Proceedings of the 2006 Winter Simulation Conference
L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nicol, and R. M. Fujimoto, eds.

SEM: ENTERPRISE MODELING OF JSF GLOBAL SUSTAINMENT

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ABSTRACT

The Joint Strike Fighter (JSF) Program is implementing a paradigm shift to a performance-based logistics environment for force sustainment. This approach produces the necessary levels of performance at a significantly reduced cost of ownership. The resulting logistics environment is multi-national, multi-echelon, and multi-service. The magnitude of the change in the support concept requires an enterprise-level model that can instill customer confidence in unproven alternatives to legacy approaches and capture investment/commitment to enable a profitable execution. The Support Enterprise Model (SEM) was developed by Lockheed Martin to provide a consistent/accurate global view for support of strategic decisions during design/implementation of a JSF global sustainment solution. SEM is a discrete event simulation that allows analysts to define operational/support environment, ascertain measures of effectiveness for performance/cost metrics, and characterize sensitivity to changes in Support System architecture, processes, and business approach as well as air vehicle reliability and maintainability characteristics.

1 INTRODUCTION

The Joint Strike Fighter Program (JSF) is a multi-national effort to develop the F-35 aircraft with three variants: conventional take-off and landing (CTOL), short take off and vertical landing (STOVL) and carrier variant (CV). These aircraft will replace aircraft currently in the inventory of the US, UK and many other nations around the globe. While Lockheed Martin is leading the development, production and sustainment effort, there are suppliers of goods and services located around the world. Besides the US and UK, seven nations are currently participating in the development phase of the program: Australia, Canada, Denmark, Italy, Netherlands, Norway, and Turkey.

The JSF fleet sustainment is envisioned to have a performance based logistics (PBL) contract that relies on an effective partnership between the customer and the contractor. A PBL contract provides incentives for meeting performance goals based on best-value or business-case analyses that minimize total ownership costs. The complete global sustainment solution for the JSF results from the design of the F-35 aircraft, the autonomic logistics (AL) functionality that senses and responds automatically to changes in JSF fleet operations, and the application of a performance based logistics contract. This will minimize risk for customers to realize best value for their fleet operations and contractors to realize profit. SEM will be utilized both as a Design Decision Tool during JSF development and a Planning and Management Decision Tool during JSF sustainment.

2 DESCRIPTION OF SEM

The Support Enterprise Model (SEM) is a discrete event simulation tool designed to model operation and support activities of multi-echelon global support enterprises. The simulation is stochastic, performing Monte Carlo sampling for each trial from probability distributions representing uncertainty in a wide range of support system parameters. It provides logistics analysts with the ability to define an operational and support environment and ascertain measures of its performance effectiveness based on the results of multiple trials. SEM characterizes the sensitivity of performance measures to changes to support system architecture, processes and business rules as well as air vehicle reliability and maintainability (R&M) characteristics. It is designed to be a robust decision support tool for evaluating operational supply chain, repair chain and on-aircraft maintenance activities. An output viewer assists the user in identifying support system limitations and analyzing results. SEM operates on standard desktop personal computers with a Windows 2000/XP operational environment to permit widespread distribution among potential users.

SEM can initiate both deterministic and stochastic events. Deterministic event examples include:

- Site activation/deactivation,

- Scheduled maintenance,
- Time phased changes for resources, and
- Operation of aircraft.

Stochastic event examples include:

- Random failures of equipment,
- Wear-out of equipment, and
- Health monitoring indications.

Conditional events can be initiated based on state parameters, e.g., re-supply of spares when stock is below a critical level.

SEM models both the depth and breadth of the support system as shown in Figure 1. The depth includes all echelons of support function from operational unit level down to original equipment manufacturer. The breadth includes all locations worldwide where support functions may be performed. SEM also models the movement of materials among the various locations. It includes business rules to model centralized management by an AL Operations Center. Finally, it models the impact of the AL Information System (ALIS) that provides multi-domain (i.e., supply, maintenance, operations, training, etc.) worldwide exchange of the information required by an AL Operations Center to manage JSF sustainment.

