Launch and Assembly Reliability Analysis for Human Space Exploration Missions

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Abstract—**NASA's future human space exploration strategy includes single and multi-launch missions to various destinations including cis-lunar space, near Earth objects such as asteroids, and ultimately Mars. Each campaign is being defined by Design Reference Missions (DRMs). Many of these missions are complex, requiring multiple launches and assembly of vehicles in orbit. Certain missions also have constrained departure windows to the destination. These factors raise concerns regarding the reliability of launching and assembling all required elements in time to support planned departure. This paper describes an integrated methodology for analyzing launch and assembly reliability in any single DRM or set of DRMs starting with flight hardware manufacturing and ending with final departure to the destination. A discrete event simulation is built for each DRM that includes the pertinent risk factors including, but not limited to: manufacturing completion; ground transportation; ground processing; launch countdown; ascent; rendezvous and docking, assembly, and orbital operations leading up to trans-destination-injection. Each reliability factor can be selectively activated or deactivated so that the most critical risk factors can be identified. This enables NASA to prioritize mitigation actions so as to improve mission success.**

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1. INTRODUCTION

Over the last several years, NASA has been analyzing strategies for future human exploration beyond Low Earth Orbit (LEO). Several of these strategies incorporate Design Reference Missions (DRMs) to various destinations including cis-lunar space, the Moon, Near Earth Asteroids (NEAs) and the Mars system. Because of the high energy requirements to reach the various destinations, some of these DRMs require multiple launch vehicles to place crew and deep space vehicle elements in an assembly orbit prior to departure to the destination. The complex nature of these missions, coupled with specific destinations having constrained departure windows, calls into question the reliability of launching and assembling all the required elements in a timely manner to support the planned departure to the destination of interest.

To assist in the reliability analysis, NASA has been developing an integrated methodology to analyze launch and assembly reliability. This work builds upon previous analyses performed for the Constellation program [1, 2] and for the Review of Human Space Flight Plans Committee [3].

The integrated launch and assembly reliability methodology starts with flight hardware manufacturing and ends with final departure to a destination. Pertinent risk factors are accounted for within a stochastic discrete event simulation for each DRM. Reliability factors can be selectively activated or deactivated to understand the criticality of each factor and aid in the prioritization of mitigation strategies to improve overall mission success.

This paper details the complexity and risks of launch and assembly in Section 2. Section 3 gives an overview of the human exploration missions that NASA is analyzing along with the concept of operation for a near Earth asteroid mission. The fourth section describes the simulation models. Section 5 lists the cases analyzed followed by the results in Section 6. Conclusions and forward work are addressed in Section 7.

2. COMPLEXITY AND RISKS OF LAUNCH AND ASSEMBLY

Exploration beyond LEO introduces complexities and risks to missions that have the potential to reduce overall reliability. It is anticipated that most deep space missions will require multiple launches from Earth with some degree of spacecraft assembly in Earth vicinity. The process of completing all of the required launches and assembly activities could be complex and will certainly require significant time. Because most deep space mission destinations have limited windows for departure from the assembly point, due to orbital mechanics, missions will have to be carefully staged so that launch and assembly activities can be reliably completed prior to the desired departure window.

Key Constraints

Deep space missions have several constraints that will directly impact the launch and assembly reliability. The primary constraint relates to the available departure window from the deep space vehicle assembly point to the destination.

The duration, timing, and repeatability of departure windows for deep space missions are highly variable and depend heavily on the selected target. Lunar missions typically have departure windows that repeat in perpetuity on an average of every 9-10 days. Minimum energy departure opportunities to Mars occur on average only once every 26 months. For NEAs the timing and duration of the departure windows are dependent on the orbit of the particular object. Certain NEAs have long departure windows that repeat over a period of years. Others may have a number of short opportunities, separated by several months. Still others may have a single departure opportunity with a total duration of only a few days.

For most destinations other than the Moon, it will be very difficult to develop a mission plan that will allow for the targeting of more than a single departure opportunity from the assembly point. It is theoretically possible that a NEA mission could be designed with a backup destination that could be targeted if the departure window for the primary destination was missed. In this case the crew launch could be delayed or a second crew launch attempted to support the backup destination. However, the targeting of a backup destination is problematic. First, having to identify a NEA with a backup destination that meets the assembled transportation system capabilities and has a departure window that is close to the one for the primary destination could severely limit the number of possible destinations. Second, it is anticipated that a large amount of preparatory work, including the conduct of robotic precursor mission and design of exploration activities, will be completed to support the primary destination mission. It would be challenging to complete these activities for multiple possible targets.

In addition to the departure window to the destination, there are other orbital constraints that could add complexity to the launch and assembly process. If the deep space vehicle is assembled at a location other than LEO, there will only be periodic opportunities to transfer elements and crew to the assembly location. In addition, if Moon and/or Earth fly-by events are used to aid in the departure to the destination, the positioning of those bodies will add further constraints on the departure window.

Launch and assembly reliability could be improved by adding time margin to the launch and assembly schedule. If launches for all elements and the crew were planned to occur earlier, relative to the destination departure window, the probability of completing all of the required activities in time to meet the departure opportunity increases significantly. However, there are additional constraints that limit the ability to add time margin to the launch and assembly schedule.

Increasing the amount of time that elements of the deep space vehicle loiter at the assembly adds additional risk to the assembly process. The probability of system failures within the elements or of micrometeorite and orbital debris (MMOD) strikes increase as loiter time is extended.

Crew time in space is also a major issue with adding margin to the launch and assembly process. Because the crew launch is typically the last launch in the sequence, adding margin between that event and the departure window will have the greatest impact on reliability. However, there are significant issues to adding to the amount of time that crew must spend in space. For many of these anticipated deep space missions the expected mission time may already be greater than one year. These long durations will already present challenges to the crew. Requiring the crew to loiter at the assembly point prior to departure will only increase those risks. Additional time loitering at the assembly location also increases the risk that a crew health event will occur that requires an abort back to Earth, ending the mission.

The constraints on departure to the destination and on loitering at the assembly point will require that a high level of reliability be achieved in the launching and assembly of spacecraft prior to the departure window. Failure to complete launch and assembly prior to the departure window would result in mission failure, as the deep space vehicle would no longer be able to reach the intended destination.

Types of Risks

The types of risks involved in the launch and assembly of the deep space vehicle can be divided into two major categories: Pre-Launch Risks and Post-Launch Risks.

Pre-Launch Risks are those that occur prior to ignition of the main engines of the launch vehicle for any launch that supports the mission. These risks involve all of the activities required to manufacture, deliver, assemble, and prepare each vehicle for launch.

Manufacturing Reliability—All elements for the deep space mission, including deep space vehicle elements, launch vehicles, and propulsive elements must be manufactured, tested, and delivered to the space center. Delays in these activities would delay the launch and assembly schedule.

Processing Reliability—Processing capabilities at the space center are limited by facilities and personnel constraints. These constraints dictate the planned launch schedule for elements. Delays in completing element processing and launch vehicle assembly could significantly impact the launch and assembly schedule.

Launch Reliability—The launch of spacecraft in Earth orbit is notoriously unreliable. Historically, the success rate for launching a spacecraft on any specific attempt has been a little above 50%. The Space Shuttle launch probability throughout its history was 0.53. Even the relatively simple Delta II only had a 0.56 launch probability for launches between 1989 and 2001 [4]. While many delays are weather related or involve minor problems that can be quickly corrected, either of which allow the next attempt to occur quickly, there are often failures on the launch pad that require long periods of time to correct. Conducting multiple launches to support a deep space mission increases the exposure to launch delays, potentially reducing the overall probability of meeting the departure window.

Post-Launch Risks are those that occur after the ignition of the main engines of the launch vehicle and involve all of the activities required to position and assemble elements, deliver the crew to the deep space vehicle, and prepare for departure.

Launch Failure—The launch and ascent of a vehicle into LEO is typically one of the most risky phases in any space mission. Conducting multiple launches into LEO to support the mission will increase the overall probability of launch failure in at least one of the launches.

Element Failure on Orbit—As elements loiter in LEO or at some other potential spacecraft assembly point, there are multiple types of failure that can occur that could endanger the mission. Potential failures include unrepairable system failures within the spacecraft elements, MMOD strikes on spacecraft elements, and damage due to radiation exposure. These risks increase as loiter period increases.

Propulsive Failure—Subsequent to launch into LEO, many missions will require elements to be relocated to the spacecraft assembly location. This will require some form of in-space propulsion. Failure or delays with these events could result in failure of the overall mission.

Assembly/Docking Failure—Assembly of the deep space vehicle will require that multiple independently launched elements be aggregated in space. That will require some form of rendezvous and docking of those elements. Because the crew will likely not be present when most of the assembly events occur, the assembly will involve automated rendezvous and docking (ARD) events. Historically, ARD has proved troublesome for in-space vehicles and a number of failures have occurred. Failure in the assembly of the deep space vehicle could result in failure of the overall mission.

Crew Issues—Problems with the crew, including health issues and injury, can occur as the crew travels to the assembly location, and/or loiters in the deep space vehicle prior to departure. Serious crew issues could require abort back to Earth and abandonment of the mission.

The constraints and risks described herein require that missions be designed in a way that the total achieved launch and assembly reliability will result in an acceptable probability of mission success. The reliability and the timing of launch and assembly events must be carefully evaluated in order to identify and mitigate those risks.

There is a fundamental tension between adding margin to the launch schedule and the amount of in-space risk exposure. A balance must be achieved between these factors in order to develop an acceptable level of overall reliability.

This evaluation should occur in conjunction with the analysis and design of the launch systems and deep space vehicle elements. Because none of these systems and many of the technologies that are incorporated into them do not yet exist, it is necessary to estimate capabilities and system reliabilities.

3. CONCEPT OF OPERATIONS FOR HUMAN SPACE EXPLORATION MISSIONS

Currently, NASA is analyzing the requirements for beyond low Earth orbit missions, including missions to cis-lunar space, the Moon, NEAs, and the Mars system. Each of the missions, designated a DRM, helps to define the transportation and in-space systems required to complete the goals of the mission. For many of these DRMs, multiple launch vehicles are required to deliver the crew, in-space elements and logistics required to support the crew for long durations in transit to and at the destinations. In addition, these DRMs may include on orbit assembly of vehicles and constrained destination departure windows.

