A Modeling Approach for Re-designing the Mission Operations System for Human Missions

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Abstract: In order to accomplish the ambitious goals of the Constellation program, NASA is examining it's underlying infrastructure and identifying and addressing the associated design and development needs. Some of these needs are in the area of new technologies and new space system engineering capabilities to support building spacecraft that are capable of meeting the program requirements. Another set of needs are those associated with operating the new constellation of spacecraft.

The Mission Operations Directorate (MOD) at the Johnson Space Center (JSC) is responsible for operating the NASA human flight projects. This system has been in operations for many years – since the Mercury and Gemini missions that provided the first human sub-orbital flight in May 1961 and later the first Apollo missions that landed humans on the moon in July of 1969, and as such has a rich heritage. It consists of the infrastructure, people, and processes that are utilized to Plan, Train and Fly the corresponding space missions. The system has been refined over time and the underlying know-how that allows the system to run smoothly is inherent in each of the system elements. Re-engineering this system to meet the goal of the Mission Operations Directorate (MOD) to reduce the sustaining costs by 50% as compared to the regular space shuttle missions entails fully characterizing it, understanding it's strengths and limitations, identifying the gaps between it's current capabilities and those required for meeting the program needs and designing a feasible transition plan for reaching the desired end state.

This paper describes the systems engineering approach for re-engineering the Mission Operations System (MOS) using advanced modeling and analysis techniques. A multi-disciplinary team of experts from various fields within and outside of MOD was formed

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to lead this effort. This paper explains the efforts undertaken by that team, the challenges faced and the lessons learned to date.

Background

MOD will support the Constellation Program (CxP) crew and flight controller training, pre-launch/launch operations, and flight operations through a methodology known as the Flight Production Process (FPP). This process is a compilation of work tasks conducted by a number of technical disciplines within MOD and its operations contractor(s). The FPP provides the products required to reconfigure the mission control center with its associated training facilities, as well the flight software/data products required for reconfiguring the flight vehicles. The training and certification of flight personnel, including crew, flight controllers and analysts, are also considered to be products of the FPP.

It is understood that the lack of a well-defined FPP for the Constellation Program will result in increased development and operational costs and could impact the Mission Operation Projects' (MOP) readiness to support CxP missions. Significant areas of concern such as the time consuming and intensive work effort needed to field a flight production scheduling tool, the demanding activity within each MOP technical discipline to conceive and develop their tools and processes, and the extensive coordination required between technical disciplines to construct a fully integrated production work flow require expert attention early in the overall production process development cycle.

Any process that is used repetitively, as will be the case for the Constellation FPP, must be as efficient as possible so as to yield the highest quality of deliverables in a repeatable manner within its allotted process time. Efficiency and productivity within a process can be built-in initially, and these can be greatly enhanced after the experience of multiple production cycles and the incorporation of lessons learned into the underlying processes as demonstrated by the twenty plus year evolution of the Space Shuttle flight production process. This is also the expectation of CxP; however, the efficiencies realized and productivity gains that resulted from the Shuttle lessons learned can be incorporated into the CxP flight production process from its inception which will better posture the much-similar CxP process to establish itself as highly effective with the first production run.

Motivation (Problem Being Addressed)

The current design of the human mission operations system has been created over time by generations of competent engineers. As time has passed, each separate aspect of the system has become more and more sophisticated and at the same time the collective information and intelligence required to fully understand the entire system in order to improve it is now overwhelming.

The MOD Space Shuttle Program (SSP) and International Space Station Program(ISSP) flight production processes(FPP) were not built as one integrated system; instead the separate and distinct production processes used for these two programs were built a piece at a time by each of the large functional areas within MOD. There are six distinct organizations within MOD. Each of these organizations had their own process for providing products to the FPP. Since there was no concerted Systems Engineering and Integration (SE&I) effort across these organizations during the production process, there was overlap in the activities conducted by these separate organizations and the integration of their associated products was inefficient and costly.

These processes have been streamlined and refined over time, but never re-engineered to maximize efficiencies. Today MOD produces over 700 products for each shuttle mission to the ISS. These products are manually integrated at a high level called the Management Level. This high level integration process allows MOD to meet its top level product delivery requirements but does not provide sufficient insight into the processes necessary to understand, integrate or re-engineer the detailed processes.

The methodology explained in this paper is based on the use of a structured modeling and architecture development approach to re-engineer this system. The goal is to optimize the system design thereby reducing the sustaining costs and increasing system efficiency, reliability, robustness and maintainability metrics.