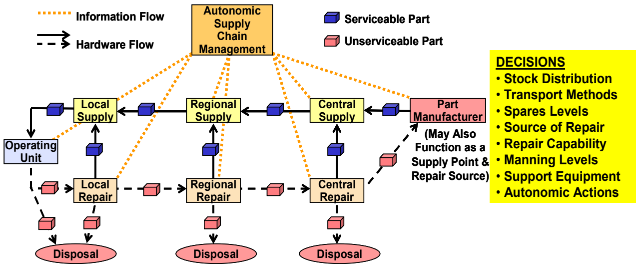

Figure 1: SEM Model Overview

SEM has several unique features that distinguish it from other available models. It provides integrated modeling of a worldwide support system including operations, supply, repair, and transportation functions. It allows for modeling of dynamic changes throughout life-cycle to include fleet build up and retirement, site activation/closure, allocation/reallocation of spares, equipment and human assets, and deployment/surge of operational units. It covers total support system performance and cost including full on- and off- aircraft support activities, Prognostics and Health Management (PHM), off-base movement/storage/repair/build of parts, global optimization of performance versus cost across enterprise, and strategic decision support through impact projections.

SEM provides several unique benefits including near real time strategic planning support, dramatic risk mitigation, and unparalleled resource management flexibility to deal with changing conditions.

3 DATA REQUIREMENTS OF SEM

SEM is a scalable model with data requirements that can be met at various levels of indenture/completeness. Thus for conceptual level studies, minimal data can be used to assess performance and cost. As design matures, data inputs can include any level of parts hierarchy desired. The cost of increased complexity is manifested in physical size of the database used and time required to complete simulation trials. SEM uses a Microsoft Office Access database format for both input and results, allowing simple exchange of scenarios among analysts.

3.1 Input Data

Input data is stored in a relational Access tables and key fields are used to link these tables. Input data is required to define:

- **Sites:** Site types include squadrons, bases, repair facilities, supply warehouses, and factories. Site data provides the location, capability and availability of each site.
- **Connections:** Connection data defines the support network established by linking the defined sites into repair and supply chains. Each site has a list of sites that provides/receives serviceable parts to/from (supply chain) and a list of sites that it provides/receives unserviceable parts to/from (repair chain).
- **Configurations:** Configuration data details the air vehicles in terms of parts, squadron assignments, and maintenance requirements.
- **Parts:** Part data provides cost, dimensions, weight, R&M characteristics, and spare availability at each base, supply, repair, and original equipment manufacturer (OEM) site.
- **Tasks:** Task types include supply, repair, maintenance, and build. Task data details the duration, resource requirements and cost factors for each task.
- **Resources:** Resource types are personnel and support equipment (SE). Personnel data provides the cost and number available at each site by skill. Costs for personnel can be accumulated annually (employee) or by usage hours (contractor). Equipment data provides costs, maintenance requirements and available quantity at each site. Cost elements for equipment include acquisition, event (repair or calibration) and consumption (fuel, oil, etc.).
- **Flight Schedules:** Flight schedule data provides launch time, duration and mission parameters for

flight operations at squadron sites. Schedules are defined in a repetitive pattern (daily, weekly, monthly, etc.).

- **Transport:** Transport data provides delivery standards and options for transport of parts from site to site. Delivery standards provide a target by priority, cargo type and from/to transport zone. Transport options provides information on available modes including weight/volume limits, average delivery time, standard deviation for delivery time and cost by cargo type and transport zone. Priorities, cargo types and transport zones are user definable.
- **Deployments:** Deployment data details the movement of squadrons from their "home" base to a temporary base including spares, personnel, and equipment needed to support flight operations at that site.

