

NASA Launches Process + Organization Simulations: Risks Fall, Predictable Results Lift Off

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Abstract. We review NASA's innovative approach of combining discrete event process and agent-based organization simulation methods to design a predictable manufacturing plan and minimize schedule risk for a new launch vehicle. The Upper Stage Simulator (USS) had to be engineered, fabricated, assembled and delivered in a year. But the new design had never been manufactured; proposed fabrication and assembly methods were untested; NASA had little organization experience on-hand; and there was no time for experimentation and rework. Simulation predictions proved accurate and resultant interventions were effective. The USS was the only Ares I-1 assembly delivered on time and it was completed within budget.

1. THE MISSION

NASA's Glenn Research Center (GRC) was tasked with manufacturing the Upper Stage Simulator (USS) for the first test flight of the Ares I launch vehicle. This risk reduction flight, known as Ares I-1, served to prove the concept of the Ares I launch vehicle. The USS was a replica of the actual Ares I Upper Stage that was accurate in terms of mass and aerodynamic properties and included a number of test sensors.

1.1 The Challenge

NASA's primary success measure for the project was on-time completion. The USS had to be engineered, fabricated, assembled and delivered for launch in about one year. To achieve that aggressive schedule, engineering development (designs, specifications and drawings) had to overlap with the start of manufacturing. Workflows had to be tightly integrated and well-coordinated. Other conditions and constraints increased schedule uncertainty:

- Fabrication and material handling floor space was constrained.
- New fabrication techniques and equipment had to be invented, proved and refined.
- The skilled labor pool was limited.
- Engineering development tasks were divided among multiple design teams, contractors and locations.

NASA adopted the dual-simulation approach with two objectives:

- Ensure that all USS components would be completed on schedule.
- Deliver within budget.

1.2 Innovative Dual-Simulation Approach

NASA determined that using two complementary simulation techniques could render a more thorough view of

the project and allow greater confidence in the findings because each modeling tool would compensate for the limitations of the other. Manufacturing process discrete event simulation excels at modeling equipment and systems. It quantifies production rates, identifies constraints and helps maximize throughput and capacity utilization. Organization simulation quantifies the complexities of human work and team dynamics. It illuminates the ways teams collaborate, communicate, make decisions and execute work.

The analysis team first used a manufacturing process model to calculate manpower requirements, estimate production rates, balance the assembly line, discover constraints and test the sensitivity of the production process to variances. We used the process simulation findings to improve the reliability and capacity of the manufacturing system design.

We then incorporated the improved process design into a SimVision® organization simulation model to gauge schedule predictability, test the organization's fitness for purpose and tolerance for variations, validate manpower requirements, uncover constraints and evaluate intervention strategies.

2. USS MANUFACTURING PROCESS

The Ares I USS is made up of a stack of twelve cylindrical segments nicknamed "tuna cans". The tuna cans are made by rolling sheet metal into two halves, welding the halves together to form a skin, and then welding a circular flange to the top and bottom of the segment. Most segments share a similar overall design, although each one contains unique structures, equipment and sensors. Details such as the location and number of sensors can impact each segment's production time.

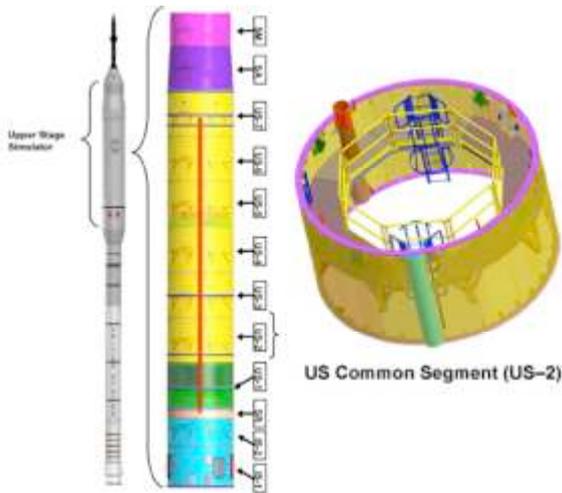


Figure 1: Ares I Upper Stage Simulator Schematic and a Representative “Tuna Can”

USS segments are assembled in assembly stands or fixtures. The number of fixtures and amount of facility floor space constrain the overall manufacturing rate.



Figure 2: Segment in Assembly Stands

3. PROCESS SIMULATION

The team used the SIMUL8[®] application published by SIMUL8 Corporation to construct a process-node model of flange fabrication, skin fabrication and segment assembly processes. Work volumes and expected durations were inferred from the manufacturing plan since no actual production history existed. Key assumptions included:

- Manufacturing process cycle times are normally distributed.
- All material is assumed available when needed.
- Learning benefits, if any, would be quantified in the subsequent organization simulation model.
- All segments are processed identically. Configuration differences would be accounted for in the subsequent organization simulation model.