Vision for the MOD Cx FPP Re-engineering Project

The goal is to design a mission operations system for the CxP that has significantly lower sustaining costs as compared to current mission operations system for the SSP and ISSP. This can only be achieved by using cutting edge Systems Engineering techniques to model the processes involved in the development of flight products and finding an optimal strategy for allocating resources to each of these processes. Since there are many processes involved in the development of the flight products, managing this process can be supported by providing decision support tools and techniques that interact with the management

Figure 1 shows a high level architecture for the desired system. This architecture includes multiple layers: At the lowest level is the layer that includes views generated based on the Department of Defense Architecture Framework (DODAF) to build the enterprise system architecture [1,2]. This layer is used to define and analyze the relationships between the key attributes of the system and their interfaces. On the right hand side is a database that includes the underlying data for the system which in turn feeds all the layers. This database is updated as the system is designed and even after it operates and more data becomes available. The next layer includes executable models such as Discrete Event Simulations and Risk Models that are used to validate the end to end architecture of the system. The actual MOS is also depicted as one page of this layer. The first page in this layer uses the data available in the data base to run simulations and demonstrate the system performance metrics such as the minimal cut-sets of the system, the critical paths, and the probability distribution function of the time to complete a full run. The second page (MOS) is the actual system which is being designed during the design phase and in operation during the operations phase. During the operations phase, the actual measures of system performance are produced by this layer and fed back into the database and other pages and layers as necessary.

The top most layer is the Manage and Control layer which serves the function of orchestration and uncertainty management. The orchestrator is called the Management Level Network Executive (MLNE) and uncertainty management is conducted by Re-planning. The MLNE has a direct interface with the components of the MOS and sends commands to them to automatically orchestrate the activities identified in the final system model that is representative of the FPP design. The Re-planning entity allows for uncertainty management during operations. It might entail making changes to the original integrated workflow process as appropriate to address change requests that are either being produced externally or internally by the system based on the state of the system and its performance metrics. The re-planner does this dynamically and automatically.

Management interfaces with the Manage/Control layer in order to get the necessary information for making executive decisions. These decisions are then communicated with the operators and translated into commands for the flight system. The performance of the system is monitored and the performance metrics are fed back into the database which in turn feeds the system models. The additional data is therefore used to update the existing data and make it more accurate.

