Developing Flexible Discrete Event Simulation Models in an Uncertain Policy Environment

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ABSTRACT: *On February 1st, 2010 U.S. President Barack Obama submitted to Congress his proposed budget request for Fiscal Year 2011. This budget included significant changes to the National Aeronautics and Space Administration (NASA), including the proposed cancellation of the Constellation Program. This change proved to be controversial and Congressional approval of the program's official cancellation would take many months to complete. During this same period an end-to-end discrete event simulation (DES) model of Constellation operations was being built through the joint efforts of Productivity Apex Inc. (PAI) and Science Applications International Corporation (SAIC) teams under the guidance of NASA. The uncertainty in regards to the Constellation program presented a major challenge to the DES team, as to: continue the development of this program-of-record simulation, while at the same time remain prepared for possible changes to the program. This required the team to rethink how it would develop it's model and make it flexible enough to support possible future vehicles while at the same time be specific enough to support the program-of-record. This challenge was compounded by the fact that this model was being developed through the traditional DES process-orientation which lacked the flexibility of object-oriented approaches. The team met this challenge through significant pre-planning that led to the "modularization" of the model's structure by identifying what was generic, finding natural logic break points, and the standardization of inter-logic numbering system. The outcome of this work resulted in a model that not only was ready to be easily modified to support any future rocket programs, but also a model that was extremely structured and organized in a way that facilitated rapid verification. This paper discusses in detail the process the team followed to build this model and the many advantages this method provides builders of traditional process-oriented discrete event simulations.*

1. Introduction

The Constellation Program was a human spaceflight program initiated by the NASA Exploration Systems Mission Directorate (ESMD) and first developed through the Exploration Systems Architecture Study (ESAS) in response to the Vision for Space Exploration announced by President George W. Bush on January 14, 2004 and the NASA Authorization Act of 2005. The goal of this Program was to design and build a suitable replacement for the Space Shuttle to send astronauts to the International Space Station (ISS), and eventually towards missions to the Moon and Mars. To achieve these goals, the Constellation Program was developing the Ares I and Ares V rockets, which would carry the Orion Space Capsule and the Altair Lander, respectively, into space. The Ares I-Orion vehicle would have a dual use: alone it could transport Astronaut crews to the ISS or it could rendezvous with the Altair Lander-Earth Departure Stage (Altair-EDS) in Earth Orbit for a long duration mission to the Moon or Mars. The Altair-EDS would be launched using the Heavy Lift Ares V launch vehicle. Ares I consisted of a single 5-segment Solid Rocket Booster and a liquid-fueled second stage powered by a J-2X engine. Above the second stage, the

Orion capsule would sit with a Launch Abort System attached to it. Ares V consisted of two 5-segment Solid Rocket Boosters and a liquid fueled Core Stage powered by multiple RS-68 engines the Earth Departure Stage with the Altair Lander would be stacked above the Core Stage . Figure 1 shows images of the Constellation vehicles.

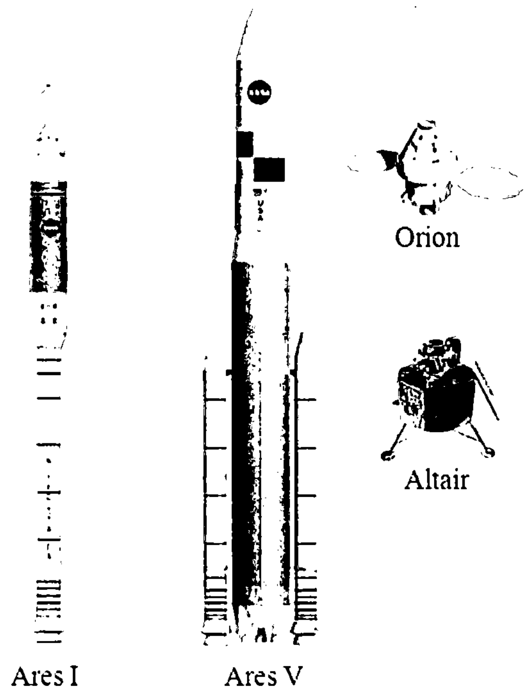

Figure 1. Ares I, Ares V, Orion, and Altair

1.1 The Constellation Discrete Event Simulation Model

To support the development of the vehicles used for the Constellation Program, a joint NASA, SAIC, and Productivity Apex Inc. (PAI) team was tasked to develop an end-to-end discrete-event simulation (DES) model (the CxDES Model) [1]. This model looked at Program operations from a NASA agency and cross-center (Level 2) perspective for the purpose of analyzing system-level performance (i.e., element production meets launch manifest demands, which must meet mission delivery expectations).The model was developed using the Discrete Event Simulation Arena (Rockwell Automation) software application and the supporting Ariana (PAI) graphical user interface. The first phase of the effort (May 2008 through April 2009) focused upon development of the model for an Ares I-Orion architecture supporting the International Space Station (ISS). The effort was continued into a second phase from May 2009 – October 2009 to complete the model and collect task duration information from Constellation (Level 3) project offices. This effort led to a first round of analysis using the model for the Program's Integrated Design Analysis Cycle 5 (IDAC-5). The third phase, performed between November 2009 and August 2010, began the development of a simulation model of the Ares V-Altair architecture.

The ultimate objective of the simulation models was to assess multiple performance indicators for Constellation's Ares I-Ares V system including, but not limited to, the number of successful missions that could be achieved within a certain time frame. The required scope of the models involved the manufacturing of the Flight Hardware Elements (FHEs), assembly and integration, offline ground operations, integration in the Vehicle Assembly Building (VAB), transfer to the launch pad and pad operations (pad flow and launch countdown), ascent of the launch vehicle, mission ops, descent, recovery, and refurbishment where applicable.

A custom Ariana Simulation Interface, using the PAI commercial software, was developed and delivered as a graphical user interface (GUI) for the Arena model. Ariana allows the users to define simulation scenarios, populate the model with new data, run the model, view the output, and compare the output. A master Microsoft Excel sheet was also developed and delivered as a way to read manufacturing lead time and launch manifest inputs and write the output data after a simulation run. Input data included FHE (e.g., Ares I, Ares V, Orion, and Altair components and their sub elements such as Interstages, Forward Assemblies, Solid Rocket Motor Segments, Aft Skirts) ordering differential times and a flight manifest. Output included mission-by-mission event occurrence time (e.g., integration start time in the VAB), weather and technical scrubs by mission, and waiting time in the VAB for each FHE per mission. An automated graphing Excel sheet was also developed that included (among other things) output graphs and plots of planned versus simulated mission times .

The Ares I model's level of detail was defined in the conceptual flow diagram (CFD) of the manufacturing, assembly, and the integration of the 5 main FHEs:

1. Orion Launch Abort System (LAS)
2. Cargo
3. Orion
4. Ares I Upper Stage
5. Solid Rocket Booster (SRB)

The Ares V model's level of detail was similarly defined in the CFD of its 6 main FHEs:

1. Composite Shroud
2. Altair Cargo
3. Altair Descent Module
4. Earth Departure Stage (EDS)
5. Core Stage
6. Two Solid Rocket Boosters (SRB)

1.2 A New Budget

On February 1st, 2010 U.S. President Barack Obama submitted to Congress his proposed budget request for Fiscal Year 2011, which proposed significant changes to NASA, including the cancellation of the Constellation Program. This change proved controversial and Congressional approval of the program's official cancellation would take many months to complete. This period of uncertainty was problematic because officially Constellation was not cancelled until Congress approved the 2011 budget, but for all practical purposes the program was coming to an end. Additionally, it was unclear what new program would take the place of the Constellation program. This left the CxDES team in a difficult position: development of the Ares V model had to continue but it would more than likely never be used because the program it was supporting was ending. The challenge facing the team at this point was to develop a model that met the requirements of the current program, while also making it readily adaptable to support any future programs.

2. Modeling Methodologies

Discrete event simulation is one of the most widely used methods for analyzing processes and systems with a proven track record in process analysis and planning in many fields and industries including manufacturing, aerospace, healthcare and transportation. Simulation modeling has shown an advantage over other analytical approaches due to its ability to assess the effect of input variability on measures of performance. It also allows the introduction of rare events that are not typically found in deterministic models. This may partly address the problems associated with poor estimation of system performance (e.g. launch rates, turnaround time, and cost).

There are several modeling methodologies in the field of discrete event simulation. The two most widely used methodologies are the process oriented and the object oriented. The *process oriented* simulation model is constructed by mainly employing the processes of the system modeled along with their interactions. The resulting model will consist of the end-to-end process flow of the system, along with other processing modules that are mainly used to capture the logic in the system being modeled. On the other hand, *object oriented* simulation is constructed by building the objects present in the system being modeled. These objects contain all the flows and logic present in the system. The end model consists of all the objects in the system along with the interaction between these objects. The benefit of this method is that once the objects are developed, they can be reused or customized. In the process oriented approach, the reusability is possible, but requires additional customization effort to work in practice.

3. Predicting the Future and other Launch Vehicle Programs

When the CxDES project started, one of the first steps the team took was to develop conceptual flow diagrams for both Ares I and Ares V operations. The Ares I CxDES model was built following the original conceptual flow models and was modified as plans for the program changed. When it came time to start development on the Ares V model, the team started following the same process; when the new NASA budget was proposed, reconsideration of the original conceptual flow diagram was required to maximize the utility of this soon to be built model, even if the Ares V rocket was cancelled. To do this, all the possible futures for alternative launch vehicles were first considered based on the current policy environment. The following options were considered along with their impact on model development:

Scenario	Impact on CxDES
1) Constellation continues, as if the President had never cancelled the program in the FY 2011 budget.	Build the Ares V model as originally envisioned and eventually integrate it with the Ares I model.
2) Constellation continues with an enhanced test flight program.	Build the Ares V model as originally envisioned and eventually integrate it with the Ares I model. Modify the existing Ares I model for analysis to support the proposed test flights, as well as use the data from the test flight program to improve the fidelity of the data used in the models.
3) Constellation is cancelled with no	Stop all work on the models, collect all work done up to

NASA program to take its place.	this point, and store the information for future use.
4) Constellation is cancelled and a new Heavy Lift Vehicle program takes its place.	Archive the Ares I model and develop a model for the new Heavy Lift Vehicle using the Ares I model as the basis or start completely from scratch.
5) Constellation is cancelled but an Ares I test flight program continues in order to test out a new vehicle's common components.	Modify the existing Ares I model to analyze the proposed test flights as well as use the data from the test flight program to improve the fidelity of the data being used in the models. Then, build a model for the new Heavy Lift Vehicle using the Ares I model as the basis or start completely from scratch.
6) Constellation is cancelled and a modified test flight program is started to test out a new vehicle's common components.	Develop a model for the new Heavy Lift Vehicle using the Ares I model as the basis or start completely from scratch. Use the relevant data learned from the test flight program to improve the fidelity of the data collected for the new model.