3.2 Output Data

Output data is also stored in Access tables. Outputs are scaleable to allow the user to store only the data needed to perform the required analysis. Summary outputs provide basic information that is sufficient for basic comparative analysis. If trending is desired, then detail output must be requested. When causative factor analysis is to be done, full event output is required. SEM also allows the user to select a specific period in the simulation to store data. The user can also select from various summary/detail period durations (daily, weekly, monthly, quarterly, and annually).

Output is stored for all events at all sites to record duration, resource usage and associated costs, e.g., aircraft maintenance, supply, part repair, part build, part transport and aircraft operations. These values can be used to assess a wide variety of metrics to determine both performance and cost effectiveness.

Summary/detailed output data is stored for:

- **Costs:** Cumulative cost is recorded by category (spare, support equipment, transport, storage, tasks consumables, SE maintenance, SE consumables, and labor) for each summary/detail period.
- **Builds:** The number of parts manufactured at any OEM site during each summary/detail period is recorded.
- **Repairs:** The number of parts repaired at a site during each summary/detail period is recorded.
- **Site:** For sites, statistics are recorded for parts (repairs, issues, requisitions, backorders, retrogrades, condemnations.) and by aircraft (sorties, flight hours, possessed hours, downtime, maintenance) during each summary/detail period.
- **Transport:** At each site and for each part, the count of transport events by transport mode and priority is recorded for each summary/detail period.

Event output data is stored for:

- **Builds:** Build data includes build site, supply site, build task, start time, finish time and part.
- **Repairs:** Repair data includes repair site, failure, repair task, failure time, repair start time, repair finish time and part.
- **Maintenance:** Maintenance data includes part, failure, criticality, failure time, maintenance down time, supply time, repair level and failure type.
- **Supply:** Supply data includes part, site, supply, start time, and issue time.
- **Transport:** Transport data includes part, from site, to site, time sent, transport priority, transport mode and time delivered.

4 USER INTERFACE

SEM provides a user interface to the input and output tables that allows entry of input data and viewing of simulation results. For large problems, use of the SEM data entry screens is not efficient. In this situation, SEM allows bulk import of the pre-processed data from accredited data sources and other applications. The SEM output viewer provides both graphical and grid views of the output tables. If the standard output is not sufficient, SEM allows the user to export results for post processing in other applications.

4.1 Input Screens

SEM has input screens for all required data tables. These screens are in grid format and provide typical editor functionality to include insert, delete, cut, copy, paste and fill. Data sort and filter is also provided for any data field. A tree is provided for navigation of input screens and help scripts are available for every input grid. The user interface also performs real-time input data validation where possible and provides an array of diagnostic data checks.

4.2 Output Screens

The SEM output analysis viewer allows the user to select from site, parameter and trials. Site selection is by type and also includes an "All Site" selection. After site type selection, available sites are listed and user selection of any site or combination is allowed. If more than 1 trial run was made, the user can select any single run or combination of runs. The user can then switch between graphical and grid view for any selected result. If multiple trials were selected, the mean and standard deviation are shown in the grid view.

4.3 Export

Export to and import from Microsoft Excel is built in for both input screens and the output viewer. This allows use of all Excel data analysis and manipulation features. Also, the Access data base can be opened and Access SQL can be used for data analysis and manipulation.

5 ANALYSIS USING SEM

SEM has been used on JSF since 2002 to answer multiple questions regarding end-state and transition issues for fleet sustainment. These analyses have been used to support design reviews by demonstrating that proposed design and sustainment solutions will provide acceptable operational performance with significant reductions in sustainment costs. Analysis has also provided insight into proposed design features that has impacted decisions for both air vehicle and autonomic logistics design as well as sustainment business approach. For example, SEM was used to determine if the placement of automatic test equipment at flight test locations was necessary for development flight testing of the aircraft. Also, SEM provided material demand profiles that allowed early planning for supply chain capacity sufficient to meet needs while eliminating the waste of overcapacity.