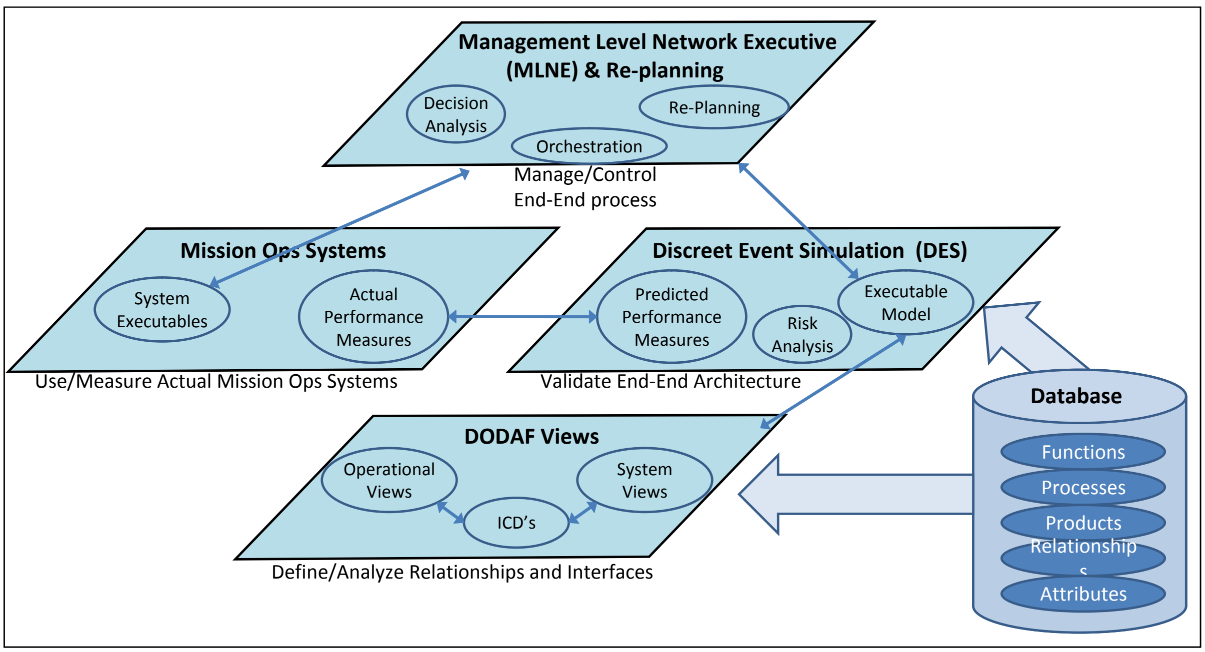

Figure 1:Multi-layered Architecture of the Mission Operations Model

The main focus of this paper is to give a high level overview of the effort of re-engineering of the MOS and the lessons learned to date. The utility of each of the pieces depicted in figure 1 during design and operations are explained in table 1.

Key Architectureal Elements	Utility and Information Content of each Architectural Element during each of the design and operations phases.			
	During Design		During System Operations	
	Utility	Information Content	Utility	Information Content
	distributed data collection; friendly user interface	Key attributes of the system model and architecture.	Data storage; used by SME's to manage their data.	Key attributes of the system model and architecture.
		Relationships between attributes		Relationships between attributes
	Used by the subject matter experts (SMEs)to manage their data.	Metrics associated with the lowest level processes; such as duration, probability distribution, resources required, etc.	Keeps system history and performance parameters	Metrics associated with the lowest level processes; such as duration, probability distribution, resources required.
Database (MODEAR)	MO-ADD text and information for building the architectural views.			System performance metrics indexed with time.
	Provides a standard means of depicting the elements that make up the enterprise, their context, the connection between those elements and the principles that govern their interactions.	representation of various system attributes and their dependencies in a structured manner.	Updated Architectural views keep the MO-ADD updated.	Updated MO-ADD
	Facilitiates development of ICD's	Dependencies within the system.	Ensure that any additions or modifications are consistent with system architecture	Updated system dependencies based on observations of system.
Selected DODAF views			perform analyses on impact of those additions or modifications.	
	Critical Paths	Information in Database and System Model	Provides a baseline for understanding and predicting system behavior.	Updated information in database.
Discrete Event Simulation Model	Validation and Verification.	Duration for each process, etc.	Provides a baseline for exercising the MLN	Updated information in system model.
	Design Optimization.			
MLNE			Activity Orchestration	Draws information from system model;
			Dynamically produces a new plan based on observed system behavior and any changes in	Draws information from

Table 1: Key elements of the architecture and their associated utility and information content during system design and operation.

Model Development Process

This section describes the model development process, which includes data elicitation from the domain experts and the development of standards and ontology's that will be used to help generate a consistent data set used for the modeling activity.

The methodology described here was a result of lessons learned during initial project formulation. Although MOD has been successfully operating missions and MOD personnel are trained to integrate the pieces of the FPP process together, the processes and their inter-dependencies had not been systematically represented and integrated in models and architectural artifacts.

It became apparent that it was necessary to assemble a core team of knowledgeable people representing the various disciplines involved in the mission operations system as well as expertise and experience is systems modeling, analysis, and architecture development for the purpose of designing the correct approach for this endeavor.

The initial model development conducted by this team leveraged the predecessor work to conduct functional analysis by building a hierarchy of all the functions performed by the system during the life-cycle of the Mission Operations Project (MOP) [5]. The modeling activity then integrated the functional analysis using specialized Systems Engineering tools. This integration was conducted in the context of the Department of Defense Architecture Framework (DODAF) 1.5 and related architectural artifacts were produced and iterated upon.

The domain experts responsible for each of these functions used an ontology defined by the modeling team to develop detailed process flow diagrams explaining the details of the operations of the processes associated with each function.

Figure 2 provides a high level overview of the modeling and analysis approach. This approach is based on combining a top-down method of building functional models to determine the functional behavior of the system with a bottom-up method for elaborating on the details of the processes underlying each of the functions by building process flow diagrams (PFD's).

The information used for building the top-down functional model included the title and hierarchy of the functions performed in the system as well as the products that flow between these functions.