Review of these alternatives showed there was overlap among most of them (Figure 2).

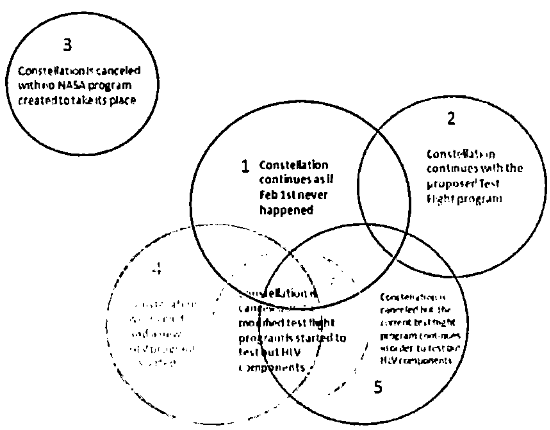

Figure 2. Venn Diagram of possible Constellation Program futures

Because many of these options were equally possible, the team decided that the model needed to be flexible enough to allow us to fit into as many of these futures as possible. Based on the Venn diagram it seemed that the possibility that overlapped with the most other possibilities was option 6: Constellation is cancelled and a modified test flight program is started to test out a new vehicle's components. In terms of the model, this meant the model needed to be of a Heavy Lift Vehicle, specifically an Ares V vehicle, but flexible enough to support changes to similar vehicles. This could mean adding or removing FHEs and their corresponding logic. This also meant that this model would be built separately without integration with the Ares I model in mind.

Since this new model would need to be able to support multiple vehicle types, the team decided it was necessary to build conceptual flow diagrams for multiple vehicle types. The team built conceptual flow diagrams for a Falcon 9-Heavy with a Dragon capsule, a theoretical Ares IV with an Orion capsule, and an Ares I model indicating how it differs from other rocket types. In addition, the Delta IV and Atlas V designs were reviewed, along with other Heavy Lift Vehicle designs NASA was considering at the time. This exercise helped understand the differences and similarities in the vehicles. From this exercise it became clear that many of these vehicles had much in common from the level of detail required in the model. All vehicles had a section that would carry some form of cargo (human or not) and at least two or more stages. The major components would all integrate in one facility immediately before going to the launch pad. Any prior assembly of smaller FHEs would occur exclusively in each of the independent section's flows, and once these smaller parts were integrated they would rarely, if ever, de-integrate. Overall, the main differences were one extra or one less FHE.

4. A New Methodology

Once this flexible approach to model development was decided, the next step was to determine how to make this possible. The previously developed model was built exclusively as an Ares I and Orion vehicle. Because of its complexity, it would have required extensive work to modify for another vehicle. The forthcoming Ares V model, on the other hand, would have to base itself on the Ares I model and at the same time be flexible enough to be changed quickly to another vehicle type.

To better understand this new approach, the Ares I model was reviewed to determine the location of natural breaks in the model flow. These natural breaks were areas where the model could be "cut" so that entire sections could be removed without affecting other parts of the model. This "surgical analysis" of the model allowed the team to determine what areas of the model could be turned into "modules," which would be self-contained components of the model. For example, one module in the Ares I model would contain everything from LAS major component manufacturing, transportation to KSC, LAS Assembly, and LAS Storage before entering the Vehicle Assembly Building for final integration. This section of the model does not have any logic that directly connects to logic for any other FHE and is self-contained.

Other modules, like those related to Orion, had to be grouped in module "families," which were made up of modules that were self-contained for the most part, but were associated with other modules in some way. One example of this was the Orion family of modules. In the Ares I model, Orion was made up of three different major components: the Crew Module (CM), the Service Module (SM), and the Spacecraft Adapter (SA). Each of these components could have comprised their own separate modules, but immediately after each individual module they would enter another module in which they would be assembled together. So, if the CM module was removed from the model, it would create a problem with the Orion Assembly module. As a result of this issue, the CM, SM, SA, and Orion Assembly modules would be considered as part of the Orion "family" of modules (see Figure 3). This would notify the developer that if the CM module was removed then some consideration would need to be given to the other members of its "family." This could mean removal of the other sections in the family as well, or at minimum a slight modification of their logic.

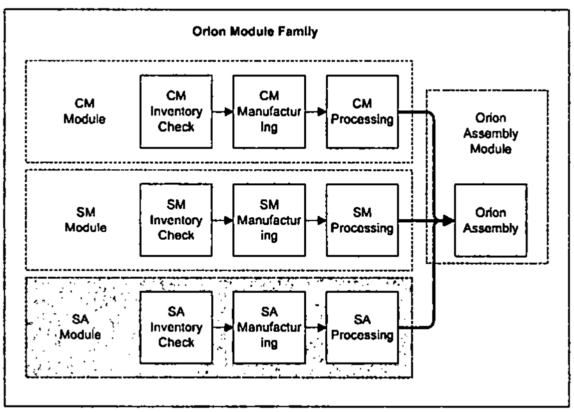

Figure 3. Module Families Example

The other aspect of the Ares I model that became clear was the many signals used throughout the model could make it very difficult to easily change the model. These numerical signals were originally named based on the order they were created. This made it difficult to determine either the source of the signal or the receiver. If a developer wanted to change out entire sections of logic, it would be very easy to leave signals hanging, which would cause havoc in the operation of the model. It also was apparent that documenting each section in the model (within the model itself) would be important to clearly understanding what was being changed.

From this exercise, it was determined that a flexible Ares V model could only be developed with diligent attention to the following:

- all signals were extensively documented
- module "families" were identified
- sections of internal logic were generalized so that they were not specific to one piece of hardware or another

The model was developed taking these lessons in mind. The model was organized in the software application modeling area in a grid-like format for easy access and reference (see Figure 4 and Table 1).

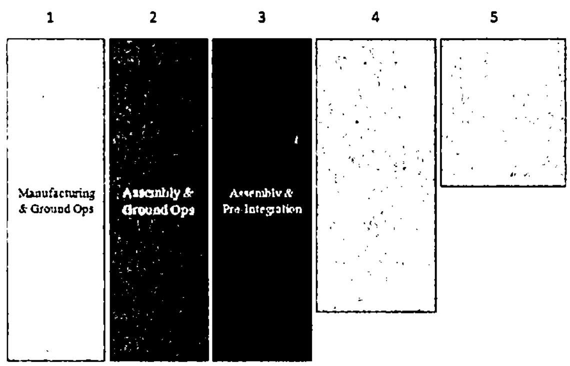

Figure 4. Model Longitudinal Grid-like Sections

For documentation purposes, every module was labeled with a brief description of what this section of the logic entailed.

For the flexible Ares V model, the following seven module families were created:

- Composite Shroud Family
    - Composite Shroud Module: From manufacturing *to* storage before Altair Hazardous Offline Processing
- Altair-Cargo Family
    - Ares V Cargo Module: From production to storage after processing
    - Descent Module (DM) Module: From manufacturing to before Altair Assembly & Close-out
    - Altair Module: From Altair Assembly & Close-out to after transport to VAB
- Integrated Earth Departure Stage (EDS) Family

- Integrated EDS Module: From manufacturing of Altair Adapter, EDS components, J2X, and Interstage to after transport to VAB
- Integrated Core Stage Family
  - Integrated Core Stage Module: From manufacturing of Core Stage components and RS-68B *to* after transport to VAB
- Forward Assembly Family
  - Forward Assembly Module: From manufacturing to after transport to VAB
- Solid Rocket Booster (SRB) Family
  - SRB Module: From SRB segment turnaround, SRB segment manufacture, and Aft Booster Buildup
- Mobile Launcher (ML) Family
  - ML Module: From ML initial inventory station to before ML stacking preps

A very specific methodology was developed for the model signal numbering system. Each signal was 7 digits long with the first two digits representing the FHE number called by the signal (e.g. 08 represents the J2X engine). The middle two digits represented the direction of the signal, with the first of these numbers representing the "from" location and the second number representing the "to" location (e.g. 41 represents a signal being sent from column 4 to column 1) (see Figure 4). These numbers work like longitudinal sections on a grid. The last three digits represented a serial number of a signal of that specific type. So, for example, Signal 0543001 will call FHE #5 (the Composite Shroud in Table 2), the signal is sent from column 4 (the integration section of the logic) to column 3 (the assembly & pre-Integration section), and it is signal number 1 of this type. The below tables show the columns used within the model and the FHEs represented by number.