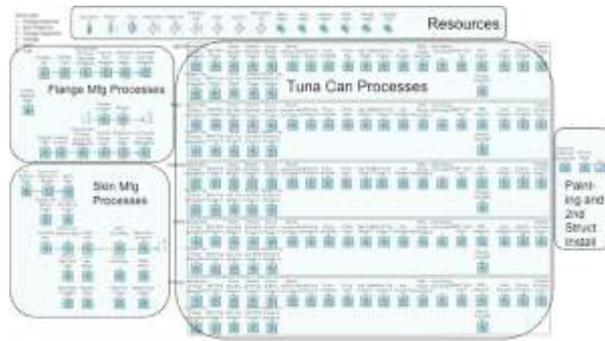


Figure 3: SIMUL8 Process Model Schematic

3.1 Process Simulation Cases

We analyzed four cases with the manufacturing process model:

- **Baseline:** Quantified results that NASA could expect from the as-planned program.
- **Weld Strategies:** Compared different skin welding strategies including mechanical welders versus manual processes, and weld-on-stand versus weld-on-roller.
- **Non-Destructive Evaluation (NDE) Process Variability:** Tested sensitivity of the weld inspection process to defect rate (frequency), repair duration for each defect, and inspection duration.
- **Clock and Mate Bottleneck:** Investigated interventions to mitigate a known bottleneck.

In each case, we averaged the simulation results of 50 independent trials.

3.2 Process Simulation Findings

The process simulation cases and analyses yielded these findings:

- The overall production schedule was highly sensitive to the number of both fabricators and welders.
- Neither the weld-on-stand nor weld-on-roller strategy offered a significant cycle time advantage over the other.
- Similarly, manual welding and automated welding equipment produced comparable process cycle times.
- NDE defect rate was the most significant factor affecting total manufacturing time followed by repair duration per defect.
- The facility needed enough work-in-process space to store at least 72 flange segments, the equivalent of twelve flanges.

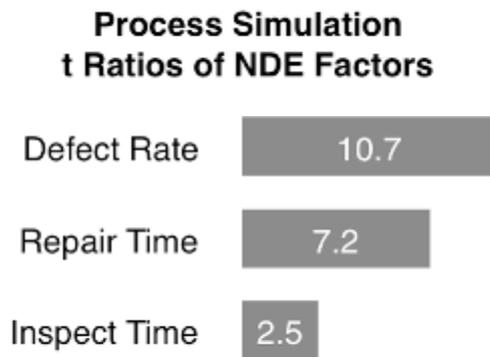


Figure 4: Influence of NDE Factors on Manufacturing Cycle Time

3.3 Process Simulation Conclusions and Recommendations

The analysis team considered the process simulation findings along with other engineering analyses and made these recommendation to NASA:

- Operate two production shifts with 8 fabricators and 6 welders on each shift to achieve the planned delivery schedule.
- Develop automated machine welding systems to minimize the weld defect rate and rework time by producing more uniform welds.
- Perform skin welding on the roller to reduce the number of heavy lifts and maximize availability of assembly stands for other work.

4. ORGANIZATION SIMULATION

The team next used SimVision® technology, published by ePM, to construct an organization simulation model.

The SimVision® model incorporated the process simulation findings and encompassed three broad elements:

- **Direct work** organized into tasks such as preliminary design, weld flange, and clock-and-mate. Tasks were characterized by parameters such as work volume (FTE-days), complexity, uncertainty and skill requirement.
- **Teams** characterized by capacity (FTEs), skills, and application experience.
- **Organizations** characterized by processes and norms for communication, decision-making, and collaboration.

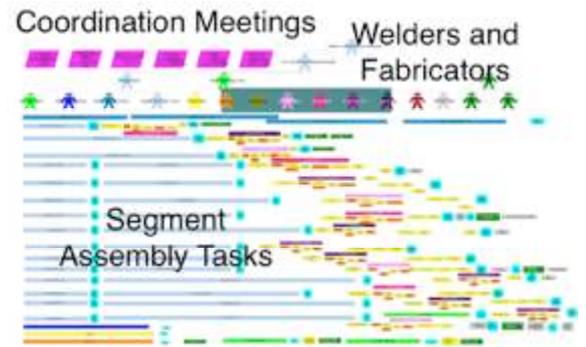


Figure 5: SimVision® Organization Model Schematic

4.1 Organization Simulation Cases

We analyzed five cases with the organization model:

- **Baseline:** Quantified schedule risks attributable to organization capability and capacity.
- **Crew Design:** Compared the expected performance and risks of two competing organization ideas: roaming functional specialists (welding, assembly, etc.) that move from one assembly fixture to the next, and stationary manufacturing crews responsible for all tasks at each fixture.
- **Welding:** Assessed the organization implications and schedule impact of the recommended automated welding process.
- **Facility Constraints:** Quantified the impact on quality, coordination and productivity of strategies to relieve facility space constraints.
- **Manpower Constraints:** Tested the recommended welder, fabricator and inspector manpower after optimizing processes and resource utilization.