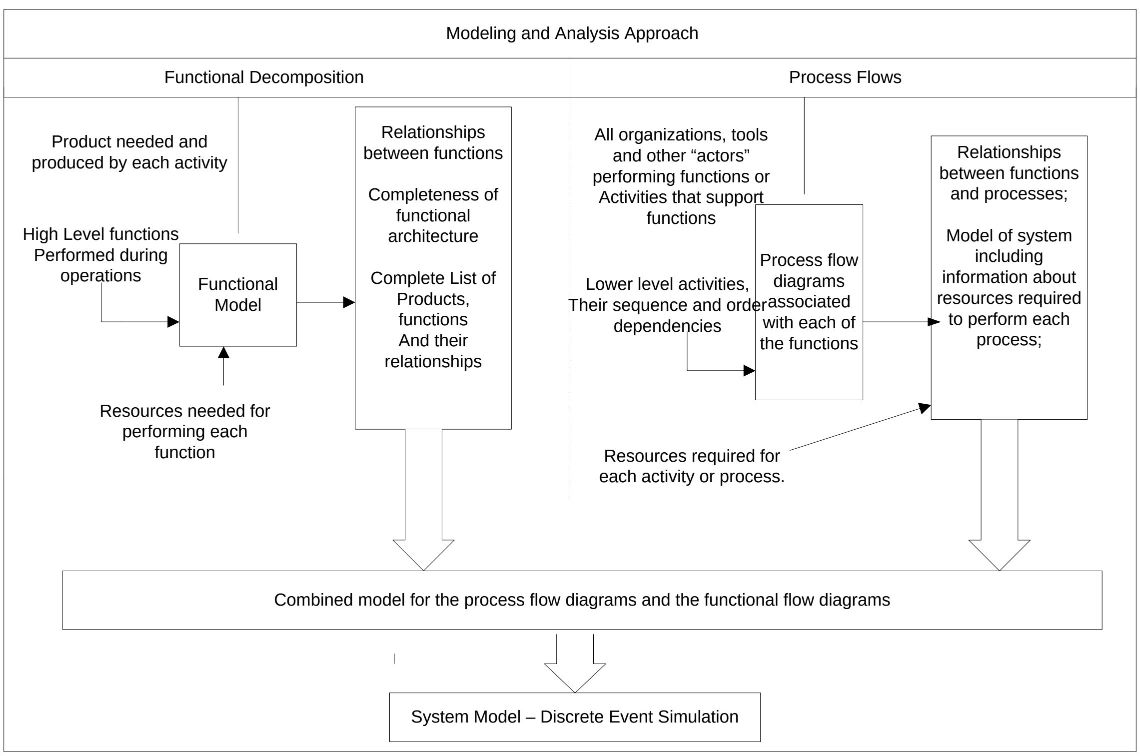

Figure 2: Modeling & Analysis Approach

At a very high level, there are two functions that happen throughout the lifecycle of missions: "Manage and Control" and "Develop and Maintain Infrastructure". The high level functions that occur in sequence during the process of a designing and executing a mission are "Plan", "Train" and "Fly." Although in general the "Plan" and "Train" functions occur pre-launch, and "fly" occurs after launch, due to the nature and duration of the missions, there are elements of planning and training that will occur during the traditional "fly" phases of flight. For example, detailed undocking and reentry planning for a 6 month docked mission may not occur until after launch and docking, and probably very close to the actual undocking timeframe. This iterative and "reuse" of the traditionally serial functions has added a unique layer of complexity when modeling the system.

The three major "Plan", "Train" and "Fly" functions permeate the "Flight Production Process" which is a main element of the Mission Operations System. Each of these high level functions are broken down in to at least three or four additional layers, and the inputs and outputs across the functions between the third and fourth layers are identified.