Table 1. Modeling Area Columns

#	Description
1	Manufacturing & Ground Ops
2	Assembly & Ground Ops
3	Assembly & Pre-Integration
4	Integration
5	Launch and Space Mission

Table 2. Numbering System for FHEs

#	FHE	#	FHE
01	Composite Shroud	12	Core Stage Components
02	Cargo	13	RS-68B
03	Descent Module	14	Integrated Core Stage
04	Altair	15	Processed Integrated Core Stage
05	CS Altair	16	Fwd Assembly
06	Altair Adapter	17	SRB
07	EDS Components	18	Aft Skirt
08	J2X	19	RSRM Segments/Aft Booster
09	Interstage	99	SRB
10	Integrated EDS	88	Mobile Launch Platform
11	Processed EDS	20	Integrated Launch Vehicle

5. Findings from the Flexible Approach

One of the detriments in following such a flexible methodology is that much more time is required for up-front planning. It is not a trivial effort in the modeling of a complex integrated system to determine what logic fits within a module, or what modules make up a family. In addition, developing a signal numbering system describing the origin, destination, and direction of a signal can also be difficult, and the layout of the model can help or hinder this. Also, while planning out the model, it is challenging to keep in mind many other possible configurations and ensure that the logic being implemented does not hinder modification into different forms. Fortunately, this up-front effort can be beneficial in the long run, and not only if changes to the model must be made to accommodate a new vehicle. It was found that this thorough planning, documentation, and modularization made the model extremely organized and easy to follow, which was extremely useful during the testing and verification of the model. The model's organization made it simple to compare what was modeled versus what was originally planned in the conceptual flow, making verification easier.

The most obvious benefit is that it should now be a simpler task to modify the model from one vehicle representation to another.

6. Conclusion

The uncertainty in the future of NASA's Constellation Program presented a major challenge to modeling efforts required to continue the development of the current program-of-record, while remaining flexible for whatever future program replaced it. This required re-thinking the development of the model and making it flexible enough to support unknown future vehicle configurations, while at the same time remain specific to the program-of-record. The team met this challenge through significant pre-planning, including a "surgical analysis" on a previous model to better understand how the logic could most easily be sectioned off. This work led to the "modularization" of the model's structure by identifying generic natural logic break points, the standardization of its inter-logic signal numbering system, and extensive internal documentation. The outcome of this work resulted in a model that was more readily modified to support any future rocket programs, and extremely structured and organized in a way that facilitated rapid customization and verification.

3. References

[1] S. Fayez, M. Steele, G. Cates, D. Miranda, M. Mollaghasemi, L. Trocine: "NASA Constellation Program End-to-End Discrete Event Simulation System Analysis" SpaceOps 2010 Conference AIAA 2010-1996, April 2010.

Author Biographies

DAVID J. MIRANDA is a NASA Simulation Engineer at the Kennedy Space Center. He received his Bachelors in Aerospace Engineering, Masters in Industrial Engineering, and Masters in Business Administration from the University of Central Florida. During his career he has worked on multiple discrete event simulation projects for the space agency in support of the NASA Constellation project.

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MARTIN J. STEELE, PH.D., is a simulation analyst in the Computational Science Branch of the Information Technology Directorate at NASA's Kennedy Space Center (KSC), FL. He has 30 years of NASA and military experience in space and ground systems engineering and operations, primarily at KSC and Cape Canaveral Air Force Station. He is currently leading an Agency-wide team in developing a guidebook for the NASA Standard for Models and Simulations, coordinating and integrating process modeling analysis using discrete event simulation in NASA's Constellation Program, and integrating discrete event simulation with a visualization environment. Martin holds a Ph.D. in Industrial and Systems Engineering, a M.S. in Simulation Modeling Analysis, and a B.S. in Electrical Engineering (with a Computer Science option).

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SISO 2011 Spring SIW

Agenda

- History
- Predicting the Future
- A New Methodology
- Findings
- Conclusion

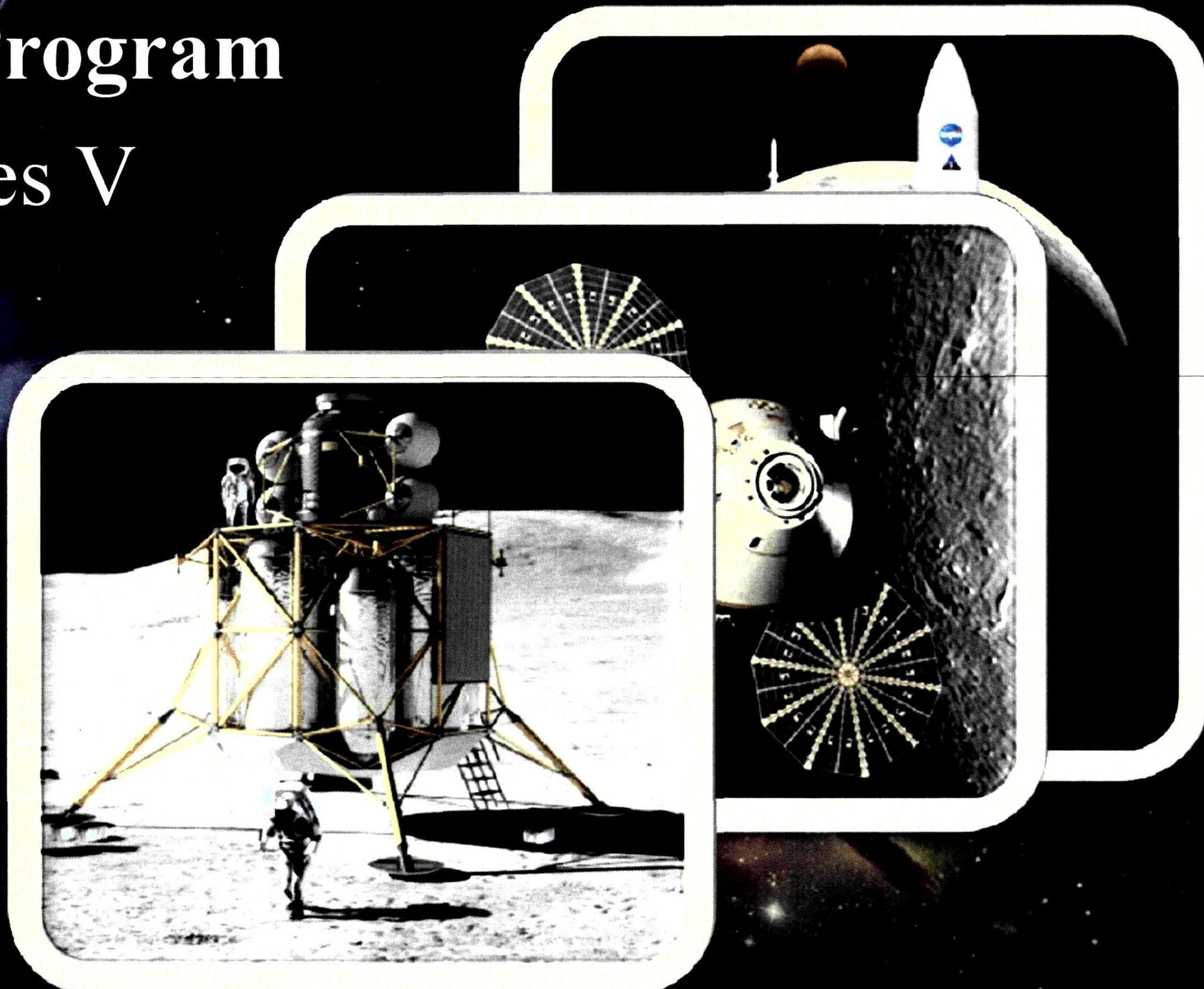
History

- **January 14, 2004:**
  - NASA Authorization Act of 2005 and Vision for Space Exploration initiates the creation of the Constellation Program