5.1 JSF Example

A depot repair study is a typical usage of SEM during JSF development. This study was conducted to determine the feasibility of placing centralized repair facilities around the globe. These regional repair centers (RRCs) should be included in the global sustainment solution based on economics and fleet performance goals (see Table 1).

The scenarios selected were appropriate given that the purpose of the study was to determine whether or not RRCs should be included in the solution. In addition, the team felt that the scenarios analyzed should include aspects of US law pertaining to depot capabilities as they are constraints.

The SEM scenarios were run for a total of six years. The first year was run as a “warm up period” to allow the task queues to fill. Discrete event simulation models typically need this period to allow the system to reach steady state. In other words, at Day 0, the simulation has no tasks in progress and no parts in transit. Many of these tasks take a significant amount of time to complete in the model. Part repairs, for instance, can take 40 days or more to complete. As a result, no parts will be returned from repair until Day 40 at the earliest. Performance suffers early in the simulation as a result of waiting on these lengthy tasks. On Day 365, however, many parts are being returned from repair everyday which is more indicative of real world, steady state operations. Output from the final five years was assessed to produce the results shown in the next section.

Table1: Solutions Modeled in SEM

Scenario	Sites Activated
Scenario 1 • No RRCs • Title 10	**RRCs:** None **US Depots:** 3 **OEMs:** 35
Scenario 2 • Unlimited RRCs • Title 10	**RRCs: 5** **US Depots:** 3 **OEMs:** None

5.2 SEM Results

Table 2 displays the technical performance results of each scenario.

Table 2: SEM Results – Global Fleet Performance

	Scenario 1	Scenario 2
MC Rate	*59.6%*	*59.0%*
NMCM%	*12.6%*	*12.6%*
NMCS%	*27.8%*	*28.4%*
% FH Accomplished	*94.9%*	*94.7%*

The results show that the performance differences are negligible between the scenarios. Differences in mission (MC) Rate, not mission capable due to supply (NMCS%), not mission capable due to maintenance (NMCM%) and Flight Hours Accomplished are all less than one percent. This result was desired and makes the cost comparison more meaningful. The performance results were also calculated to allow for individual country fleet performance comparisons across the two scenarios. Table 3 contains the results by country fleet.

Table 3: SEM Results Country Fleet Performance

	Scenario 1				Scenario 2			
	MC Rate	*NMCM%*	*NMCS%*	*FH%*	*MC*	*NMCM%*	*NMCS%*	*FH%*
A	45%	8%	47%	92%	57%	8%	35%	98%
B	47%	17%	36%	88%	49%	17%	34%	89%
C	47%	29%	24%	99%	52%	29%	19%	99%
D	56%	17%	27%	88%	53%	16%	31%	85%
E	58%	15%	28%	90%	53%	15%	33%	87%
F	51%	24%	25%	66%	51%	25%	24%	70%
G	70%	10%	20%	100%	66%	10%	24%	100%
H	56%	14%	30%	89%	58%	15%	28%	90%
I	61%	12%	27%	96%	60%	12%	28%	96%

One country (A) saw the only significant change from Scenario 1 to Scenario 2 with a 12% increase in MC Rate and a 6% increase in % Flight Hours Accomplished. Further analysis of the output data has not fully revealed the cause for this result. The differences between country performances in both scenarios are a result of several factors. The primary drivers appear to be the number of shifts operated in the country and the on-site delivery time which occurs when the base sends a part to one of the squadrons and vice-versa. The shift times affect both NMCM% and NMCS% because both maintenance events and supply deliveries are often delayed until the next shift begins. As might be expected, the best performers are typically the countries that operate three shifts. The on-site delivery time negatively affects NMCS% because each squadron demand passes through base supply and experiences the delay. A third factor is the flight schedule flown by each country. This factor is related to the previous two as it influences the magnitude of their impact. As more flight hours are attempted in the model, more parts are moving in and out of the bases. These additional delays will have the greatest impact on countries with the most aggressive flight schedules. The SEM output can further broken down into per squadron performance results. Figure 2 depicts the cost of each scenario. Scenario 2 results in a 13% savings from the Scenario 1.