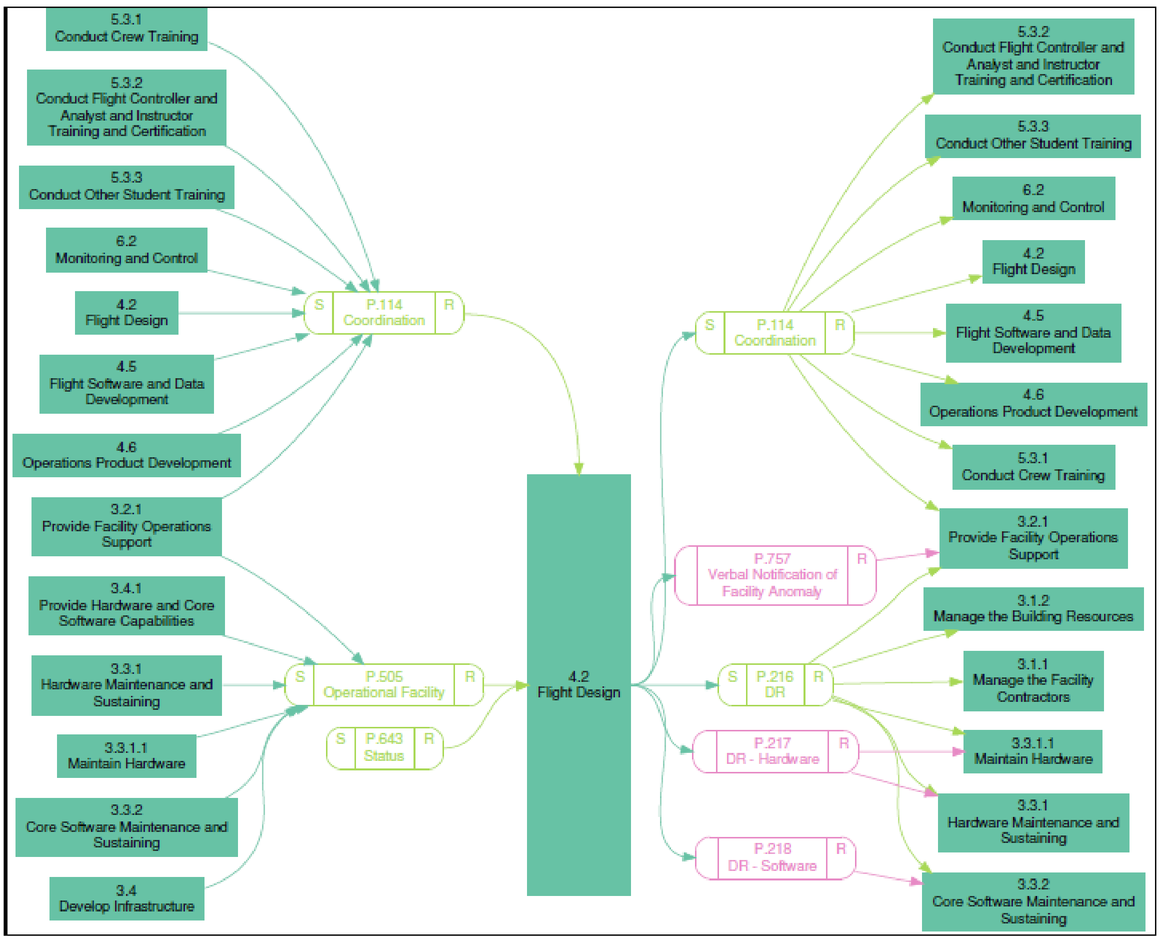

Figure 3: Sample OV-5 (DODAF construct)

Figure 3 shows a sample DODAF artifact (OV-5) that was produced for an example function (Flight Design) within our functional hierarchy. This figure shows the product input and outputs to this particular function along with their source and recipient functions. Note that the color codings and the letters on the right and left hand side of the ovals containing the products are meant to indicate whether the exchange has been indicated by the source or recipient of the product in question. Throughout the course of this project, several sets of OV-5's were produced and iterated upon in order to ensure the consistency of the data and the agreement between multiple stakeholders that were owners and recipients of the data products.

The process flow diagrams provide a bottom-up approach for modeling the system. They include details such as the "actor" that performs each process, the sequence of execution for the processes, and the other dependencies between the processes and functions such as the start and end points for each of the threads in the process flows and the storage units used for storing information generated by these processes.

Decomposing the functionality of the system into the details of it's execution and allocating resources to the processes that perform these functions allow us to execute the model to obtain the systems' measures of performance, such as the total amount of resources used for producing each specific product, the various paths available for this production, the redundancies and sensitivities in the system, the single points of failure, the critical paths and possible mitigation or re-planning paths.

The next section elaborates on some of the subtleties of the data elicitation process from the subject matter experts.

Data Elicitation

The MOS has a rich heritage – it has been refined over many years and the system runs smoothly in a brute force manner based on the expertise of engineers. The knowledge associated with the system has not been fully captured and represented in any single document to date.

The data elicitation process started by refining the existing functional decomposition of the system. The next step was to identify subject matter experts (SME's) who own each of the functions. These SME's were then responsible for decomposing these into lower level functions and identifying the inputs and outputs associated with these functions, as well as the source and recipient functions for each of the products.