History

Constellation Program

- Ares I and Ares V
- Orion
- Altair



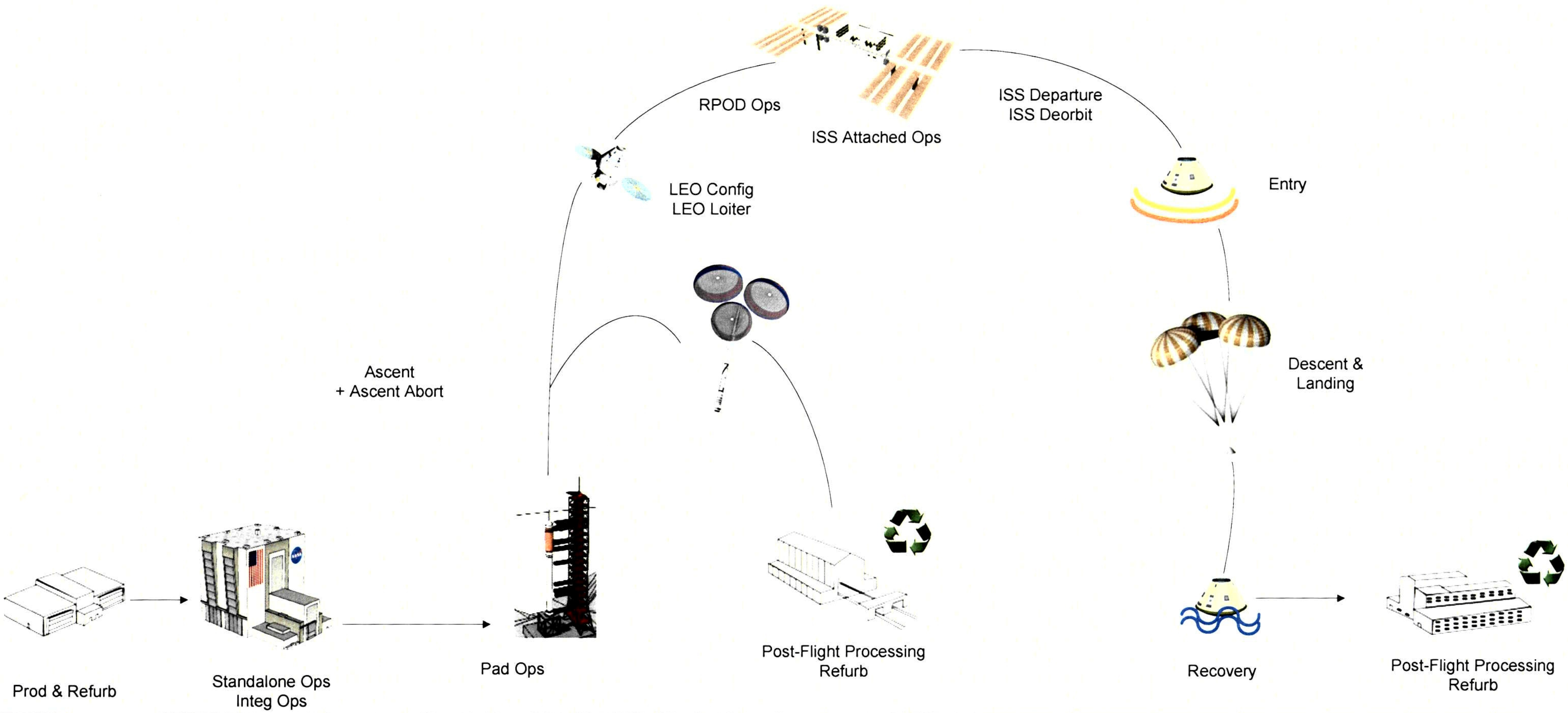
History

- **Constellation Discrete Event Simulation**

CxDES

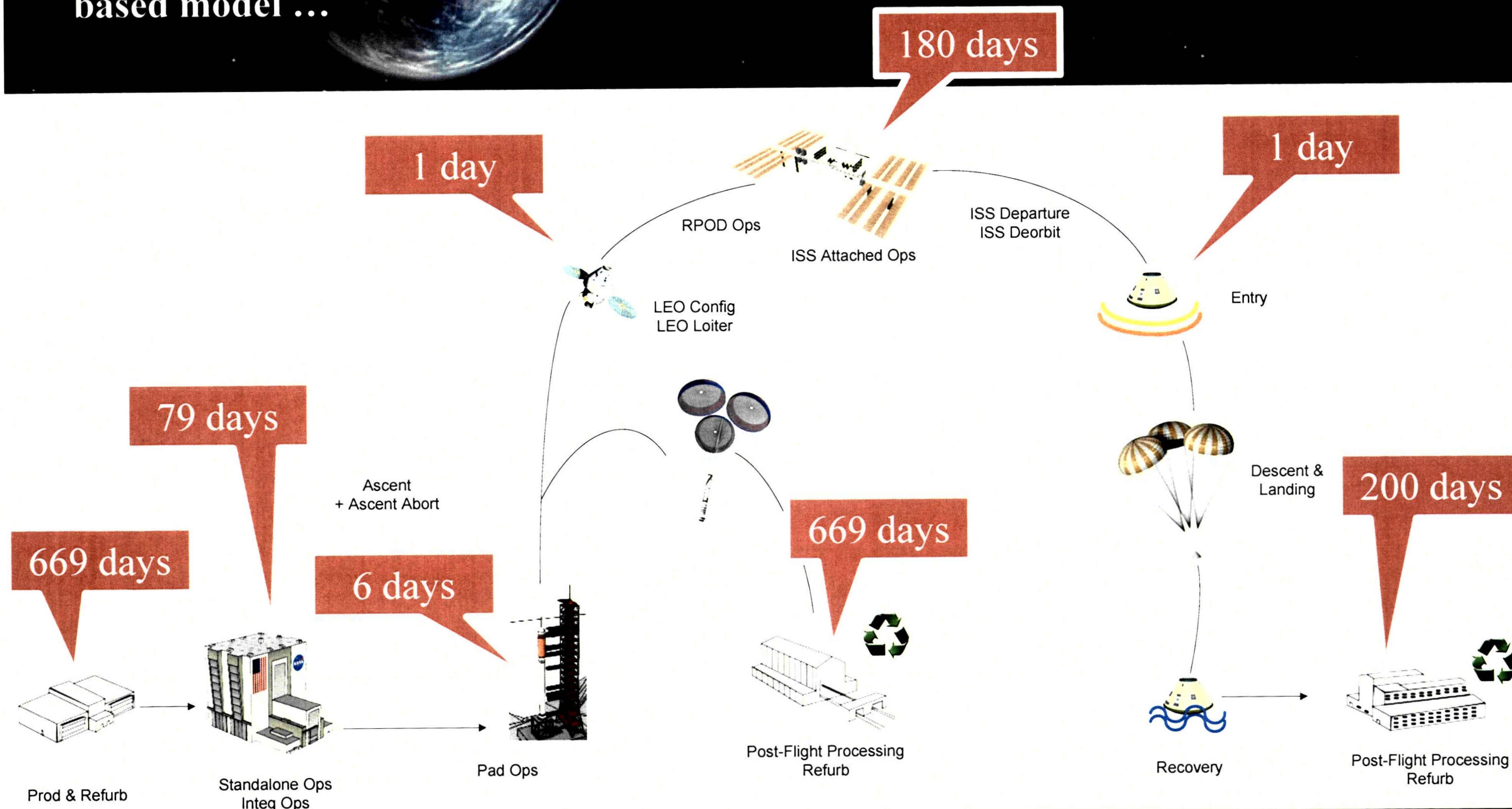
History

Constellation Discrete Event Simulation models the end-to-end process flow of the Cx Program