As NEA missions typically include both multiple launch vehicles and constrained departure windows, a NEA DRM to 99942 Apophis (2004 MN4), Apophis for short, was chosen as a test case. Figure 1 shows this example with an all-chemical propulsion transportation architecture to a NEA. This particular DRM requires three launch vehicles of the Space Launch System (SLS) to deliver the crew, in-space elements and in-space propulsion stages to an assembly orbit. The first launch places the Deep Space Habitat (DSH) and Robotics & Exploration Module (REM) into the 5-day period High Earth orbit (HEO) through the combined propulsion of the launch vehicle and the Cryogenic Propulsion Stage (CPS). After arrival of these elements, the CPS is undocked and moved into a proper disposal orbit. The DSH and REM remain in the assembly orbit until the second launch arrives. The second launch consists solely of a second CPS. This CPS places itself in the assembly orbit and is used for part of the HEO departure burn and the NEA arrival burn. The CPS docks to the elements in the assembly orbit and waits for the crew arrival. The third launch consists of the Multi-Purpose Crew Vehicle (MPCV), crew and a third CPS. This CPS places the crew in the assembly orbit and performs a portion of the HEO departure burn. After the elements are assembled, there is a minimum 9 day checkout period of the DSH & REM prior to departing for the NEA. From this HEO, there are two departure opportunities, spaced 30 days apart. The transit time from leaving the HEO to arriving at the NEA is approximately 302 days for this particular NEA. The crew then stays at the NEA for 14 days, performing science, exploration and EVA activities. Prior to departure from the NEA, the REM is undocked and left at the destination to perform further science and exploration activities robotically. The Crew departs the NEA and transits back to Earth in the DSH and MPCV. Prior to Earth entry, the DSH and MPCV SM (Service Module) are undocked and disposed of at appropriate locations.

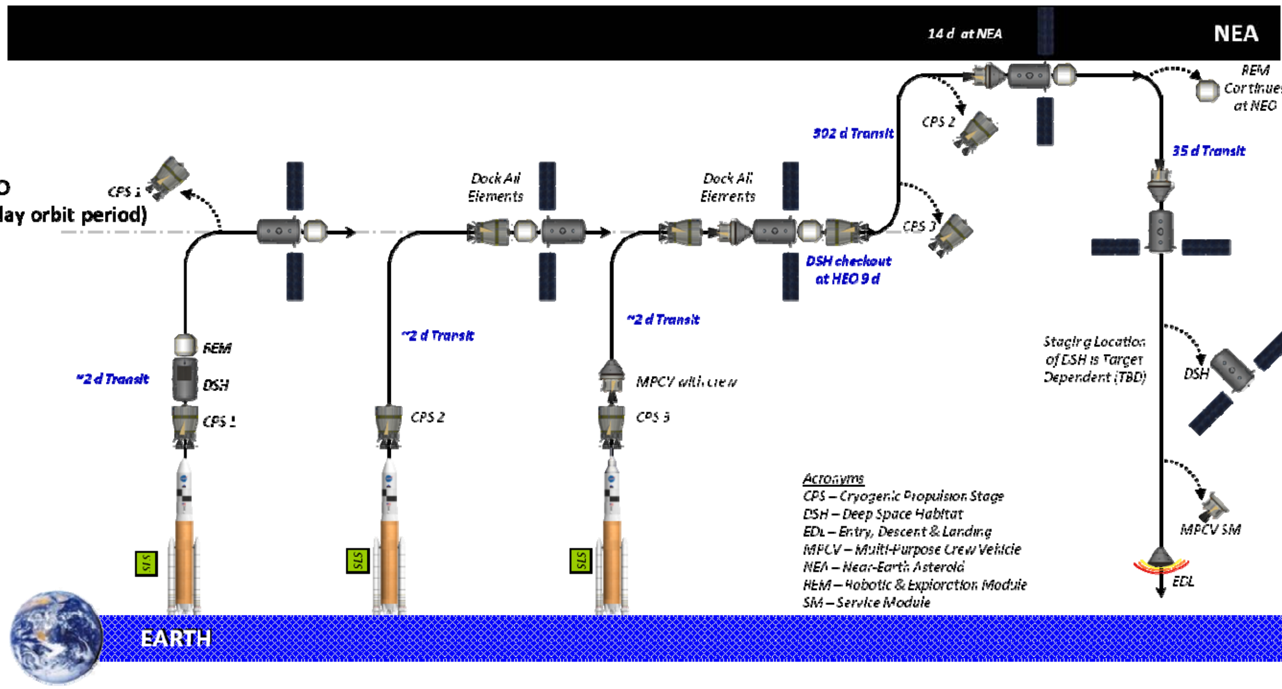

Figure 1 – Example Design Reference Mission to a Near-Earth Asteroid

4. DESCRIPTION OF SIMULATION MODEL

A stochastic discrete event simulation model was created using Rockwell Automation's Arena simulation software [5].

Figure 2 provides a high level overview of the model, which includes linkages to Excel files for inputs and results. The model logic includes entity routing to reflect all of the major processes and operations in the launch and assembly sequence from manufacturing completion through readiness for the destination departure burn - from the assembly location.

The simulation is run for 1,000 replications, with each replication representing one possible manifestation of the launch and assembly sequence. The only difference between the replications is the random numbers used to drive the various risk models.

Different components of the mission such as in-space elements, launch vehicles and crew are represented as entities within the simulation. Each replication starts with an entity representing the mission reading in all of the manifest information regarding planned flight hardware delivery dates, planned launch dates, and departure window information. The entity then splits into multiple entities representing each flight hardware element along with a remaining entity that represents the mobile launcher. The entities representing flight hardware elements follow the routing path shown in Figure 3.

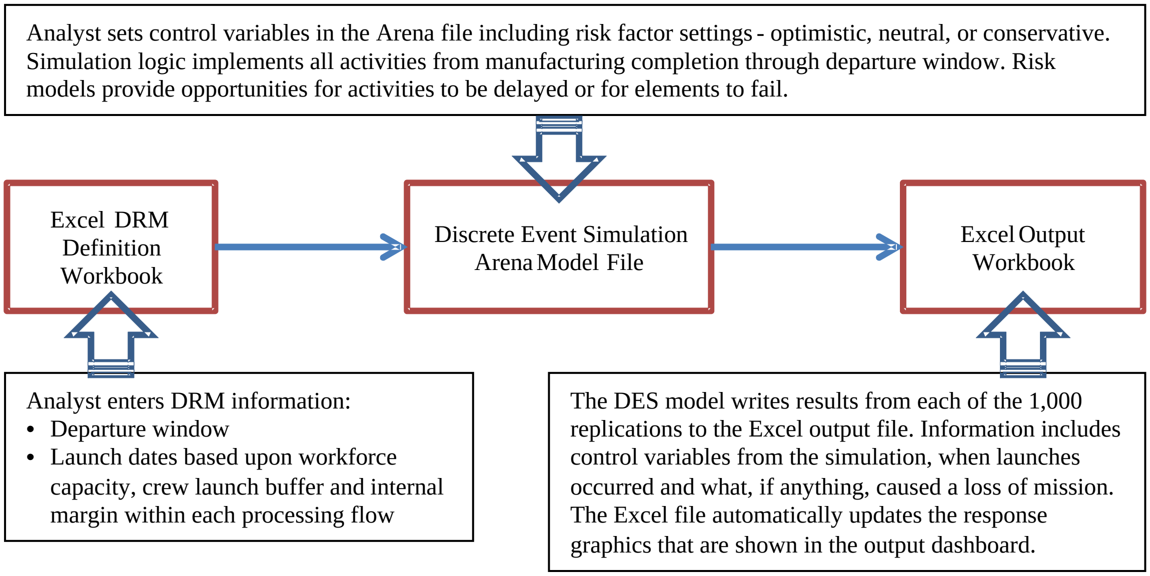

Figure 2: Model Overview

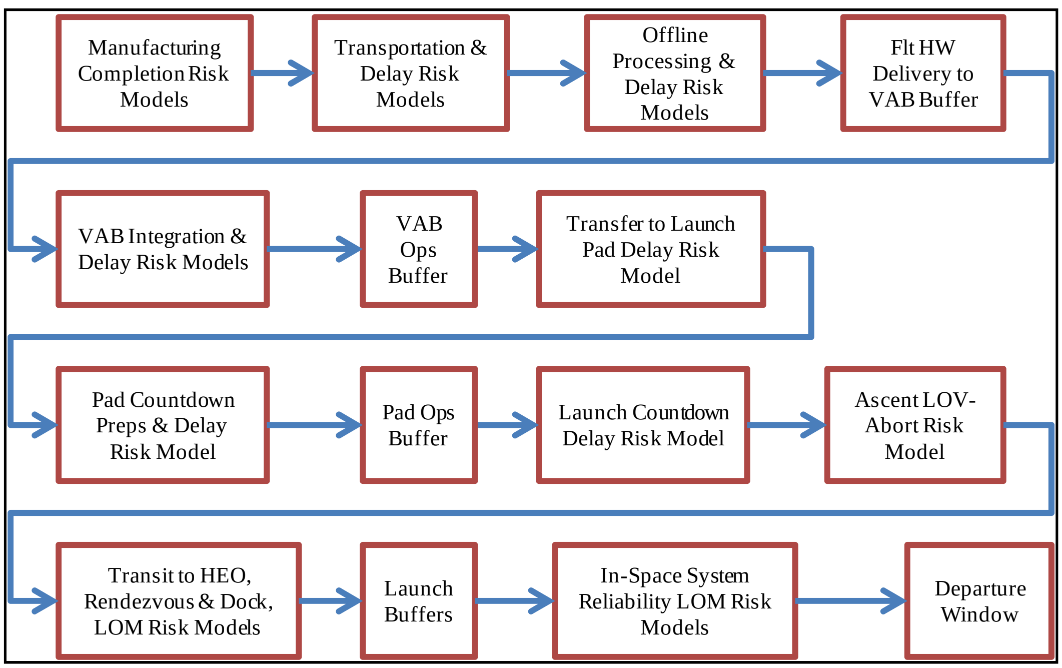

Figure 3: Flight Hardware Elements Entity Routing Within Model

Each flight hardware entity holds until its planned manufacturing completion date, whereupon it is routed to a delay risk model where the chance of the manufacturing being delayed is analyzed. If a delay occurs the duration of the delay is determined using a probability distribution.

Individual delay risk models were developed for each flight hardware element type. For example, historical data for Solid Rocket Booster (SRB) elements including Aft Skirts and Reusable Solid Rocket Motor (RSRM) segments were documented by the Space Shuttle Program on Kennedy Space Center (KSC) Milestone Interface charts for each Space Shuttle mission. 99 total Milestone Interface charts were reviewed. The probability that the Aft Skirts experience a manufacturing delay was found to be approximately 0.34. The magnitude of the delay ranged from 1 to 64 days. The probability of the RSRM segments being delayed in manufacturing was found to be 0.454. The magnitude of the delays ranged from 1 to 49 days. The delay data points for Aft Skirts and RSRM segments were analyzed using statistical fitting software (ExpertFit by Averill M. Law [6]), which is specifically designed to assist discrete event simulation. A Geometric distribution was found to be a reasonable model for the Aft Skirt manufacturing delays. A logarithmic distribution was determined to be a reasonable model for the RSRM segment delays. Alternatively one could use empirical distributions built from the historical data sets.