In order to organize and integrate this data set and ensure its consistency, a combination of the Systems Engineering tools, CORE and Systems Architect was used. CORE was used to run consistency checks to determine the orphan products, or the products missing an input or output function. Numerous other representations of the data, such as N-squared diagrams, functional flow block diagrams (FFBD's), and tabular representations of the integrated data set, including a master product list that defines all the products and their associated features in alphabetical order were also developed. Iterating on these representations with the subject matter experts and having group discussions with all the stakeholders for each of the functions facilitated the validation of the data and helped to improve its quality.

Figure 4 shows an example process undertaken that proved to be very effective. Due to the complexity of the task and the number of participants, it was difficult to manage the volume of information required to understand and document the processes. Stakeholder meetings allowed the owner of a process to explain the preferred title and content of the product and gain concurrence on many aspects of the process. For example, both the owner and user needed to agree on the need to exchange the product. To aid these discussions, the OV-5 diagrams were used to identify areas where both parties in an exchange did not agree, leading to discussion and resolution. The participants used the database to further verify that all parties agreed which processes generated the products, who consumed those products and which interface was used in the exchange. Meetings were repeated until resolution was achieved and documented in updates to the process flow diagrams and database.

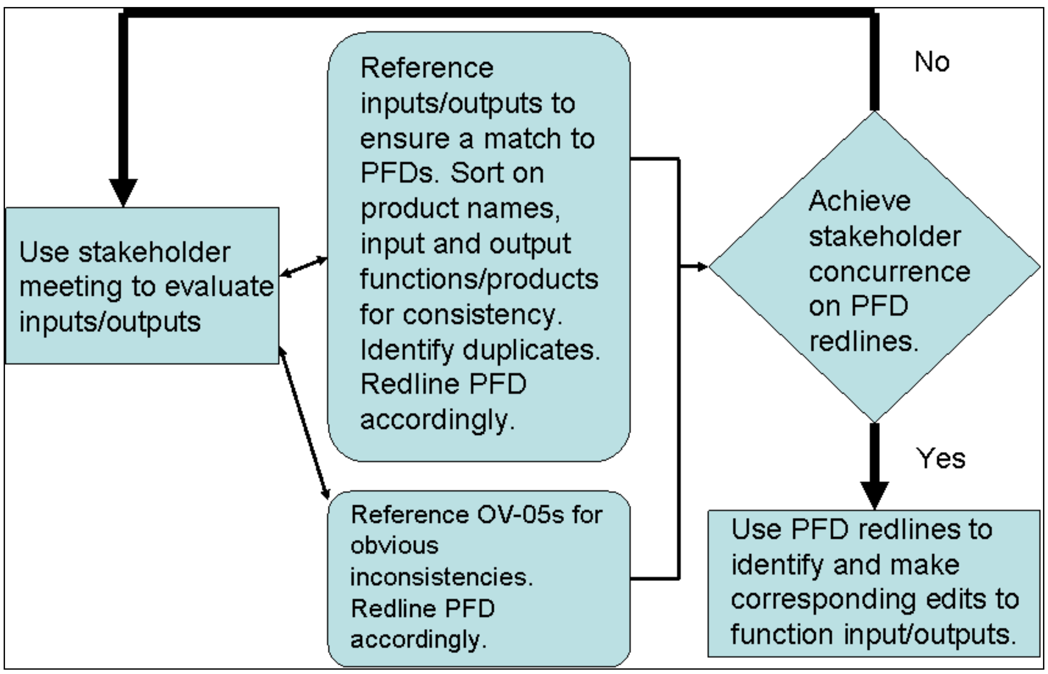

Figure 5: Efficient Process for data gathering and consensus building

Key Challenges Encountered

The challenges encountered during the course of this activity can be broadly classified as those relating to Systems Engineering processes, and those associated with the tool interoperability or lack thereof.

Systems Engineering & Integration Processes

The standard Systems Engineering Practices have been well documented in various books, journals and standards documents [1, 3, 4]. Re-designing the MOS with consideration of the goal of reducing its sustaining costs by 50% entailed the customization of these standards to our particular application.

Some of the unique characteristics of the system are as follow:

- The Mission Operations Directorate at JSC has a long history and rich heritage. It is a service organization that provides flight products for use by the projects.
- It has been designed and refined by generations of competent engineers.
- The know-how for maintaining this system is mainly expert information which has been passed from generation to generation of engineers. It has not been captured and is not represented in any kind of formal model or database.
- The work breakdown structure within the MOD is primarily based on its' organizational structure. In other words, the organizations make their contributions to the work or product development cycle based on their experience and competence. These contributions are then integrated at a higher level called the Management Level Network.
- Much of the activities involved in the FPP are performed by humans and as such there is uncertainty in the time it takes to perform them and there can be variance in quality of the products developed based on these activities.