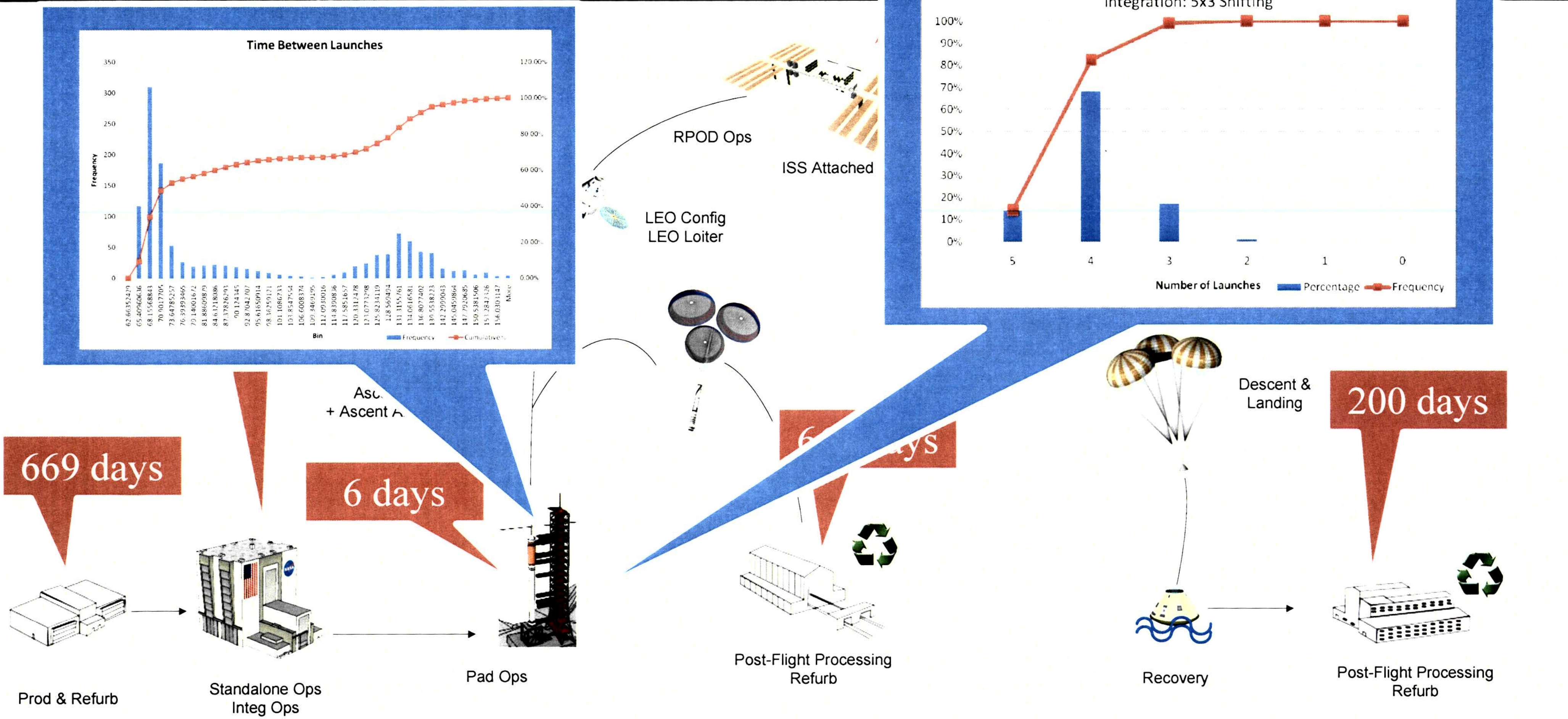
History

Representing system processes in a time-based model …



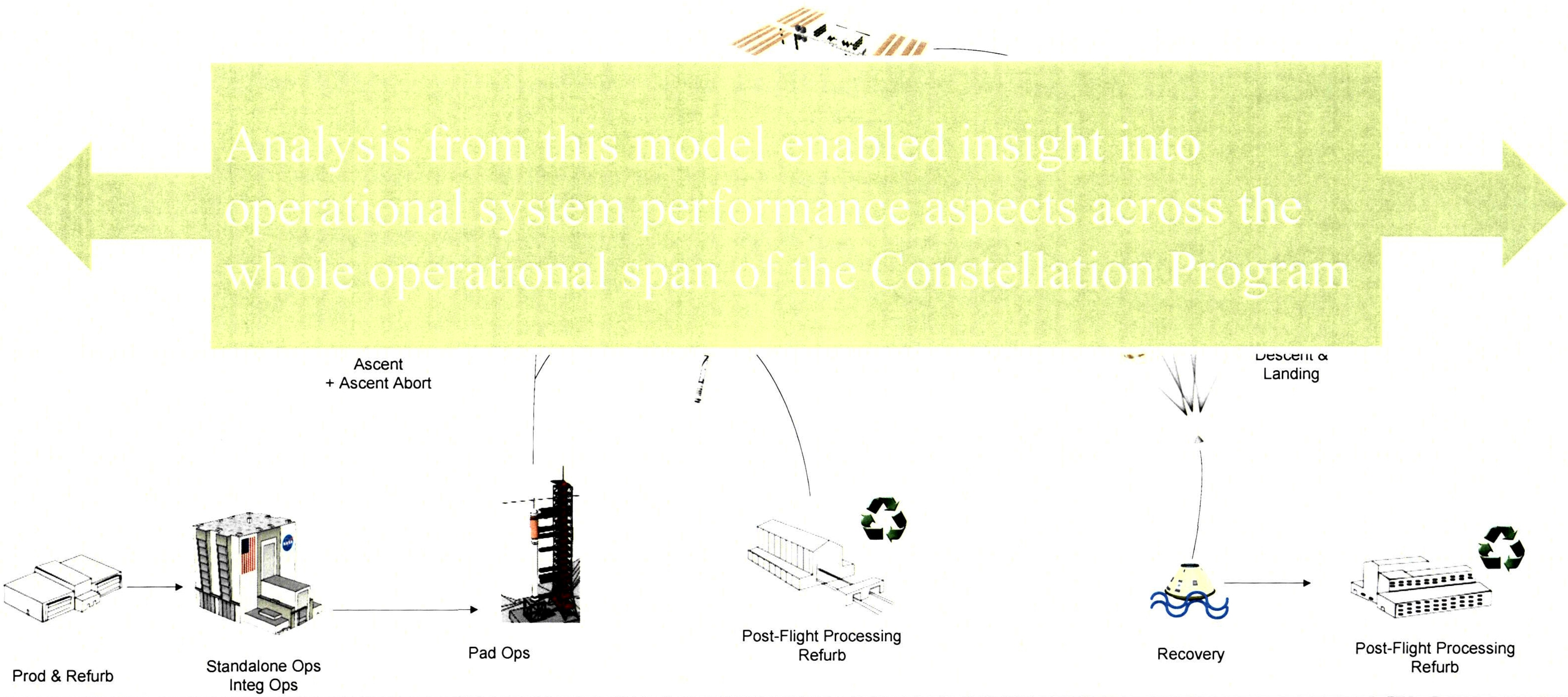
History

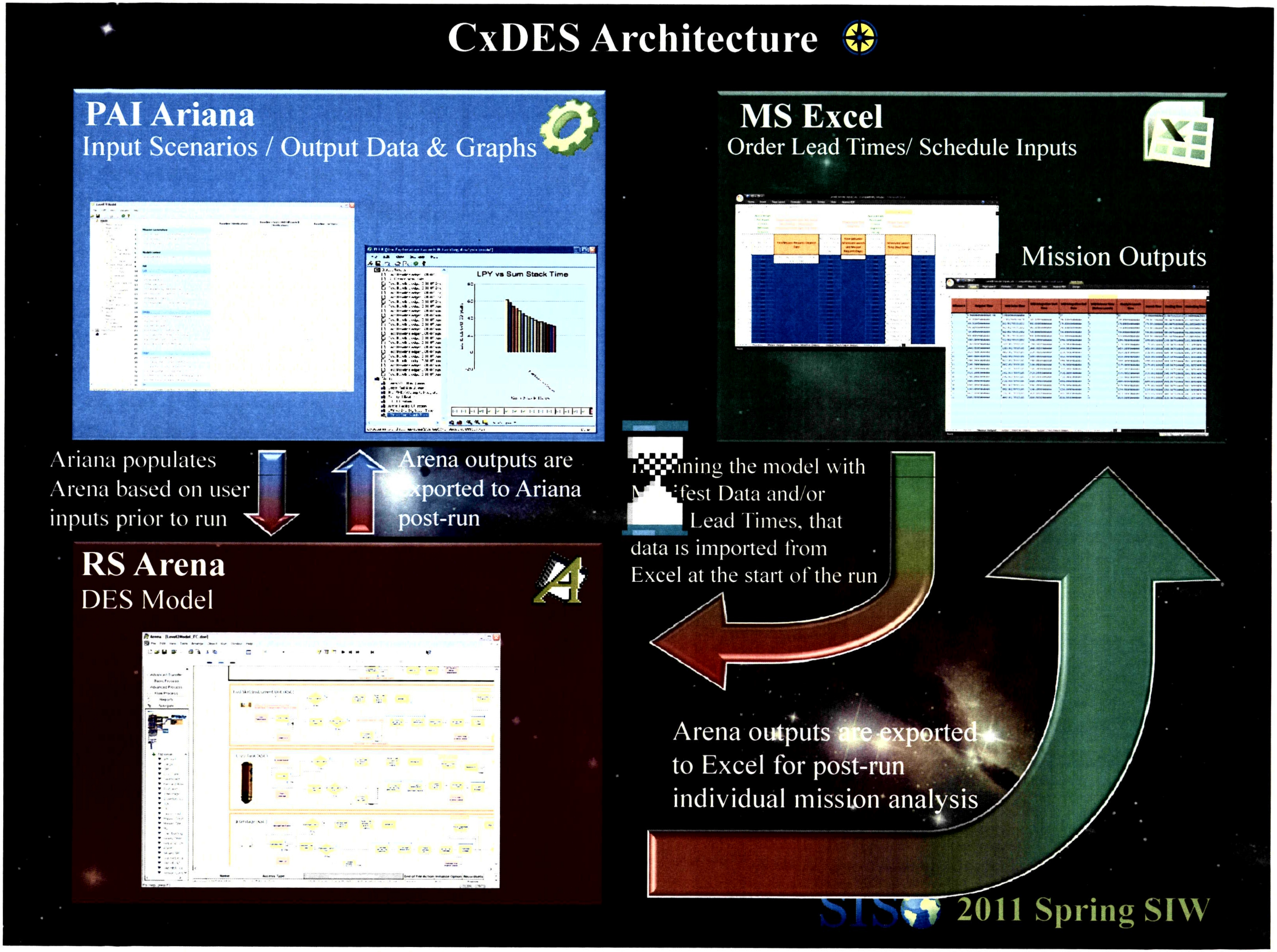
Representing system processes in a time-based model … to perform capacity/time/resource systems level analysis



History

Analysis from this model enabled insight into operational system performance aspects across the whole operational span of the Constellation Program

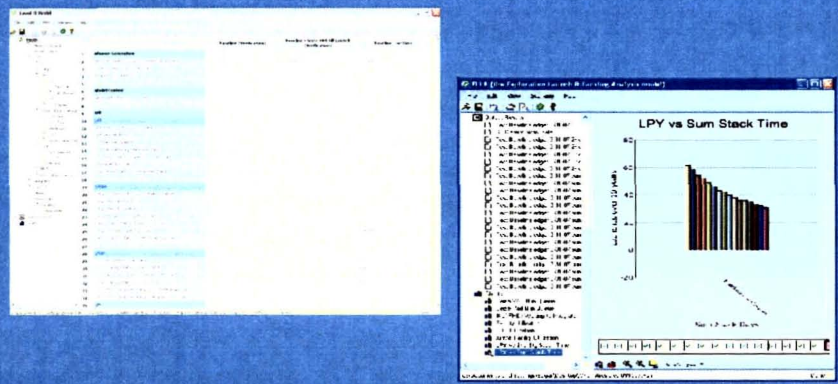



CxDES Architecture
PAI Ariana
Input Scenarios / Output Data & Graphs
LPY vs Sum Stack Time
MS Excel
Order Lead Times/ Schedule Inputs
Mission Outputs
Ariana populates Arena based on user inputs prior to run
Arena outputs are exported to Ariana post-run
ning the model with
fest Data and/or
Lead Times, that
data is imported from
Excel at the start of the run
RS Arena
DES Model
Arena outputs are exported to Excel for post-run individual mission analysis
SISO 2011 Spring SIW

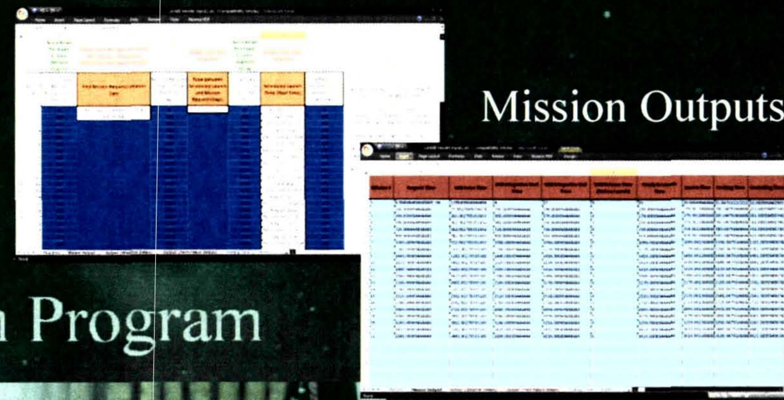
CxDES Architecture

History

PAI Ariana
Input Scenarios / Output Data & Graphs



MS Excel
Order Lead Times/ Schedule Inputs



Mission Outputs

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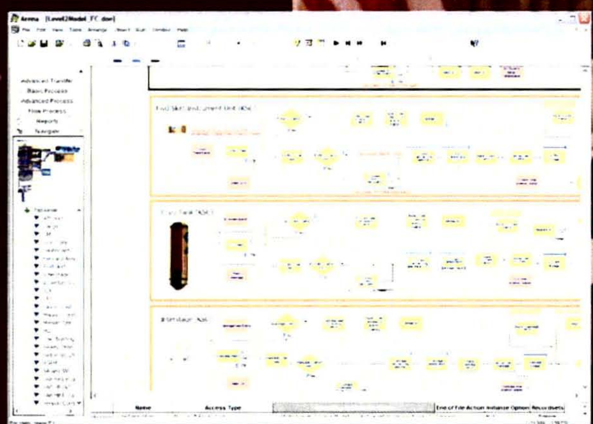
ellation Program