Historical data for the probability of the Forward Assemblies being delayed coming out of manufacturing and the magnitude of the delay were not available. During the Space Shuttle program, Forward Assemblies completed manufacturing well in advance of actual need date and thus, were stored in the VAB. This technique was apparently successful as no Space Shuttle mission processing milestones showed a delay due to Forward Assembly availability. Consequently, it is difficult to determine the delay model (probability of a delay and duration of the delay) for manufacturing completion of the Forward Assemblies. The simulation uses a uniform distribution of 0 to 7 days for the Forward Assembly delay risk model to acknowledge that there is risk. Further work such as performing sensitivity analysis using alternative risk models based upon subject matter expert will be required.

In the case of the Core Stage and Upper Stage elements of the SLS, which have yet to be developed, analog information from the Space Shuttle External Tank manufacturing history was used. Similarly, the DSH, REM, CPS, and MPCV have no manufacturing completion history. Since they are in some respects spacecraft sharing similar functions with the Space Shuttle orbiter, historical data from the history of orbiter delays in coming out of the Orbiter Processing Facility was used as their analog for manufacturing completion.

The probability of an External Tank (ET) being delayed coming out of manufacturing was found to be approximately 0.29. The magnitude of the delay ranged from 1 to 56 days and follows a logarithmic distribution.

Following manufacturing, each flight hardware entity is routed from its respective manufacturing site to the launch site for offline processing or integration in the Vehicle Assembly Building (VAB). Risk models for transportation delays are associated with the mode of transportation i.e., rail, barge, and tractor-trailer.

Historical data for RSRM segment shipments between Utah and KSC was used for the rail mode delay risk model. Assuming an 8-day planned transit, delays occur approximately 50% of the time and range from 1 to 4 additional days. There is also a small probability (approximately 8.3E-3) of a train derailment and when this occurs the model injects a delay of between 30 and 90 days to account for additional time for derailment recovery which may include segment inspections, repairs, or replacement.

The model assumes that both the SLS Core Stage and Upper Stage are manufactured at the Michoud Assembly Facility (MAF) near New Orleans and require separate shipment by barge. Historical data for ET shipments via ocean-going barges from MAF to KSC were used for the barge mode delay risk model. Assuming a 5-day planned transit, delays occur approximately 23% of the time and range from 1 to 6 additional days. There is also a small probability (approximately 1.5E-3) of the barge sinking and when this occurs the model injects a delay of 180 days to account for additional time to replace the lost flight hardware element and the barge.

The SRB Aft Skirts and Forward Assemblies are towed on dollies from their manufacturing completion location on KSC to either the Rotation, Processing and Surge Facility (RPSF) or VAB. Historical delay data was not readily available. The model assumes a Uniform distribution between 0 and 2 additional days to account for potential delay risk stemming from adverse weather or transporter malfunctions. These types of transportation delays tend to be 1 or 2 days at most.

Flight hardware elements requiring offline operations include the SRB and RSRM elements, the Upper Stage, and all the mission elements—DSH, REM, Block 2 CPS, and MPCV. The offline processing occurs for a planned amount of time followed by a risk model in which there is a chance that the offline processing may take longer than planned. The SRB and RSRM offline processing delay risk model is based upon directly applicable historical data. Space Shuttle orbiter processing data were used as an analog for the other elements requiring offline processing.

Table 1 shows the various probabilities of delays that may occur during offline processing, vehicle integration in the VAB and operations leading up to the start of launch countdown. There is a corresponding empirical delay duration distribution for each delay probability. The probabilities and duration distributions were derived from Space Shuttle historical data after factoring for differences between the Space Shuttle and the SLS – MPCV.

Following completion of its offline activities, the flight hardware element entity is routed to the VAB for integration.

Integration in the VAB begins with arrival of the entity representing the mobile launcher on its planned arrival date and proceeds through preparations for the start of SRB stacking. A risk model accounts for the chance that mobile launcher arrival and preparations for stacking may be delayed. The mobile launcher stacking preparations delay risk model is based upon the "Delays to Start of SRB Stacking" shown in Table 1.

After the mobile launcher is verified to be ready, the SRB elements begin routing to the VAB for stacking. A delay risk model derived from Space Shuttle historical data accounts for potential SRB stacking delays that impact the subsequent mate of the Core Stage between the twin SRBs. See "Delays to Core Stage Mate / Upper Stage Mate" in Table 1.

The Core Stage does not require offline processing since it is assumed to be ready for integration upon arrival from the manufacturing site. The model allows it to be stored temporarily in the VAB if the SRB stacking has not been completed when it arrives. There is a risk model to account for potential delays during Core Stage integration. Analogous historical data from the ET integration with the Space Shuttle was used to develop the risk model.

Integration of the Upper Stage occurs after Core Stage integration completion. There is a risk model to account for potential delays during Upper Stage integration. This risk model is identical to the Core Stage integration delay risk model.

After Upper Stage integration, the SLS is ready for payload integration. This will be an encapsulated payload in the case of the DSH-REM on the first launch and the Block 2 CPS on the second launch. The MPCV on the third launch is not encapsulated but the model assumes that the payload integration times are the same for each of the three launches.

Table 1. Space Shuttle History Derived Processing Delay Probabilities

Delays to Start of SRB Stacking		Delays to Core Stage Mate / Upper Stage Mate		Delays to Payload to SLS Mate		Delays to SLS Readiness for Rollout		Delays to Countdown Readiness	
Subcategory	Delay Prob	Subcategory	Delay Prob	Subcategory	Delay Prob	Subcategory	Delay Prob	Subcategory	Delay Prob
MLP Post Launch Problems	0.1682	VAB (Crane Problems, MLP etc.)	0.1193	VAB Crane Problems	0.0190	Range Availability	0.0476	SRB Induced Delays to Launch Countdown Start	0.0571
VAB Problems (Crane, etc.)	0.1405	RSRM Segment Delivery Delays	0.0158	Orbiter Availability	0.6076	SRB/RSRM induced delays	0.0667	SSME-MPS induced Delays to Launch Countdown Start	0.1274
VAB Major Mods / Major Maintenance	0.0190	SRB-RSRM Stacking Problems	0.3274	Miscellaneous	0.0286	SSME induced delays	0.0381	Environment Induced delays to Launch Countdown Start	0.0416
MLP Stack Prep Delays	0.0667	Cold Weather	0.0381			Monoball induced delays	0.1000	Ground Systems	0.0429
Crawler Transporter	0.0095	Miscellaneous	0.0286			Flight Crew	0.0000	Flight Crew	0.0000
Aft Booster Delivery Delays	0.0190					Miscellaneous Flight Hardware	0.0467	Miscelleous Flight Hardware	0.0262
Miscellaneous	0.0286								
File:	**GOMES STS Based Risk Factors 2009_10_02 R1.xlsx**								
Sheet:	**SLS Risk Factor Table**								

Risk models account for potential delays during payload integration, integrated vehicle testing, and preparations for rollout to the launch pad. These models were developed using historical data from the analogous Space Shuttle operations including orbiter mate to the ET, integrated testing and preparations for Space Shuttle rollout to the launch pad. See “Delays to SLS Readiness for Rollout” in Table 1.

Depending upon the scenario, there may be a buffer prior to rollout to the pad that protects for delays that occur prior to VAB rollout. This buffer can be sized to help increase the likelihood of being able to start the VAB to launch pad transfer on the desired date.

Rollout to the launch pad occurs no earlier than its planned date. If delays from manufacturing, transportation, offline processing, and integration exceed the available buffer amount, if any, then start of rollout to the pad will be delayed.

There is an additional risk model to account for delays for the VAB to pad transfer operation stemming from adverse weather delays, ground equipment failures, and flight hardware problems, known as 11^{th} hour delays. This risk model is based upon the Space Shuttle history of vehicle transfers between the VAB and the launch pads as shown in Figure 4.

After the integrated vehicle arrives at the launch pad, pre-launch countdown pad operations are conducted. There is a risk model to account for delays that can occur at the launch pad prior to the commencement of the launch countdown. See “Delays to Countdown Readiness” in Table 1. This risk model is based upon the Space Shuttle historical data, but takes into consideration the reduced amount of time and operation planned for the SLS at the launch pad prior to launch.

The model allows for there to be a buffer between the end of pre-launch countdown operations and the start of launch countdown. This buffer can be sized to help increase the likelihood of being able to start the launch countdown on the desired date.

The launch countdown will start no earlier than its planned date. A delay risk model accounts for delays that occur during launch countdown. The simulation allows the analyst to choose between alternative launch countdown delay risk models. The countdown delay risk models are displayed with their representative cumulative distribution functions in Figure 5.

One launch risk model is based purely upon Space Shuttle a.k.a. Space Transportation System (STS) historical data. An alternative model is also based upon the Space Shuttle historical data but takes into consideration differences between the Space Shuttle and the SLS vehicle configuration and concept of operations. The results presented in this paper are based upon the STS launch delay risk model.