The predecessor work to this task had accomplished the goal of building a hierarchy of all the functions performed by the system during the life-cycle of the Mission Operations Project (MOP). The subject matter experts (SME's) for each of these functions had developed a qualitative description for the functions and the functions along with their description created a document called the Baseline Operations Plan (BOP) [5].

The goal of the analysis team was to leverage from the existing work with an eye towards re-engineering the system such that it would have a much reduced sustaining cost. After some examination, it became clear that functions identified by the SME's were actually their assessments of the "Functional Requirements" for the system. Furthermore, the explanations provided for the functions were not appropriate for the structured analysis of the system necessary for assessment and optimization purposes. Hence the decision to define a standard ontology or language that the SME's could use in depicting and expressing the processes involved in the conduct of each of their functions. In defining this ontology, the team used several existing ontologies as a starting point and tailored and extended them based on the specific behavior of the system under consideration. The existing ontologies were constructs from standard UML/SysML/BPMN schema's and the JPL standard ontology [6]. The Process Flow Diagrams (PFD's) that were built using the customized ontology were a means for the SME's to express "how" they perform the functions that they had previously specified.

Furthermore, analysis of the existing functional descriptions and input-outputs made it clear that the interfaces between the functions were not consistent as defined by the SMEs. This inconsistency was due to the fact that the SMEs had not reached a consensus with other SME's with whom they were exchanging data products. Moreover, they often used different terminology for similar products or similar terminology for different products. After several cycles of integrating the data using specialized SE tools and reviewing it, the analysis team was able to work with the SME's to produce a standard lexicon for the MOS. The analysis of this data was further facilitated by building a customized database with a user friendly web-based interface which enabled the SME's to interface with each other "virtually" and resolve conflicts. It's important to note that at some point, there were a total of 900 products and 110 functions. The large scale of this system in itself made the task of consolidating and organizing the data set extremely challenging.

The next layer was then the development and integration of the PFD's. A quick study of the various stakeholders for the Cx-MOS-FPP and the qualities that they valued in the system helped determine the DODAF views that would be beneficial for this architecture development effort. Since the MOD is primarily a service organization, the main analysis vehicle for the system is a Discrete Event Simulation (DES) model. The information required for the DODAF views and the DES drove the further refinement of the ontology used for defining the PFD's by the SME's. The work involved in integrating and refining these diagrams and building a repository to contain their associated data is still in progress.

Tool Interoperability

It became very clear, from the outset of this task that it is necessary to use cutting edge systems engineering technologies for this purpose. The contracting team that has the main responsibility of building DODAF style architecture for this project uses the "IBM Rational Systems Architect" tool for this purpose. The JPL team member was using the CORE Systems Engineering tool. The analysis team identified the need to synergize these activities but this was not a trivial task as it was not easy to share information across the tools and conduct configuration control across the corresponding data sets for each of the models. Even though these tools both provide the capability of importing and exporting a variety of file formats, the totality of the information included in the models in them is difficult to import or export. Moreover, neither of them have an open API and as such they cannot be used in a networked architecture.

On the other hand, since a lot of significant data was being collected from the SME's, the analysis team identified the need to build a single repository that can store and maintain this data. While many enterprise architecture tool suites provide repositories for the capture of architectural information, to the best of our knowledge, none of them fully satisfied the particular goals and requirements that the analysis team identified for a repository. One such goal was the durability of the underlying database. Since the MOD at JSC is the primary human mission operations system in the country, it is imperative that the repository of its architectural information is sustainable. Other requirements include the ease of use of the system by the SME's without the need for any training. This requirement is based on the fact that there are many stakeholders and SME's for this data and requiring them to take specialized classes for the purpose of accessing it seems counterproductive.

Another key element of the analysis is building and studying a corresponding Discrete Event Simulation (DES) model for this system as it is a service organization. There are many DES tools available in the industry for this purpose. The analysis team therefore conducted a survey of these tools before making a selection. Tool interoperability is an issue in this case also. Importing the data associated with the PFD’s which are currently built in Microsoft Visio by the SME’s into the tool is not a trivial problem and is being conducted manually at this time. The capability of containing this data in the main repository is under development. Moreover, the analysis team is developing standard templates in Visio (which is a drawing development tool) for the SME’s to use for the development of their PFD’s. It is expected that the XML output associated with these PFD’s would be importable to the repository and/or other modeling tools.