RS Arena
DES Model

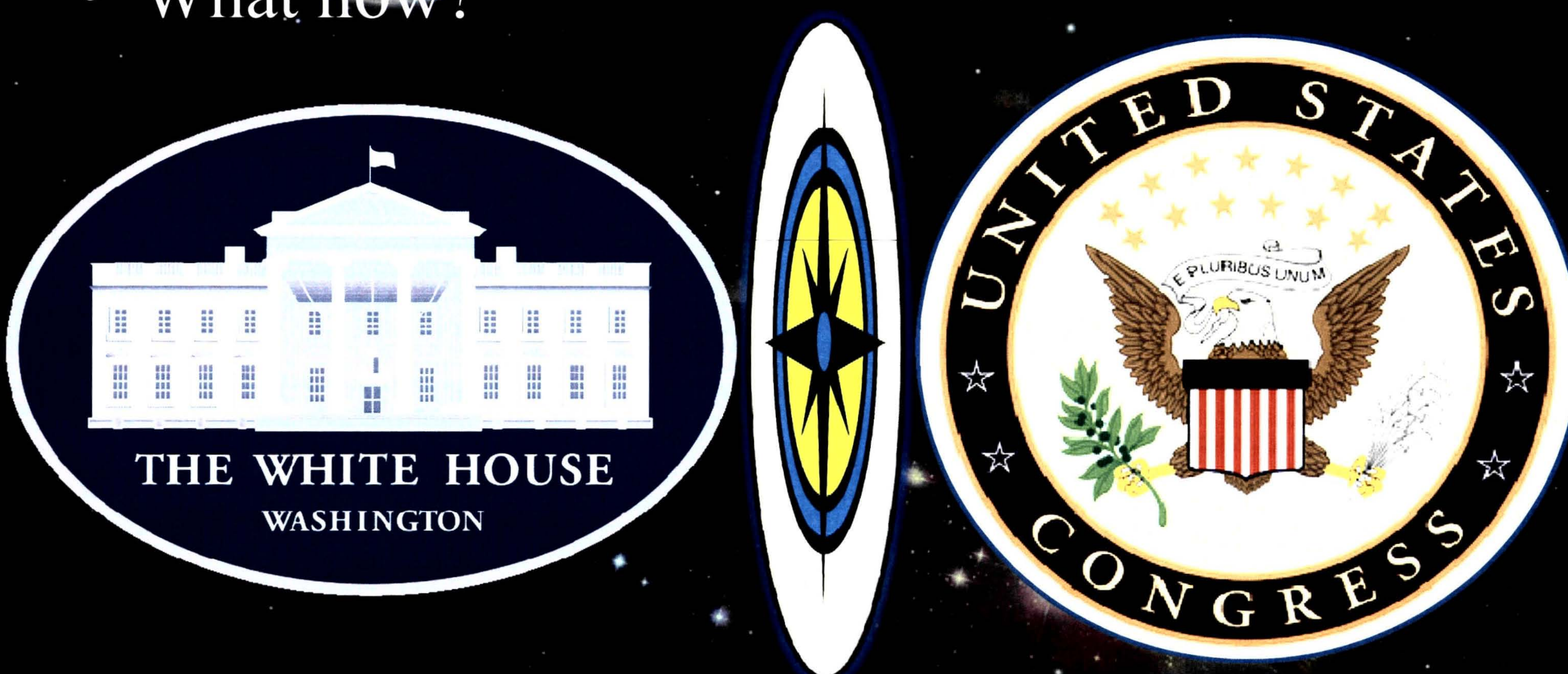


Predicting the Future

- Presidential direction is to **cancel** Constellation
- Congressional direction is to **continue** Constellation
  - **By law** program of record must continue
- …but for all practical purposes Constellation was **finished**

Predicting the Future

- What now?



Predicting the Future

- What are the alternatives?
  - We narrowed it down to 6 possible scenarios

Predicting the Future

- Scenario 1
  - Constellation **continues**, as if the President had never cancelled the program in the FY 2011 budget.
- Impact on CxDES
  - Build the Ares V model as originally envisioned and eventually integrate it with the Ares I model.

CONSTELLATION

Predicting the Future

- Scenario 2
  - Constellation continues with an enhanced test flight program.
- Impact on CxDES
  - Build the Ares V model as originally envisioned and eventually integrate it with the Ares I model. Modify the existing Ares I model for analysis to support the proposed test flights, as well as use the data from the test flight program to improve the fidelity of the data used in the models.

CONSTELLATION

DEVELOPMENT FLIGHT TEST
ARES I-X

Predicting the Future

- Scenario 3
  - Constellation is **cancelled** with no NASA program to take its place.
- Impact on CxDES
  - Stop all work on the models, collect all work done up to this point, and store the information for future use.

CONSTELLATION

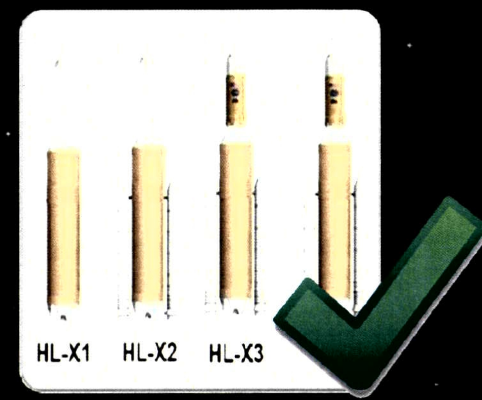
Predicting the Future

- Scenario 4
  - Constellation is cancelled and a new Heavy Lift Vehicle program takes its place.
- Impact on CxDES
  - Archive the Ares I model and develop a model for the new Heavy Lift Vehicle using the Ares I model as the basis or start completely from scratch.

Predicting the Future

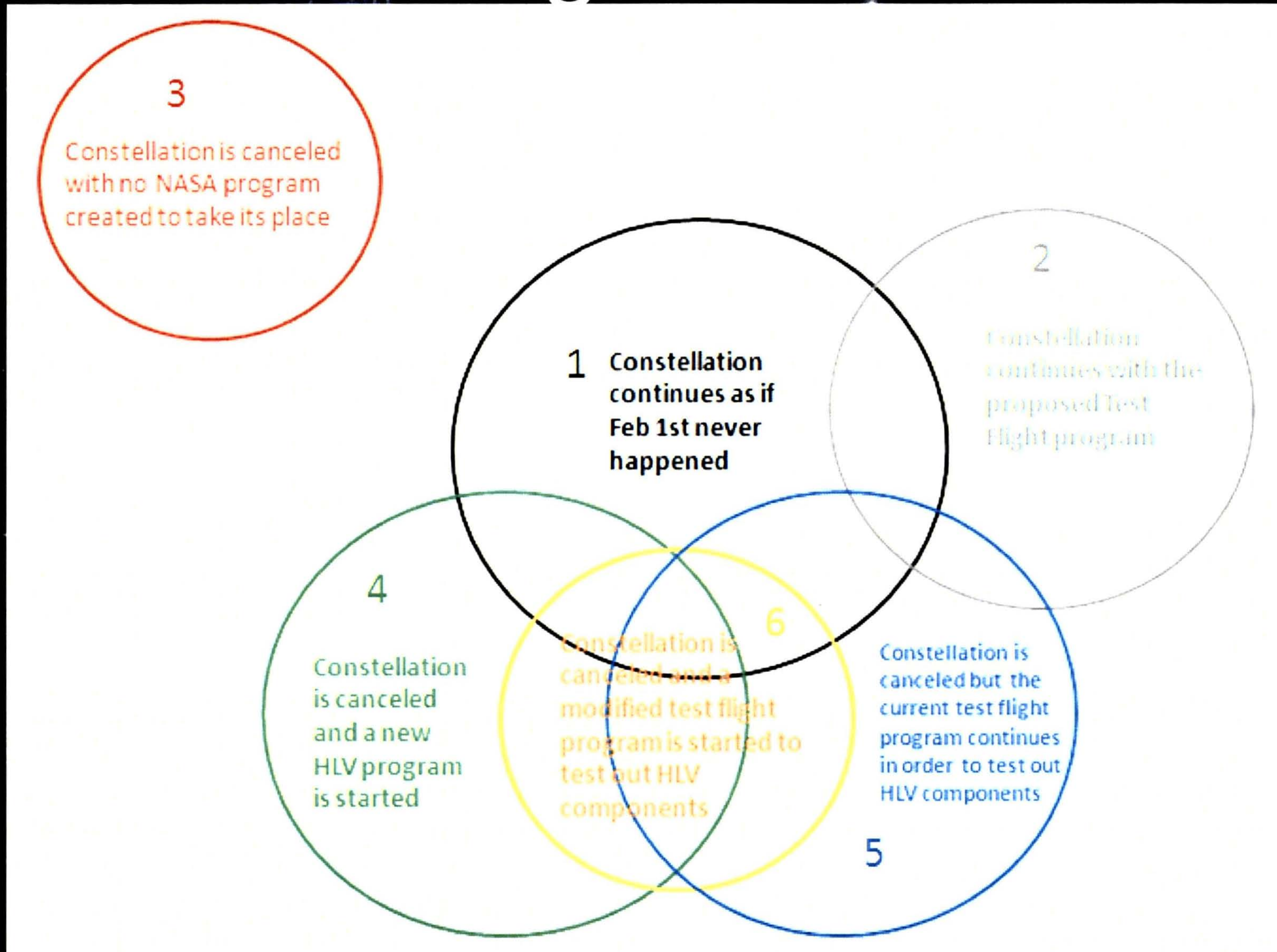
- Scenario 5
  - Constellation is cancelled but an Ares I test flight program continues in order to test out a new vehicle's common components.
- Impact on CxDES
  - Modify the existing Ares I model to analyze the proposed test flights as well as use the data from the test flight program to improve the fidelity of the data being used in the models. Then, build a model for the new Heavy Lift Vehicle using the Ares I model as the basis or start completely from scratch.