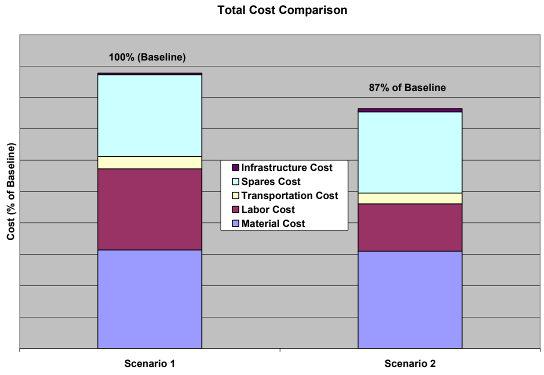

Figure 2: SEM Cost Results

6 OPTIMIZATION USING SEM

An effective logistics support system ensures that spare parts are delivered to end-users in a timely fashion, such that the aircraft can achieve target mission capable rates or other performance metrics. In addition to spare parts, the required resources (personnel with the necessary skills and support equipment) must also be available to meet maintenance and repair needs. All of this support infrastructure must be provided at the lowest possible cost to the customers that operate JSF. It is anticipated that JSF logistics support will be furnished competitively by the private sector on a "power-by-the-hour" basis. Novel challenges in spare parts inventory and resource optimization for the JSF include:

1. Problem scale:
   - (a) Large and complex globally distributed multi-echelon support system
   - (b) Several thousand parts (line replaceable units or LRUs)
   - (c) As many as 500 types of support equipment
   - (d) Several hundred squadrons deployed at many tens of bases
   - (e) On the order of 10 regional supply and repair depots distributed globally
   - (f) Dozens of major OEMs
2. The application of Just-In-Time (JIT) manufacturing and distribution to military systems:
   - (a) Commercial third-party transportation providers
   - (b) Streamlined deployment and minimal-inventory strategy
3. Integrated, overlapping part supply and part repair systems:
   - (a) Common parts across aircraft configurations (and thus common OEMs, supply, and repair depots)
   - (b) Multiple customers with differing performance goals
   - (c) Branches of service and governments have to share more than they're used to doing.

SEM supports two basic types of optimization: achieving a target aircraft performance metric for the lowest inventory and resource cost, and achieving the highest possible aircraft performance metric for an available budget. The variables are recommended inventory levels at each site (by part), the number of personnel at each site (by skill type), and the quantity of each type of support equipment at each site (by equipment type). In performing optimization, the SEM simulation becomes a sustainment system evaluator. By this we mean that, for a given global distribution of part inventory (and associated inventory control rules) and a given arrangement of personnel and support equipment, the SEM simulation can evaluate the expected performance of the aircraft fleet. Aircraft performance is measured in terms of metrics such as mission capable rate, availability, fraction of scheduled flight hours achieved, and sortie generation rate (during wartime).

SEM is a stochastic simulator, meaning that each run, after sampling from multiple probability distributions representing uncertain variables, will produce different results. In consequence, the simulator cannot be run once to determine the expected performance of the sustainment system: multiple trials are required to properly characterize the uncertainty in system performance. Furthermore, the "best" inventory and resource solution in early years (with only a relatively small number of aircraft) will not be a good solution in later years when perhaps 3,000 aircraft are in service. Thus, optimization must be performed for individual time periods such that sustainment conditions can be assumed to be relatively close to steady state.

Given the challenges summarized above, it should be apparent that an "off-the-shelf" optimization approach is unlikely to be useful. Instead, the SEM team developed a hybrid optimization approach tailored to the unique challenges of global sustainment systems. The approach addresses the problem in distinct phases and was designed to take advantage of high-performance computer clusters when available. The phases are illustrated in Figure 6-1 and are described below.