Other upcoming analysis capabilities that our application needs include risk analysis and planning/optimization engines. These are yet to be included in the architecture but based on experience the transfer of data between tools will not be a trivial issue.

In a nutshell, any major development effort such as ours requires different types of analysis that are cross-cutting across multiple disciplines and have different sets of associated tools. The absence of seamless methods for interoperability between tools, is, it seems to us, a major technological weakness.

Lessons Learned and Recommendations

Below is a summary of the lessons learned and recommendations.

	Lessons Learned	Recommendations
Process	Developing an on the fly Systems Engineering process with the larger team is an inefficient and ineffective methodology.	Form a core team of competent systems engineers upfront who are able to clearly define the process, communicate it with the SME's and implement it smoothly.
	Subject Matter Experts(SME's) may be unfamiliar with the Systems Engineering process.	
	Various experts might have different interpretations of the Systems Engineering processes.	Develop and execute test cases for proposed methodology to ensure their success before implementing the approach broadly.
		Monitor progress and refine and update the process as appropriate.
Data/Inputs	There can be ambiguity in the assumptions used by various SME's and the rationale for their decisions.	Standardize the overarching assumptions as much as possible;
		Include "Design Rationale Capture" in the process and create user-friendly approaches for conducting it.

	Each member of the main categories associated with the system, such as products, functions, and other concepts can be called different names by various SME's.	Define a standard glossary for products, functions, organizations and other key concepts related to the system. Make this list available for use by the SME's as they design their subsystems.
	There will be open issues and inconsistencies in the data collected from SME's	Develop and implement an approach for resolving each type of inconsistency.
	A single product title may include a collection of files or sub-products.	Determine the standard level of aggregation which is appropriate for the level of modeling/analysis being conducted.
	Products with the same title can have different contents based on the when they are produced during the process.	The standard language used for capturing this information should include necessary semantics, such as versions and instances that enable the user to discriminate between such products.
Interfaces	As the SME's update and refine their design information, they need access to information from other SME's that directly affects them.	Develop a methodology and associated tool that allows for the concurrent use and updating of design information by all relevant stakeholders.
	Assumptions that SME's make about exchanges with other SME's/stakeholders can be inconsistent.	
	The system boundaries and interfaces with outside organizations are not trivial.	Clearly define the system boundaries early, including how the transitions will occur.
Modeling	The MOS has a strong human component and therefore there is significant dynamism and uncertainty in the system behavior. Capturing the details of the human decision making process and representing it in a model is a daunting task.	Determine the level of detail necessary for the modeling activities. Develop an approach for generalizing the human activities at appropriate level and aggregating lower level data and information in a correct and consistent manner.
		Leverage on possible existing work in automating service tasks to generalize and model the system correctly at a higher level.

Table 2: Lessons Learned and Recommendations

In retrospect, one of the most imposing obstacles the team had to overcome was trying to adequately explain to management what is involved in true systems engineering and modeling and how it would improve their situation. This was largely due to the management past experience and the belief that they had done SE&I before. The management base equated systems integration and operations integration as constituting the entire experience and totally leaving out process integration and overall Systems, Process and Ops design and Integration as the final effort.

Any effort of this area of systems engineering should always endeavor to be prepared to show early results at closing the architecture of the system(s)/process(s) so that management can understand what benefits can be achieved. This can be accomplished by taking the analysis team best guess at which processes and systems are on the critical path and modeling them first.

Future Directions

The analysis team is currently in the process of expanding the repository to contain the attributes of the process flow diagrams. Many of the PFD's created by the SME's have been integrated into a workflow process model and is being continuously refined and analyzed using a DES model. This integrated workflow model will be extended to include the end to end FPP process activities. Moreover, alternative model formulation strategies are being explored for the purpose of optimizing resource allocation strategies within the system. A significant amount of data related to the system processes, and their durations has also been collected, organized, assessed, and analyzed. Additional data about the resources required to perform the processes will be collected to support further DES analysis studies. After the design phase is completed, automated re-planning engines will be used during operations for the purpose of uncertainty management. Workflow execution engines will also be used for the automated execution of the FPP integrated workflow.

There is currently an effort underway to build a DES model for the entire ground system architecture of the Cx project. This system includes elements which are at the Kennedy Space Center as well as elements at the Johnson Space Center. Our models therefore have to interface with models built at the program level. We are in the process of collecting relevant information from various sources and designing integration methodologies.

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