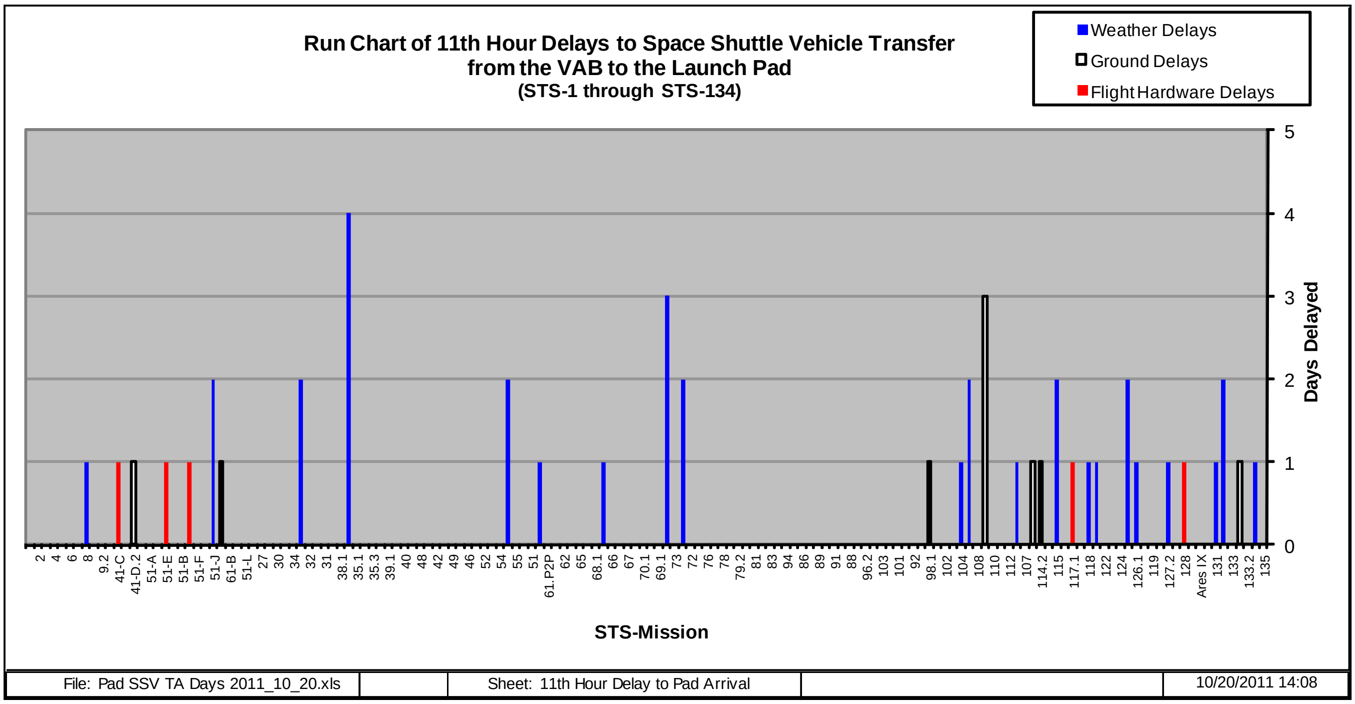

Figure 4 – 11th Hour Delays Transfer Launch Vehicle from VAB to Launch Pad

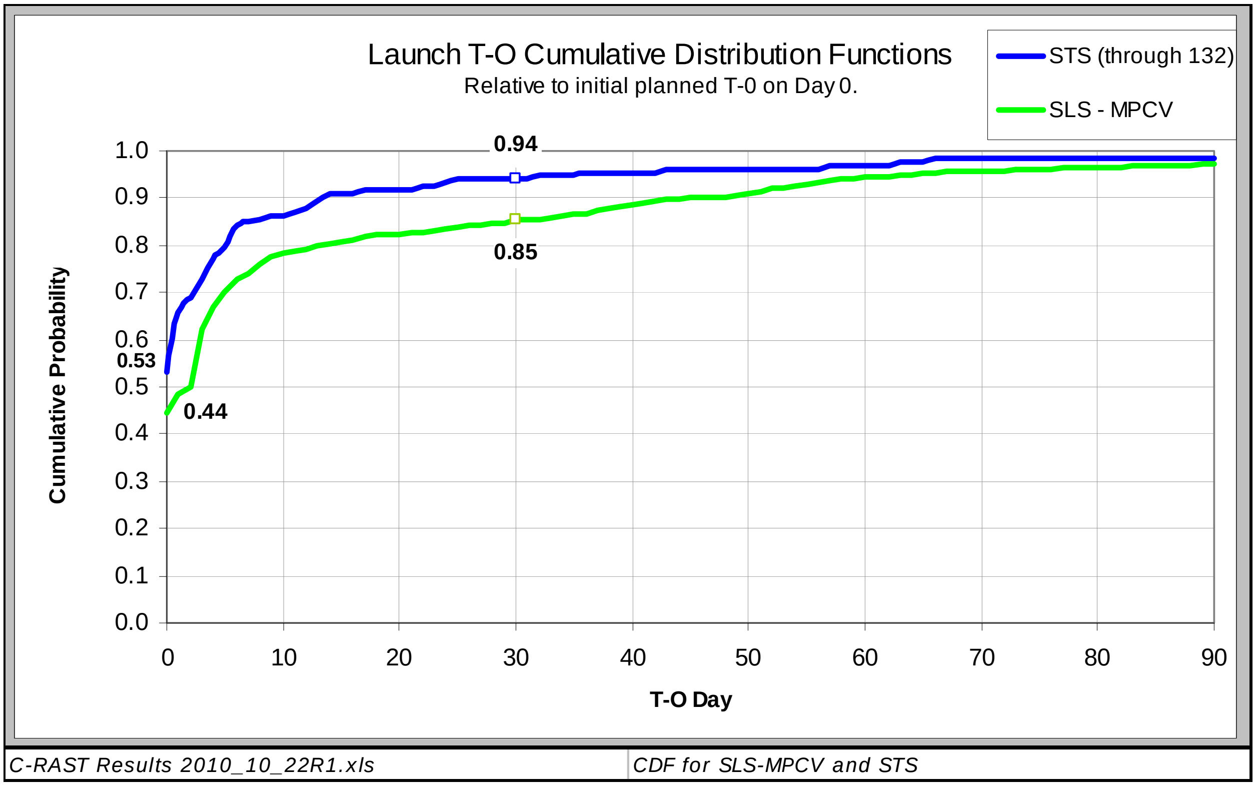

Figure 5 – Launch Countdown Delay Risk Models

If a mission's no-later-than launch date is going to be exceeded, the mission is not actually launched but instead the replication is ended and a message is sent to the output Excel file stating which mission was too late.

Once a launch occurs in the simulation, two entities proceed down separate paths. The first entity, representing the mobile launcher, is routed to logic for post-launch refurbishment and transportation back to the VAB to begin the integration flow for the next launch. There is a risk model to account for potential delays to post launch refurbishment. This risk model is based upon Space Shuttle historical data.

The second entity, representing the launch vehicle and spacecraft, is routed to a risk model where there is the chance that an ascent loss of vehicle event can occur.

Due to the uncertainty in the ascent reliability that may ultimately be achieved by the SLS, three different values—optimistic, neutral, and conservative—are used for the probability of an ascent failure. The optimistic ascent failure rate is based upon the SLS goal to achieve a failure rate of 1 in 250, which equates to a 0.4% chance of an ascent failure. The neutral estimate is set at 1.5%, which is consistent with the Delta II launch vehicle's demonstrated reliability through 149 launches and the Space Shuttle's demonstrated reliability over 135 missions. The conservative value of 3% is consistent with the Soyuz launch vehicle, which is the most flown launcher (over 700 launches). Alternatively, the conservative setting could be set at 7% based upon the current average launch reliability of launchers worldwide [7].

For a cargo mission, the spacecraft is assumed to be destroyed in a loss of vehicle (LOV) event. For a crewed mission, the event is categorized as an ascent abort. The efficacy of the abort system and resulting crew survivability are not modeled.

Once the spacecraft successfully gets into orbit it takes up to 2 days to enter the HEO assembly orbit. The Block 2 CPS and MPCV entities are routed upon insertion into HEO to a risk model where there is a chance that their respective rendezvous or dock events fail resulting in a loss of mission.

The Block 2 CPS is planned to make an automated rendezvous and dock (ARD) with the DSH in HEO. No crew is on-board the DSH to take corrective action in the event of an anomaly. Probability of failure for a single ARD is estimated to be between 0.015 (optimistic) and 0.1 (conservative). The Progress automated docking system has the most experience and is considered sufficiently reliable to be used on the ISS. However, a review of 45 automated Progress ISS docking missions found that in 7 missions the automated docking system failed to such an extent that the crew on board the ISS had to take over and conduct a manual rendezvous and docking [7]. This indicates a failure rate of approximately 16%. There was also an instance where a resupply ship unintentionally impacted the Mir space station during a re-docking maneuver.

The probability of a rendezvous and dock failure for the crew-assisted MPCV docking with the DSH is much lower than that for the fully automated procedure for the CPS. The presence of the crew to take over in real time mitigates much of the risk. Additionally, the historical data for Space Shuttle and Soyuz crew docking with the Mir and ISS indicate a high level of reliability. When failures do occur they typically get resolved through subsequent docking attempts. The risk model uses reliabilities ranging from 99.5% (optimistic) to 95% (conservative) that the rendezvous and dock will be achieved without a failure. If there is a failure, 90% of the time the failure is resolved but the model incurs up to a 2-day delay in the completion of docking. The other 10% of failures result in a loss of mission.

Once established in HEO, an entity representing each spacecraft is sent to a system reliability model where there is a daily chance of a system failure resulting in a spacecraft loss of mission. This daily risk of system failure for each spacecraft in HEO continues until trans-NEA-departure.

Potential failures include MMOD impacts and failures of spacecraft systems. Since these spacecraft have not been built and operated yet, it is difficult to develop an accurate reliability estimate. A range of estimates was used to test the sensitivity of the model to various values. The optimistic estimate assumes a 2-year in-space design life with achieved design reliability of 99%. This equates to an approximate 1.0E-5 daily probability of a loss of mission failure. The neutral setting and conservative setting assumes a 93% and 70% design reliability over two years respectively. These settings result in daily loss probabilities of 1.0E-4 and 5.0E-4 respectively.

The model does not, at this time, account for the potential that the crew arriving with the MPCV could repair a failed DSH, REM, or Block 2 CPS. Instead, if a failure occurs the launch of any remaining subsequent elements is halted and the replication is ended.

After the MPCV has rendezvoused with the DSH, the crew transfers to the DSH. An entity representing each crew member is then routed to a crew health risk model where there is a daily probability that a significant medical event will develop prompting need to abort the mission and return the crew to Earth. Inputs for the crew health risk model are based upon work performed by NASA's Integrated Medical Model (IMM) project team [8]. The IMM is being developed to respond to a significant need identified in NASA's Human Research Roadmap [9] to quantify likelihood and consequence of medical conditions that could occur in spaceflight [10].

The IMM is responsible for estimating crew health risks on the International Space Station (ISS). These include risk of crew evacuation (EVAC) as well as the sudden mortality risk of loss of crew (LOCL). The ISS is a reasonable analog for the DSH, with one notable caveat being the medical capabilities on the ISS today versus what those capabilities may ultimately be on the DSH. This will depend upon DSH mass and volume constraints, which may limit what kind of medical kit can be supported.

The IMM derived ISS EVAC rates range from 0.021 to 0.030 events per person-year. These values coupled with the LOCL risk of approximately 0.005 events per person-year are used as inputs to the optimistic and neutral settings. Their values are 0.0259 and 0.0349 events per person-year respectively. For the conservative setting a value of 0.072 events per person-year is used, which is the high end of the Russian Historical Space Flight Data as analyzed by the IMM team [8].

The corresponding daily rates are 7.19E-5, 9.72E-5 and 2.05E-4 LOM health events per astronaut-day respectively for the optimistic, neutral, and conservative risk settings. The daily risk of a LOM health event continues until trans-NEA-departure.