Predicting the Future

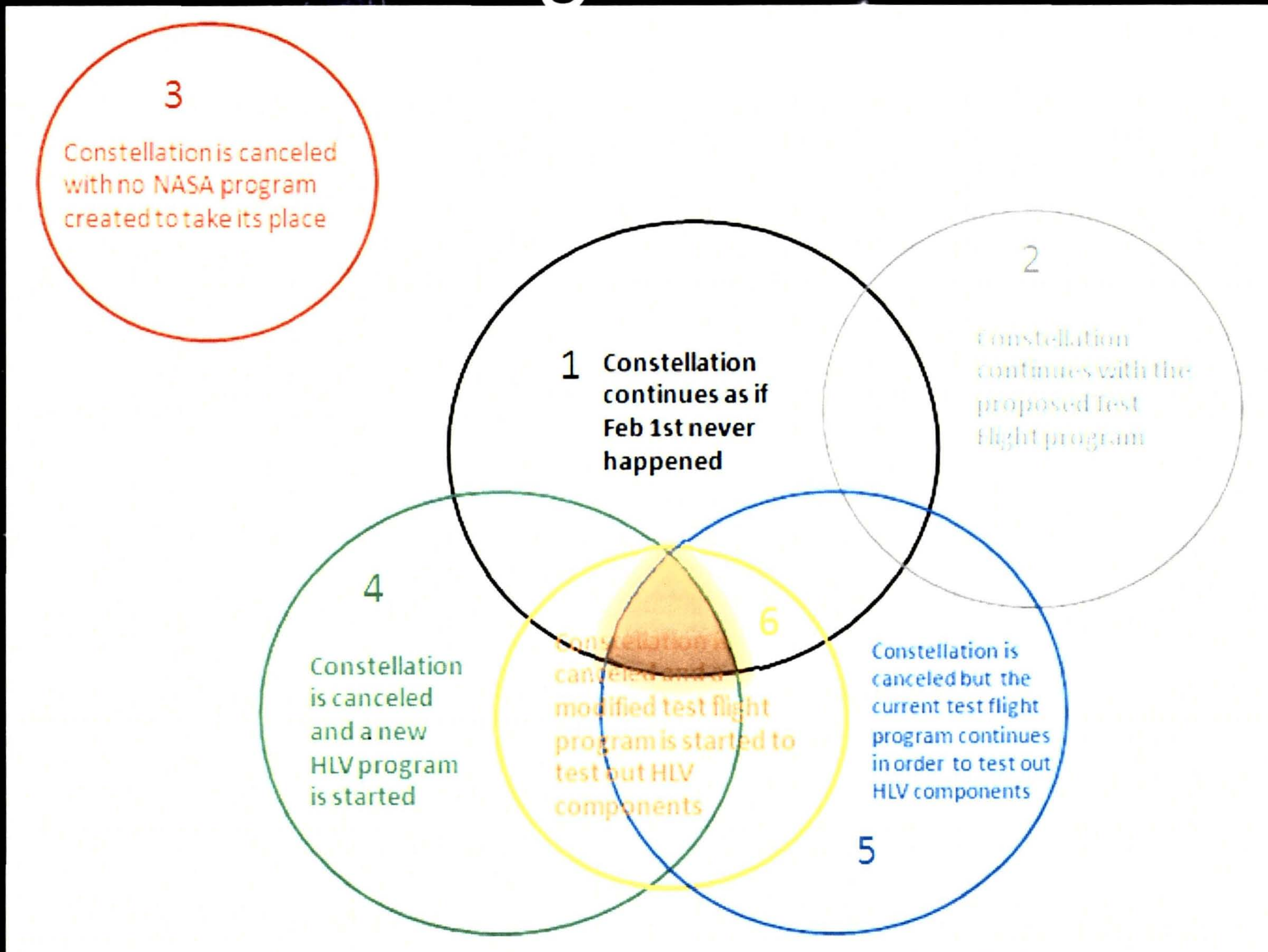


- Scenario 6
  - Constellation is cancelled and a modified test flight program is started to test out a new vehicle's common components.
- Impact on CxDE
  - Develop a model for the new Heavy Lift Vehicle using the Ares I model as the basis or start completely from scratch. Use the relevant data learned from the test flight program to improve the fidelity of the data collected for the new model.