In each case, we averaged the results of 100 simulation trials and tested sensitivity to assumptions.

4.2 Baseline Organization Simulation Findings

Simulation of the baseline plan predicted a one-year completion delay. Schedule pressure came from several sources:

- Manufacture of the Pathfinder / DIS tuna cans took longer than planned.
- Coordination work volumes was significant, especially in rolling and wall fitting tasks.
- Welders and fabricators were backlogged and could not meet peak demand.
- The capacity of floor space and assembly stands was constrained.
- Preliminary segment design took longer than planned.

Based on these results, we tested an intervention: reprogramming the design tasks sequence to give priority to early production segments (e.g., US-6) over later seg-

ments. This relieved the schedule pressure on subsequent assembly work and reduced the variability of the total cycle time.

4.3 Crew Design Organization Simulation Findings

The project team’s experience indicated that a welder’s productivity and product quality would benefit from a learning effect if the welder was allowed to specialize in and repeat certain types of welds. We modeled two crew design options to test this:

- **Roaming Functional Specialists:** Functional teams of fabricators and welders, each with different skill sets move from one segment to the next. Welder experience was allowed to increase over time to represent the learning benefit.
- **Stationary Crews:** Welders and fabricators, pulled from a pool of undifferentiated workers, perform all tasks at each assembly stand.

Roaming specialists completed the work approximately four months faster than stationary crews. However, the coordination work volume was greater.

4.4 Welding Organization Simulation Findings

The process simulation model indicated that automated and manual welding processes produced comparable cycle times. The project team postulated the use of automated welding would produce higher quality welds, reduce rework, and relieve pressure on inspection and testing processes. We used the SimVision® model to quantify the impact to the organization and validate the hypothesis. The use of automated weld machines recovered approximately 3 months of the predicted schedule slip.

Figure 6: Welding Organization Design Work Volume Breakdown Comparison

4.5 Facility Constraints Organization Simulation Findings

We tested the facility constraints uncovered in the simulation where weld machines were combined with functional specialists. In this test, the model permitted increased space for work in process material (WIP) storage, and several tasks were moved off the assembly stands.

- Increased WIP storage space allowed component fabrication to start earlier, reduced resource backlogs and reduced component shortages during assembly.
- Combined with the reduced demand for assembly stand time, roaming crews and weld machines cut the predicted completion delay was by seven months compared to Baseline.
- Reduced facility constraints shifted pressure back onto the assembly work. However, the resultant backlogs were minor (less than two weeks).

Relieving facility constraints increased worker utilization and raised coordination risks which impacted worker performance. This was particularly evident in inspection. Inspection tasks experienced significant delays due to increased decision wait times and the delays rippled through the rest of manufacturing process.

4.6 Manpower Constraints Organization Simulation Findings

The prior interventions (weld machine, roaming crews and reduced facility constraints) cut the predicted completion delay from twelve months to one month. The remaining schedule pressure was due mainly to manpower constraints. To mitigate this condition, we tested two interventions:

- Increased welder manpower from 6 FTEs to 8 FTEs on each shift.
- Increased fabricator manpower from 8 FTEs to 14 FTEs on each shift.

This relieved the manufacturing backlog, but shifted the bottleneck to inspection tasks and manpower. We next simulated two more interventions:

- Dedicated a quality engineer to the inspection process and streamlined the nonconformance review process cycle time to 24 hours.
- Dedicated one inspector to each assembly stand.