The replication ends when either there has been a loss of mission event or the trans-NEA-departure has occurred. At the end of each replication, the model writes results in an Excel output file.

Figure 6 shows an example of the output dashboard in the Excel output file. The SLS launch vehicle's booster type is identified in the upper left corner. The shifting assumption is also identified in the upper left corner along with the planned spacing between launch 1 and 2 as well as the planned spacing between launch 2 and 3. The Gantt chart on the top of the dashboard presents the launch and assembly sequence that the simulation attempted to execute in each of the 1,000 replications. Yellow bars indicate offline processing activities beginning with the first flight hardware elements scheduled manufacturing completion date through the final delivery of the payload element to the VAB for integration with the launch vehicle.

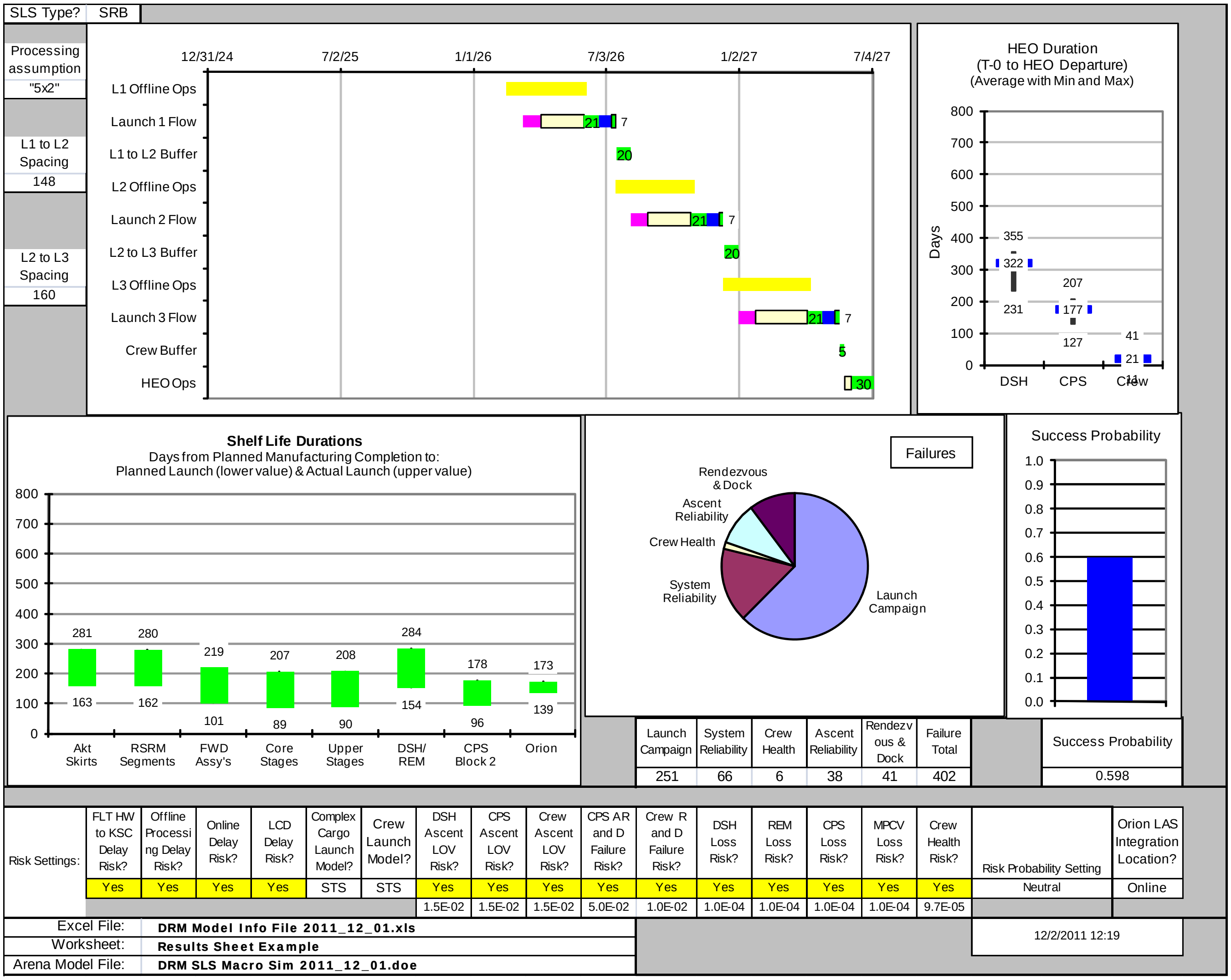

Figure 6 – Model Output Dash Board Example

The three launch flows are displayed with a tri-color bar indicating: (1) in purple the Mobile Launcher stacking preparations (including post launch refurbishment for the second and third launches); (2) in white the activities in the VAB beginning with SRB stacking and ending at VAB rollout; and (3) in blue the launch pad flow through liftoff.

Green bars and embedded numbers indicate available schedule margin (buffers) as well as the HEO to NEA destination window. In this example, there is a 30-day departure window, protected by a 5-day crew launch buffer. There are 20-day buffers between each of the three launches. Each of the launch flows has a 21-day buffer embedded at the end of the VAB flow prior to the vehicle being transported to the launch pad and a 7-day buffer just prior to the start of launch countdown.

The column graphic below the Gantt chart shows shelf-life durations for each of the major flight hardware elements. The lower values represent the planned duration from manufacturing completion through the planned launch. The upper values represent the maximum durations, manufacturing completion to actual launch, experienced during the 1,000 replications.

The pie chart provides the proportion of failures for each of the major LOM categories: launch campaign failing to launch all three missions in time; on-orbit system reliability failures; crew health events; ascent reliability failures; and rendezvous & dock failures. Below the pie chart is the corresponding table showing the count of each failure type as well as the total number of failures out of 1,000.

The blue column graphic shows the probability for how many of the 1,000 replications successfully achieved readiness for the trans-destination departure burn within the departure window. This is the metric that should be maximized.

The stock chart above the success metric indicates the in-space time for each of the mission elements in HEO prior to the departure burn. The chart provides maximum, average, and minimum durations experienced.

The bottom portion of the dashboard shows the various experiment settings that were set for the analysis case along with the model file name, the Excel file name and worksheet, and the date and time the case was executed.

NASA is currently planning on implementing a minimal cost ground architecture called "single-string," which means that there will only be one mobile launcher, one VAB highbay to perform SLS integration, and one launch pad. Consequently, it will not be possible to process launch missions in parallel. In addition to having a single-string architecture, NASA is also planning on reducing the size of the workforce relative to what it was for Space Shuttle operations. This will mean that processing operations will not be worked round the clock but will instead be limited to 5 days per week at either one or two shifts per days.

The workforce processing assumption can have a significant influence of the launch and assembly sequence duration. Within the input Excel file, the analyst can specify the work force processing assumption, i.e., 5 day – 1 shift processing (5x1) or 5 day – 2 shift processing (5x2). A 5x1 workforce would be the lowest cost but the processing duration would be essentially twice that of a 5x2 workforce. Figure 7 shows a high level Gantt chart of the launch sequence and HEO assembly operations assuming 5x1 processing. Figure 8 shows the same sequence but with 5x2 processing.

An effective hours per day normalized to round the clock processing over a 365-day year was determined to take into account weekends and holidays and other off days that are not available to be worked without overtime funding. A 5x1 workforce provides approximately 5.5 hours per day while a 5x2 workforce provides approximately 11 hours per day.

The processing times automatically adjust in the Excel file based upon the selected processing assumption. For example a task that requires 16.5 serial hours would take 3 days given a 5x1 workforce versus 1.5 days given a 5x2 workforce.