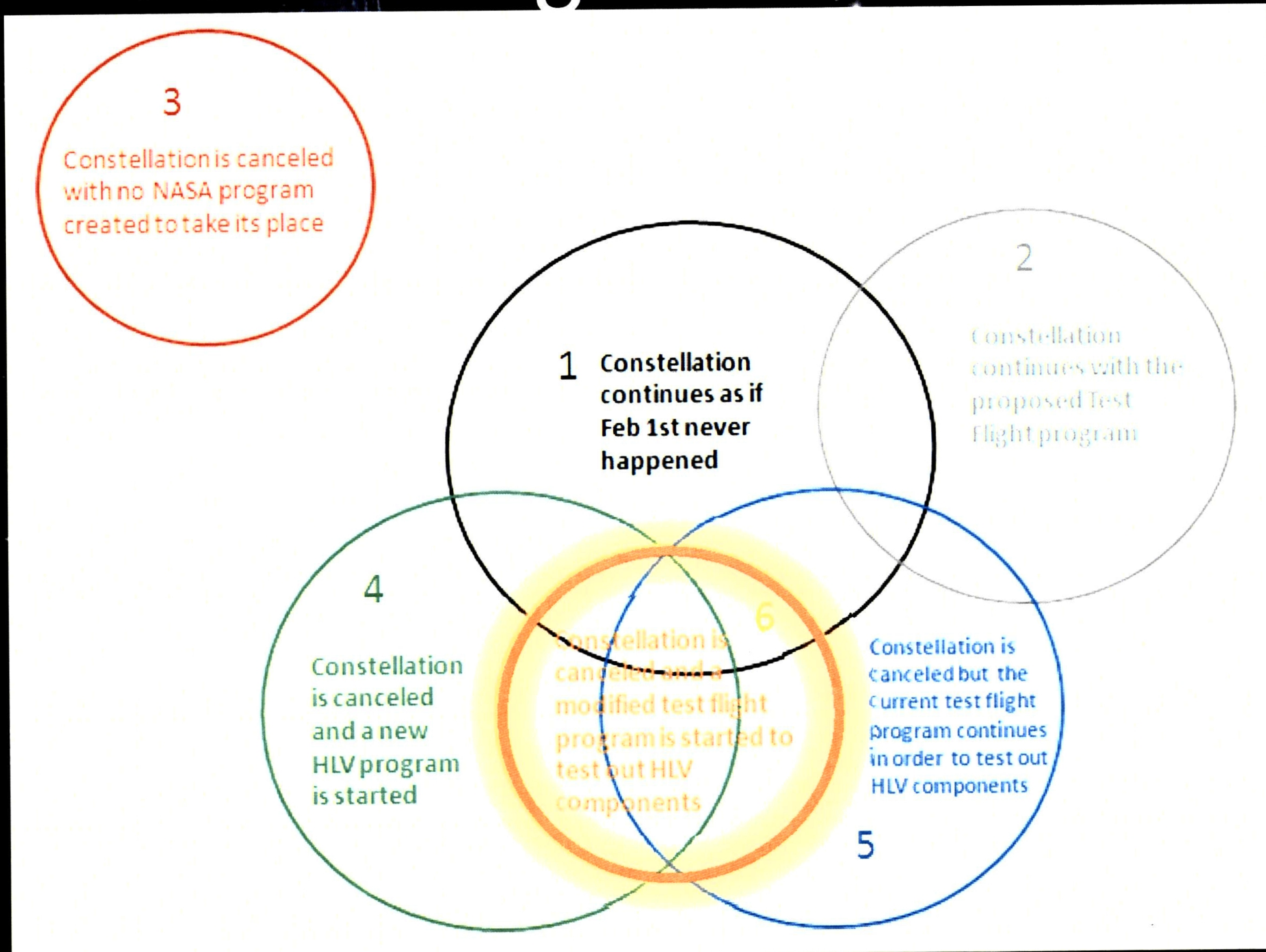
Predicting the Future



Predicting the Future



Predicting the Future

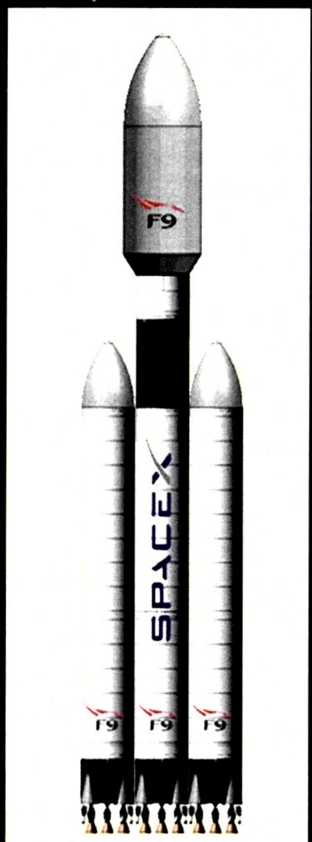


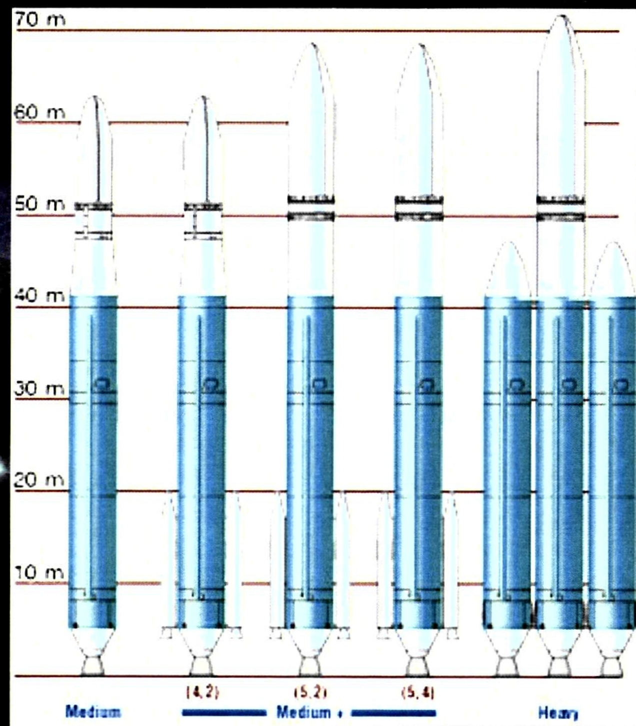
Predicting the Future

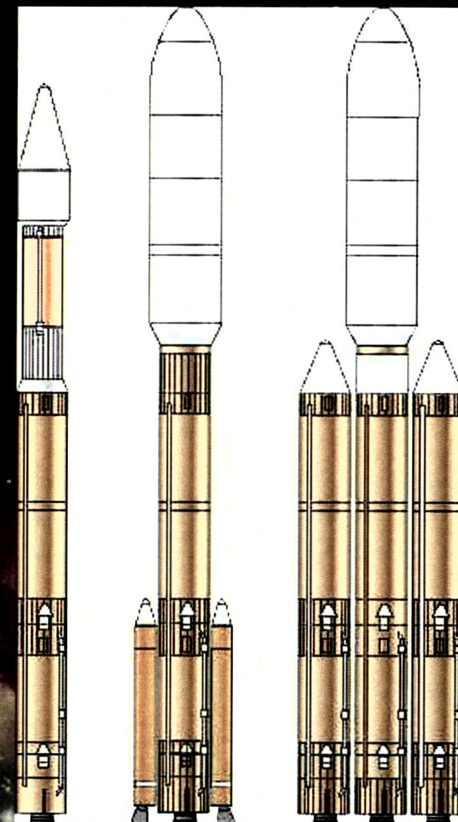
- Model to be built:
  - Start with a Heavy Lift Vehicle of an Ares V-type
  - Flexible to support a test flight program

A New Methodology

- Review of Potential Vehicle Configurations





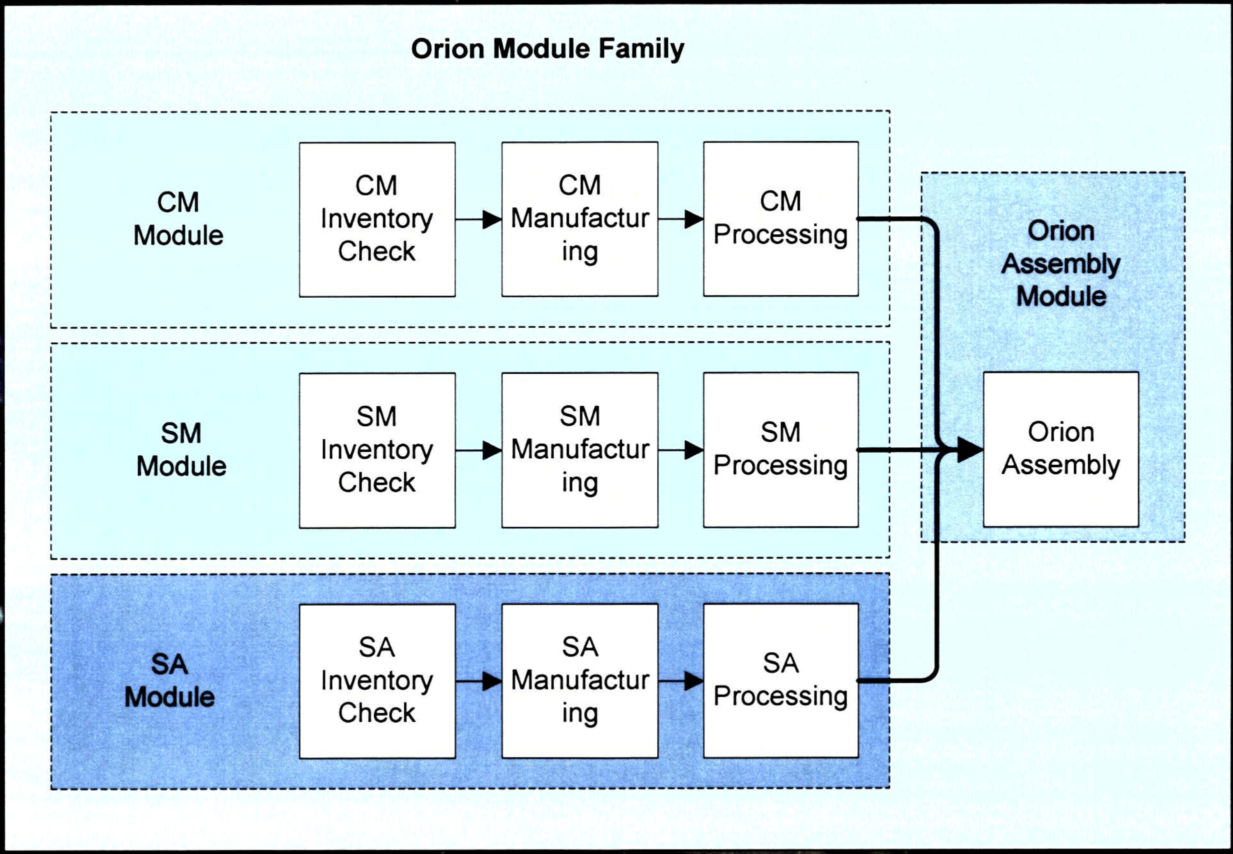


A New Methodology

- The Ares I model was reviewed to determine the location of natural breaks in the model flow. These natural breaks were areas where the model could be "cut" so that entire sections could be removed without affecting other parts of the model. This "surgical analysis" of the model allowed the team to determine what areas of the model could be turned into "modules," which would be self-contained components of the model.

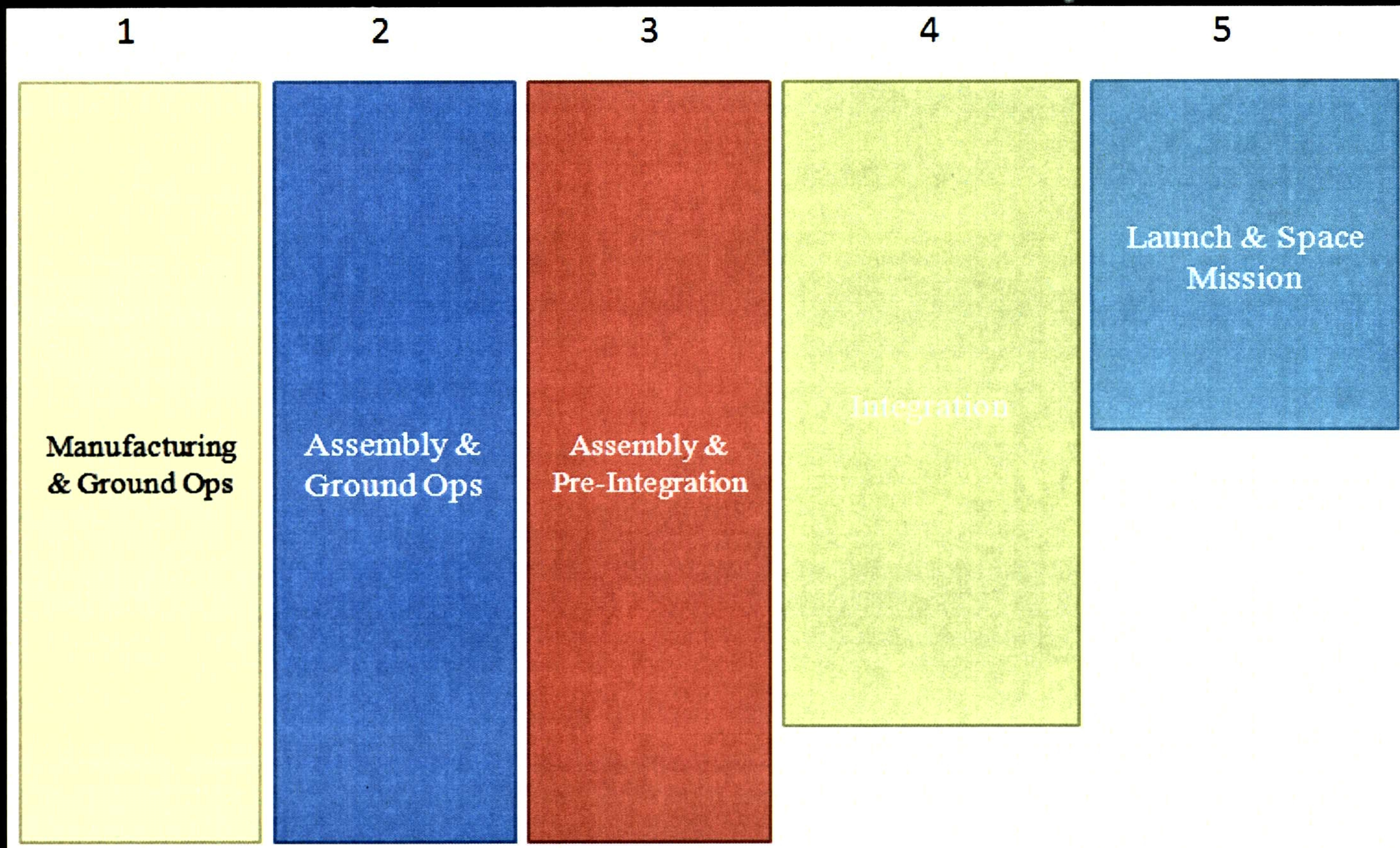
A New Methodology

- **Module "families":** made up of modules that are self-contained for the most part, but are associated with other modules in some way.



A New Methodology

The model was organized in the software application modeling area in a grid-like format for easy access and reference



Findings

- One of the detriments in following such a flexible methodology is that much more time is required for up-front planning.
- This up-front effort can be beneficial in the long run, and not only if changes to the model must be made to accommodate a new vehicle.
  - It was found that this thorough planning, documentation, and modularization made the model extremely organized and easy to follow, which was extremely useful during the testing and verification

Conclusion

- The outcome of this work resulted in a model that was more readily modified to support any future rocket programs, and extremely structured and organized in a way that facilitated rapid customization and verification.