.
13. Newell, A. and H.A. Simon, *Human Problem Solving*. 1972, Englewood Cliffs, NJ.: Prentice-Hall.
14. White, S.A., *Introduction to BPMN*, in *IBM*, http://www.bpmn.org/Documents/Introduction%20to%20BPMN.pdf, Editor. 2005.
15. Buckingham-Shum, S.J., et al., *Hypermedia Support for Argumentation-Based Rationale: 15 Years on from gIBIS and QOC*, in *Rationale Management in Software Engineering*, R.M. Allen H. Dutoit, Ivan Mistrik, and Barbara Paech, Editor. 2006, Springer-Verlag.
16. Selvin, A., et al. *Compendium: Making Meetings into Knowledge Events*. in *Knowledge Technologies 2001*. 2001. Austin, TX.