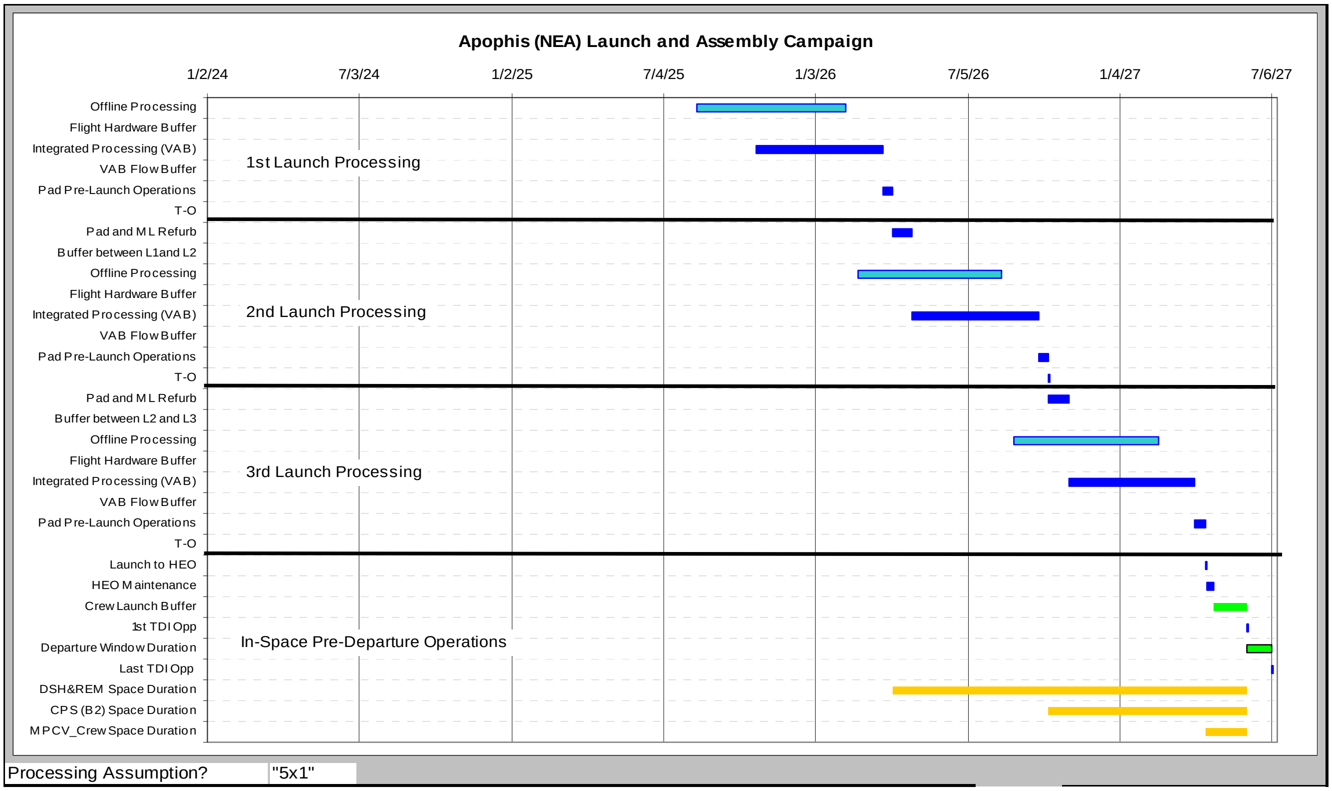

Figure 7 – Launch and Assembly Sequence with 1-Shift (5x1) Processing

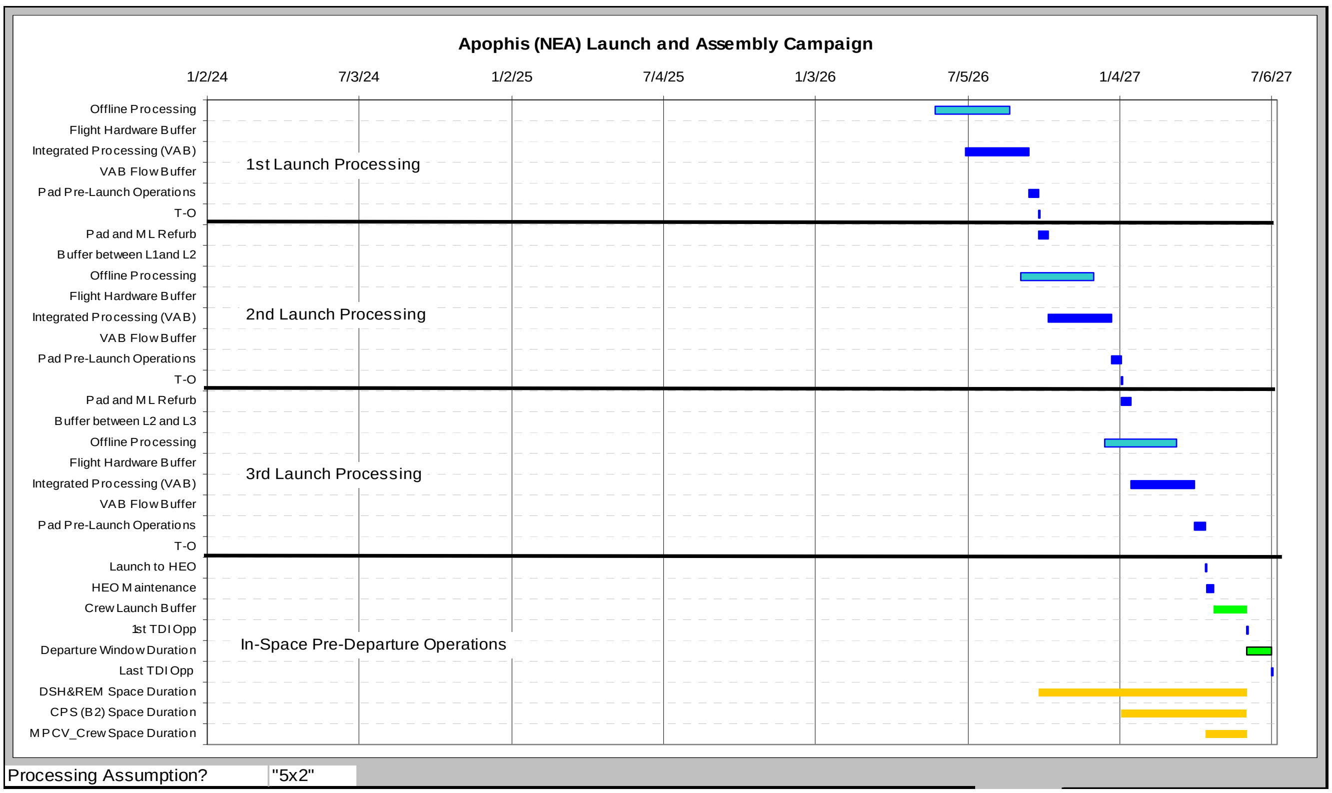

Figure 8 – Launch and Assembly Sequence with 2-Shift (5x2) Processing

5. DESCRIPTION OF CASES ANALYZED

A total of 6 cases were explored to represent two alternative workforce processing capabilities under varying risks settings. The workforce processing cases were 5 day 1 shift per day processing (5x1) and 5 day 2 shifts per day processing (5x2). Each of these two cases were analyzed with the in-space risk factors set at the Optimistic, Neutral, and Conservative settings discussed in Section 4 and summarized here in Table 2. Because of the uncertainty in many of these risk factor settings, cases were analyzed with all three settings.

The first scenario analyzed was the launch sequence as initially proposed and using the Optimistic set of risk factor settings. This sequence assumed 120-day launch-to-launch spacing provided by a 5x2 processing capacity. The sequence provided no buffer between the last scheduled launch and the opening of the 30-day departure window.

Using the model in an iterative fashion, the optimal launch sequence, as defined by planned launch dates and buffer sizes, was then searched for that provides the maximum probability of success. The crew launch buffer was limited to no more than 40 days due to concerns expressed about launching the crew too early. This constraint along with the planed LEO to HEO duration of nominally 2 days and the 9 days of checkout at HEO thus limits the maximum crew time in space prior to departure to no more than 51 days.

Table 2. In-Space Risk Factor Settings

Risk Factors	Optimistic	Neutral	Conservative
Ascent LOV-LOM Probability (Cargo Launches	4.00E-03	1.50E-02	3.00E-02
Ascent Abort (Crew Launch)	4.00E-03	1.50E-02	3.00E-02
CPS to DSH / REM Automated Rendezvous & Dock Failure	1.50E-02	5.00E-02	1.00E-01
MPCV to DSH Rendezvous & Dock Failure (Crew assisted)	5.00E-03	1.00E-02	5.00E-02
DSH Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
REM Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
CPS Block 2 Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
MPCV Daily Loss Probability	1.00E-05	1.00E-04	5.00E-04
Crew Health LOM (Daily risk per crew member)	7.19E-05	9.72E-05	2.05E-04

6. RESULTS

The model dashboard for the first scenario is shown in

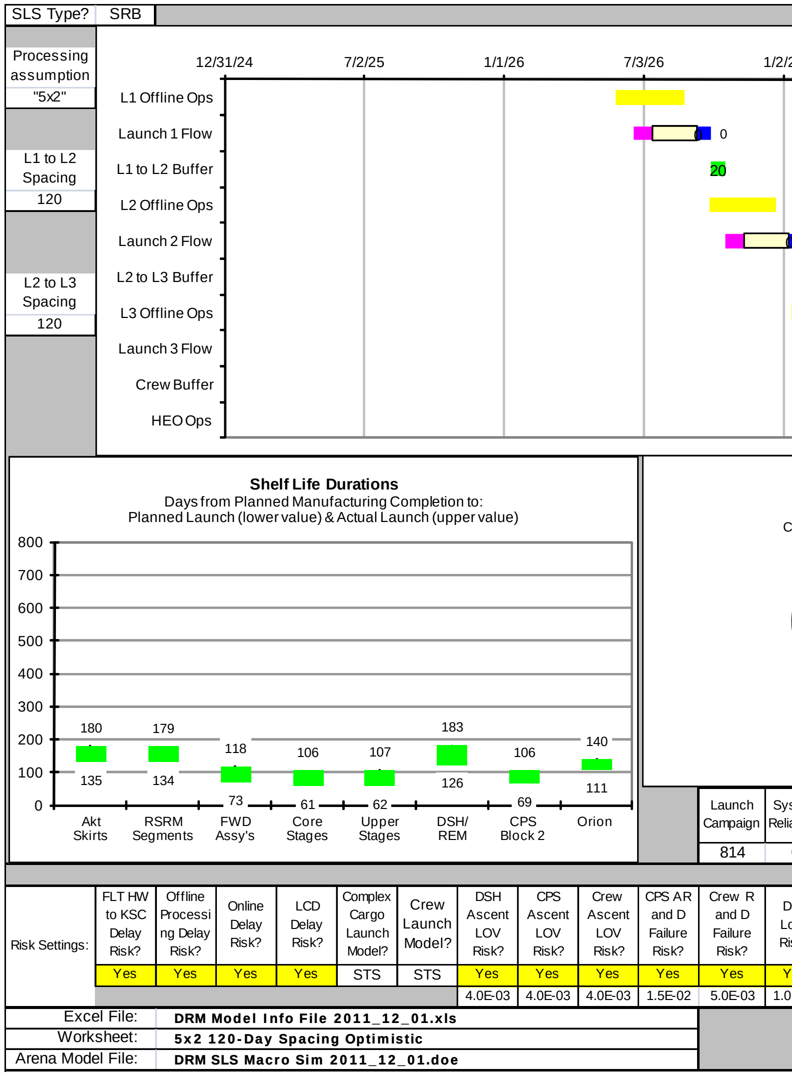

Figure 9. The available margin to protect for launch sequence delays includes the 30-day departure window since the sequence is set up to theoretically achieve the opening of the window. Additionally, assessments of the processing timeline indicated that a 5x2 workforce provides the capability to achieve a 100-day launch-to-launch spacing between cargo launches and 112-day spacing between a cargo launch and a crewed launch. Consequently, the Gantt chart in the model dashboard reflects 20-day buffers between the first 2 launches and an 8-day buffer between the 2nd and 3rd launch.

The success probability was quite low at 0.18. The launch campaign being late was the primary driver with 814 of the replications experiencing a launch campaign failure. There was 1 replication that had a crew health failure, 3 that had an ascent failure, and 2 that had a rendezvous and dock failure.