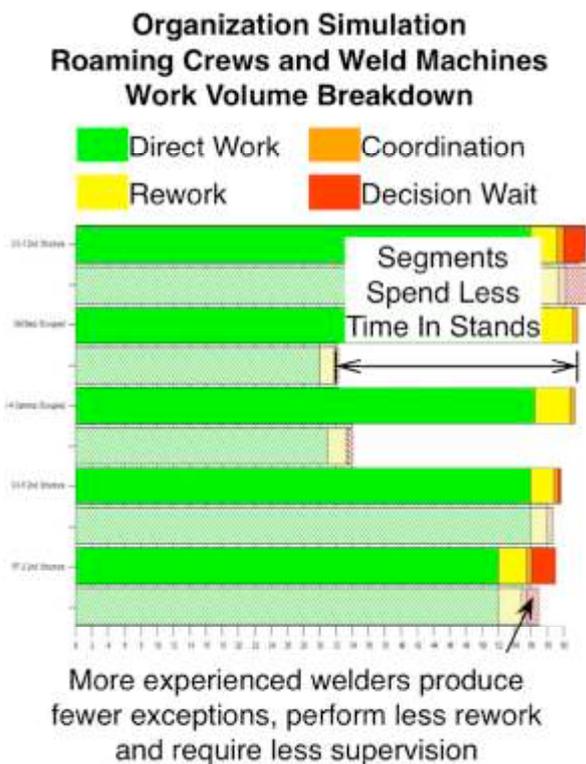




Figure 7: Cumulative Schedule Recovery of Organization Interventions

The SimVision® model predicted on-schedule completion. Competition for assembly stands was mostly relieved, but remained an issue for stands Beta and Alpha. Decision wait and coordination work volumes due to inspection delays continued to drive schedule pressure. Additional intervention tests showed further improvement would be difficult:

- Cutting the nonconformance review cycle time in the inspection process from 24 hours to 8 hours would be necessary to see a significant schedule acceleration. We determined that such a reduction was unrealistic.
- Increasing inspection manpower did not appreciably accelerate the schedule.

5. SUMMARY OF RECOMMENDED INTERVENTIONS AND NASA'S RESPONSE

Based on the process + organization simulation results discussed above, the analysis team recommended several interventions to the NASA project team. NASA accepted and implemented all of these.

1. Adopt automated MIG welding for skin-skin and flange-skin to minimize weld defects and subsequent rework.
2. Reprogram design tasks and reallocate design manpower to prioritize common segment designs. Common segments US-2, 3, 4, 6, 7 became the focus of first incremental USS Critical Design Review.
3. Adopt functional specialist (crew-based) teams to leverage welder learning, maximize productivity and minimize rework.
4. Implement a schedule dashboard to track schedule progress and communicate it to the manufacturing teams. Establish daily manufacturing and Material Review Board (MRB) meetings.

5. Increase flange WIP storage space. Set up a new material lay-down area in west end of AMF building.

6. VALIDATION OF SIMULATION RESULTS

NASA's project team compared actual operating results to the simulation predictions over the subsequent year.

Table X: Validation of Simulation Results

| Simulation Predictions | Observed Operating Results |
|--|---|
| Optimum Staffing: 4 to 6 welders, 8 to 12 fabricators | Validated: Steady State Staffing (Per Shift) 6 welders, 9 fabricators |
| Two shift operation required to meet schedule. | Validated: Project implemented two shift ops from outset. |
| Accelerate early Common Segment design and delay Complex Segment design. | Validated: Three serial critical design cycles/reviews implemented, to feed three serial manufacturing Charges. |
| Increase welding skills and experience, utilize mechanized welding to minimize defect rate. | Validated: Had to contract out to obtain welders with sufficient skill. Once obtained, mechanized welding was no longer needed! |
| Plan for in process holding area for machined parts (flanges, tangs, lugs). | Validated: Need for more floor space drove set up of Temp Storage Facility. |
| Dedicate staff to improve AMF floor coordination and reduce rework decision making time to 24 hours max. | Validated: Floor Director position created per shift; Segment Lead Engineer positions created; MRB set up to meet daily. |

7. NASA PROJECT TEAM'S CONCLUSIONS REGARDING THE DUAL-SIMULATION APPROACH

The dual-simulation approach provided actionable interventions subsequently validated by actual project experience. It is highly recommended for future NASA use.

Solving the facility and process issues uncovered in the process simulation model shifted the schedule risk to the organization. Organization risks were dominant.

- As the facility issues were resolved, coordination and communication risks increased and began to affect performance.

- The centralized decision making and formalized communication norms present in the Ares project team increased risk of delays and need for coordination.
- In particular, inspection tasks experience increased decision wait times as these resources are constrained and backlogged.

Developing specialized teams of resources and tying them to tasks reduces schedule pressure as shown in both the process and SimVision[®] models. The SimVision[®] model quantified the resultant need for greater coordination.

The competition for constrained facilities (assembly stands and floor space) shown in both models put stress (overtime, rework, quality issues) on the organization to maintain schedule. The SimVision[®] model quantified the organizational impacts of these facility constraints. Resource backlogs and facility competition drive schedule delays larger than those predicted by the process simulation, but in line with project team experience.

The highly interrelated manufacturing effort and stressed organization made upsets and schedule slips likely. A dashboard and manufacturing flow map for use in Building 50 was developed by the project to coordinate the required, highly choreographed manufacturing flow.

Managers have better information than could be obtained using a single tool. USS was the only Ares I component delivered on schedule.