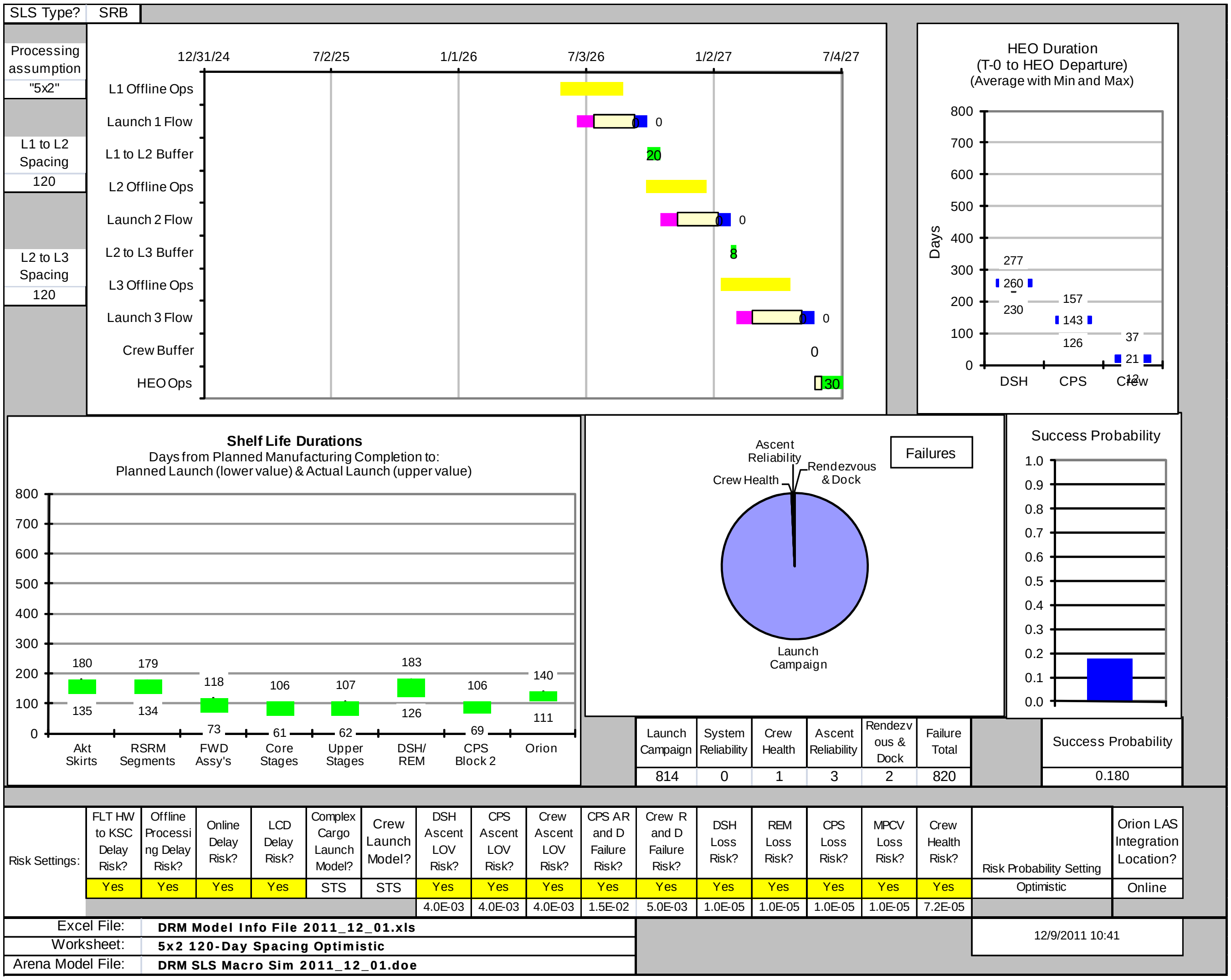

Figure 9 – Dashboard for Initial Results

The next strategy implemented was to insert buffers that would help improve the launch sequence performance but not change the given launch dates. There were two areas where this could be achieved. The first was to have flight hardware complete manufacturing early so that offline processing could begin early. In this way, the manufacturing, transportation, and offline processing risk could be mitigated. Most of the risk was mitigated by completing manufacturing approximately 4 months early. The second area was to insert a large buffer prior to the launch of the first mission. A 90-day buffer was inserted prior to rollout to the launch pad and a 14-day buffer just prior to starting the launch countdown was included.

The results are shown in Figure 10. The success probability improved to 0.65. The launch sequence was still the primary driver. Note how the offline processing bars have increased in the Gantt chart and the shelf life durations increased. Shelf life durations limits are unknown at this time but may restrict the ability to mitigate manufacturing and offline processing risk depending upon their requirements.

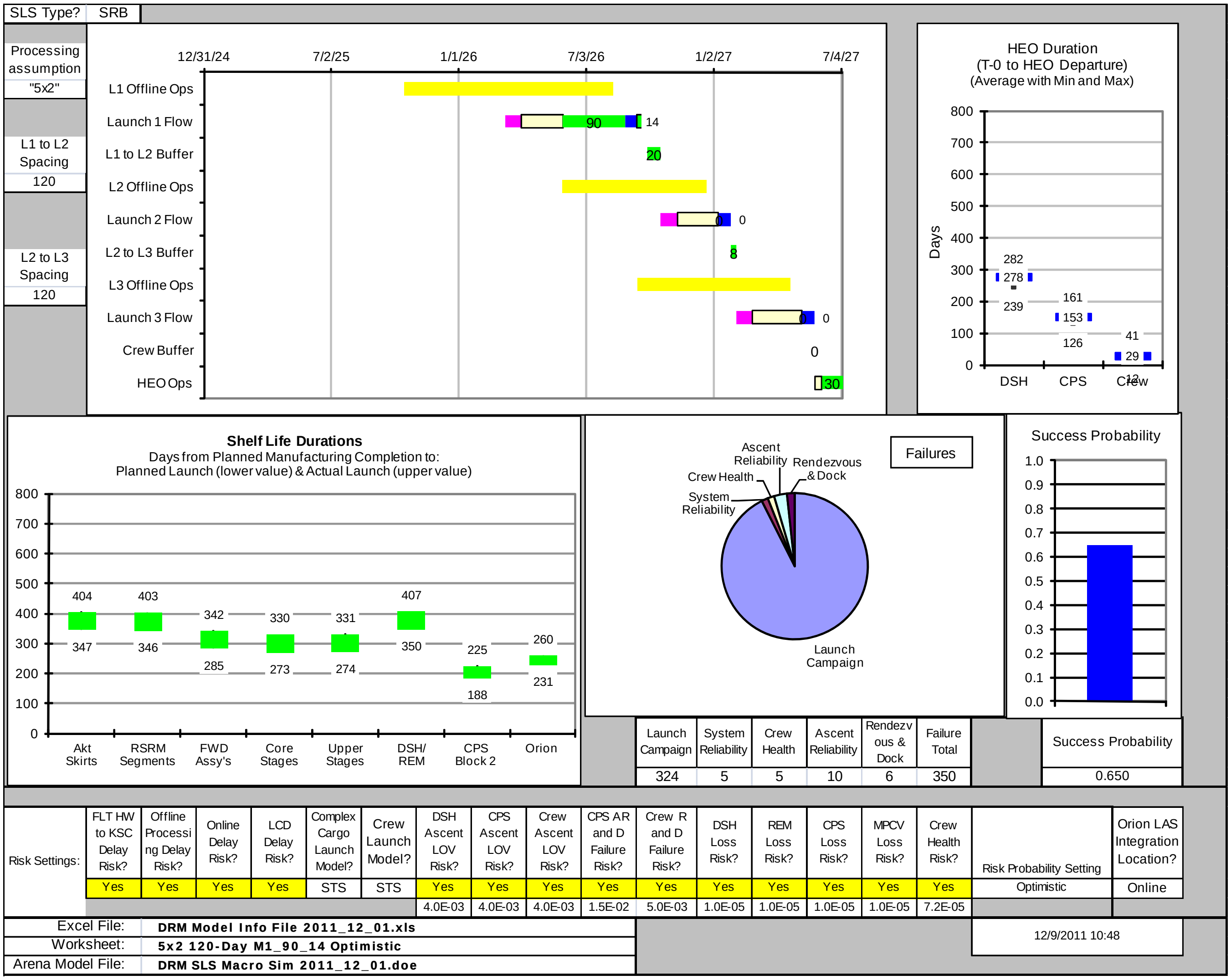

Figure 10 – Dashboard for Improved Results with Buffers

Following the first two initial analysis runs, the next step was to add in a crew launch buffer and insert buffers within and between the launch flows. While this does cause the launch dates to be earlier than originally planned, and results in both longer shelf life durations and flight hardware elements being in space longer than planned, the overall success probability was improved.

The results for estimated maximum probability of success for each of the six cases are shown in Figure 11. As expected, the probability of success is highest when the risk settings are optimistic and lowest when the risk settings are conservative. Given the optimistic set of risk factors, the success probability is approximately 93% regardless of the processing capacity. Thus there is no apparent need at first glance to have the larger workforce required to achieve 5x2 processing.

Figure 12 shows the simulation dashboard for the optimistic case with 5x1 processing corresponding to the 0.927 data point in Figure 11. The bottom portion of the dashboard has been truncated for spacing. The pie chart in Figure 12 is relatively balanced implying that there is no main culprit to blame for the remaining 7% risk of loss of mission leading up to the departure burn.

Of potential concern, however, are the very large values for shelf life prior to launch and the time spent in HEO for the DSH and CPS Block 2 prior to the departure burn. If these durations cannot be supported, then switching to 5x2 processing might be required in order to reduce the shelf life and HEO loiter demands.

The success probabilities for the neutral risk factor settings are approximately 78% with 5x2 processing and 75% with 5x1 processing.. The difference in success probabilities for 5x2 processing versus 5x1 processing gets even larger when the risk factor settings are at the conservative values. With those values the success probabilities are 52% versus 42%.

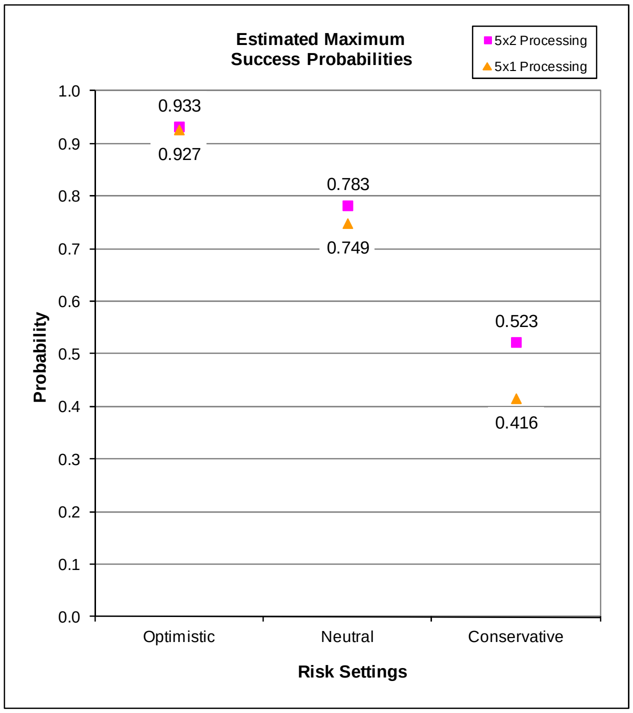

Figure 11 – Summary Results for the Estimated Maximum Success Probabilities

The reason 5x2 processing is better when the risk factors are other than optimistic is because the increased processing capacity allows for spacing the launches closer to the departure window and thereby decreases the amount of time that the flight elements are in-space and subject to the daily system failure risk.

Figure 13 shows the simulation dashboard for the conservative case with 5x2 processing corresponding to the 0.523 data point in Figure 11. Note the reduced shelf life durations and HEO loiter durations relative to those in Figure 12.

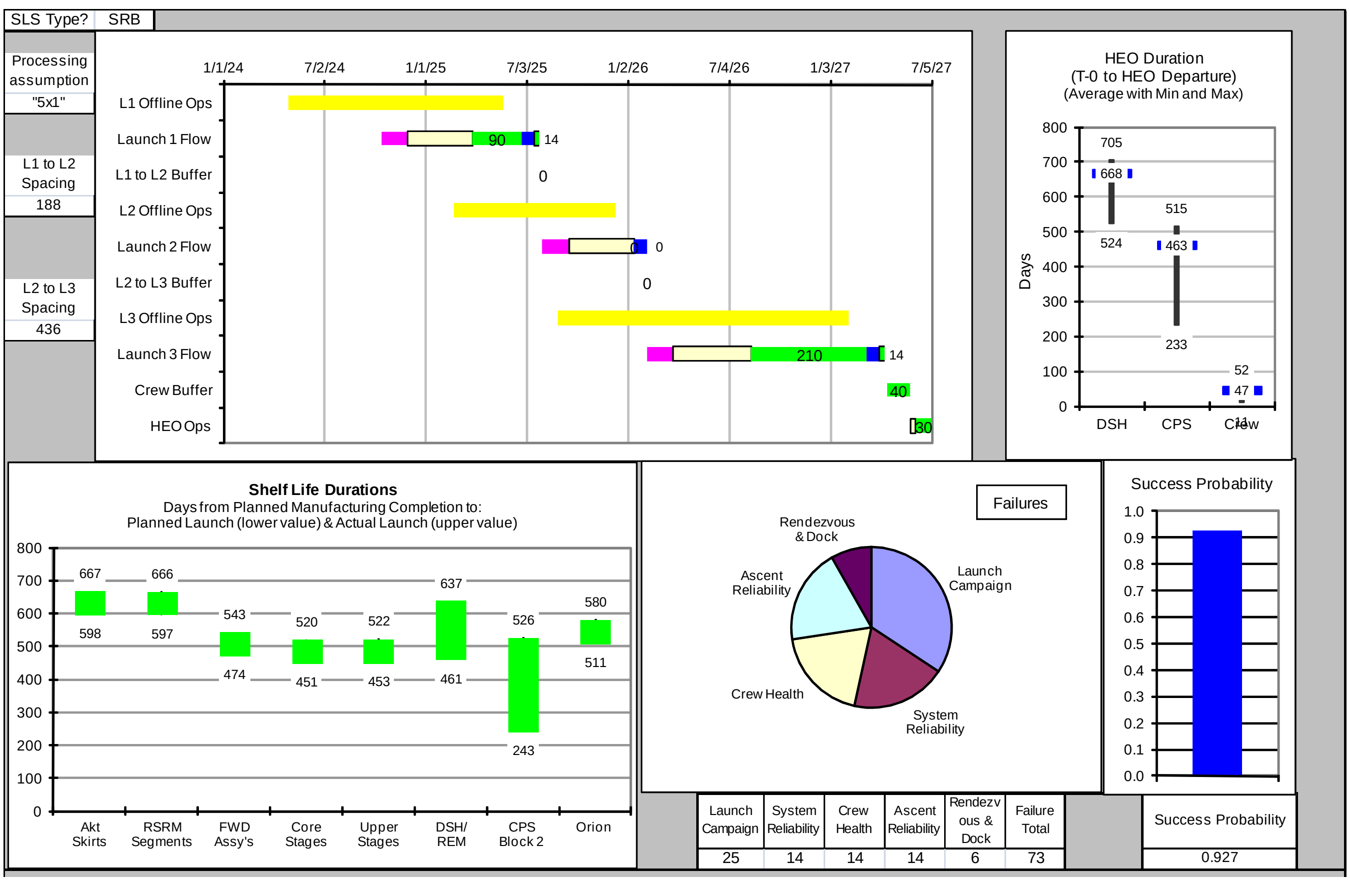

Figure 12 – Contributions to Failure for Optimistic Case with 5x1 Processing

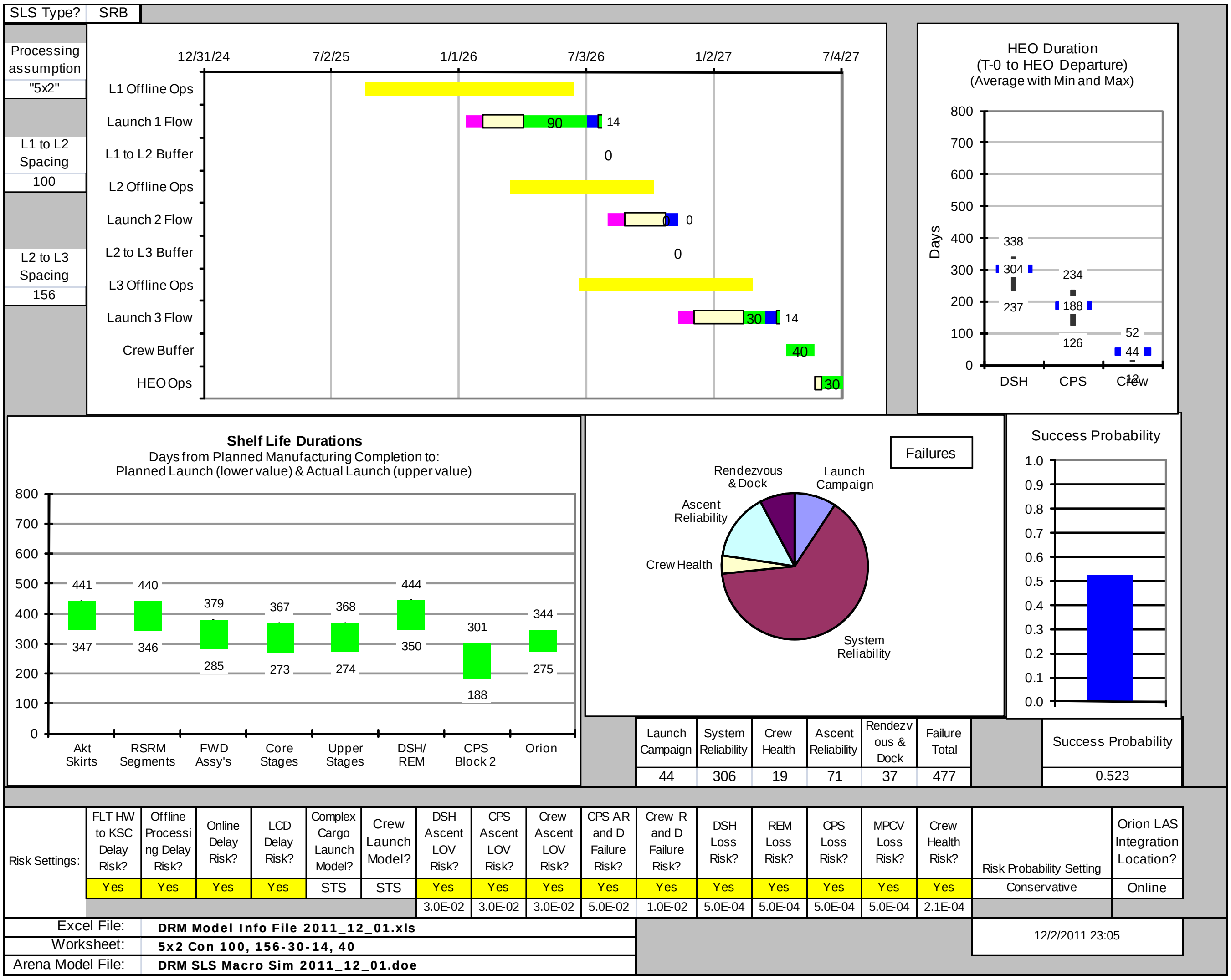

Figure 13 – Contributions to Failure for Conservative Case with 5x2 Processing

7. Conclusions and Forward Work

A capability to perform integrated launch sequence and assembly reliability risk has been established.

Initial findings indicate a significant relationship between the risk factor settings and mission success. Consequently, it will be important going forward to obtain an accurate estimate for the Space Launch System's ascent reliability, the reliability of the mission elements once they have been placed in orbit by the SLS, and the crew health risks. Understanding the investment required to achieve reliability improvements and crew health risk mitigation will also be key to making informed trades.

The influence of the processing capacity upon mission success may not be as important as system reliability. However, future cost trades may be warranted if system reliabilities are less than the optimistic values. Additionally, other emerging constraints upon flight hardware pre-launch shelf life and in-space design life may necessitate quicker launch-to-launch times than provided by a 5x1 work force.

Forward work includes updates to risk factors and adding additional constraints as they emerge from the NASA programs designing, building and operating the systems that will be required for the Design Reference Missions. The models will also be extended to account for beyond the departure burn readiness point risks.

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BIOGRAPHIES

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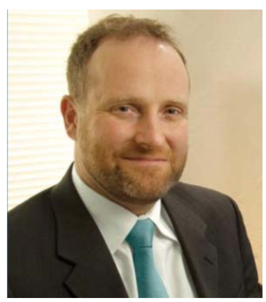
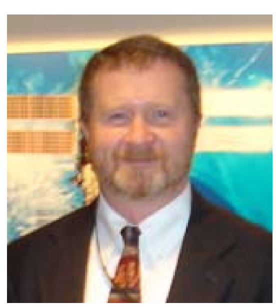


Chel Stromgren *currently serves as the Chief Scientist of Binera, Inc. Risk Analytics Division. In this role, Mr. Stromgren leads the development of probability and risk-based strategic models and strategic analysis of complex system development. Mr. Stromgren has supported NASA in the analysis of Space Shuttle and International Space Station operations in the post-Columbia environment and has led the development of strategic campaign models for the lunar exploration initiatives. He holds a Bachelor of Science degree in Marine Engineering and Naval Architecture from the Webb Institute and a Master of Science degree in Systems Management from the Massachusetts Institute of Technology.*



William Cirillo *currently serves as a Senior Researcher at NASA Langley Research Center in Hampton, Virginia, where he has worked for past 20 years in the area of Human Space Flight Systems Analysis. This has included studies of Space Shuttle,* *International Space Station, and Human Exploration beyond low Earth orbit. In 2005, Mr. Cirillo served at NASA Headquarters as a core member of the Exploration Systems Architecture Study (ESAS) team, where he was responsible for studying the use of Ares I/Orion in meeting future ISS crew and logistics transportation needs. Mr. Cirillo currently leads a team of analysts within the NASA Constellation Program in assessing at a strategic and tactical level the manifesting of assembly and logistics flights for establishing permanent human presence on the Moon.*

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