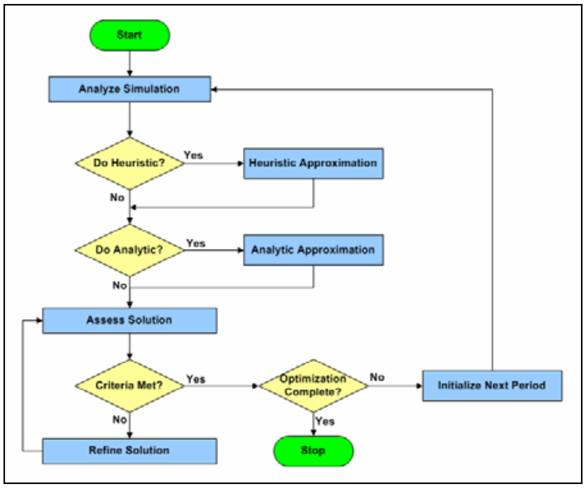

Figure 3:. SEM Optimization Phases

6.1 Analyze Simulation

SEM Optimization starts each optimization period by analyzing the result of a "flooded" run for this period. By "flooded" we mean that an essentially unlimited number of parts are placed in inventory and personnel and support equipment quantities are also unlimited. The "flooded" simulation creates a baseline for the current period, and the results are used to determine the maximum achievable performance metric for each site when resources/parts are unconstrained. In the case where the user selected a target metric that is greater than the maximum achievable value, the target value is set to the maximum achievable value. This ensures that the target for each site is attainable for the current period.

6.2 Heuristic Approximation

The heuristic approximation mechanism generates recommended inventory levels using a simple variant of marginal analysis that is specialized to SEM. Marginal analysis, developed by Craig Sherbrooke, has found widespread use in spares inventory management throughout the DoD. Many well-known commercial products, including Vari-METRIC, are based on marginal analysis.

The mathematical development of marginal analysis assumes specific part failure distribution types, in particular random failures characterized by an exponential probability distribution. Although the analysis has been extended to handle additional distributions, extensions to the specific non-random wear out distributions used in SEM (e.g., time change and wear out failures) have not been developed. Consequently, the heuristic approximation mechanism currently only handles random failure parts whose distribution is characterized by an exponential. However, this omission is not a limitation in the broader context of the SEM optimizer, as these distributions are handled by the analytic approximation described below.

The heuristic approximation mechanism generates recommended inventory levels for all random failure parts at all sites (except individual squadrons) that are active during the current optimization period.

6.3 Analytic Approximation

The Analytic Approximation is an integer program (IP) approximation to the key processes simulated in SEM. While not capturing all of the subtleties of the full simulation, the current formulation provides a better approximation than can be obtained with the heuristic approach. The IP would become too large to solve if all parts and resources were included. For this reason, we use the analytic model for a subset of the full problem, specifically for "high-impact" parts. We define high-impact parts as those with a relatively high failure rate. The paradigm here is to use the simulator to generate a demand stream for parts and then use the IP model to generate part inventories (for the high-impact parts) that "cover" the demand stream. Use of the IP model in SEM optimization requires access to the commercial AMPL/CPLEX toolset. If not available, this optimization step is bypassed, requiring more computational effort in the solution refinement step that follows.

6.4 Solution Assessment and Refinement

Solution assessment and solution refinement are performed iteratively to complete the optimization process. The preceding steps dramatically reduce the problem space and in general provide a very good starting point for the refinement phase. Because they operate on simplified models of SEM processes, both the heuristic and analytic approximation approaches frequently yield optimistic inventory levels for a number of site/part combinations. Consequently, it is typically necessary to refine the solution generated by one or both of these approaches to obtain inventory levels that yield the target performance metric in the context of an actual SEM simulation.

Solution evaluation is a crucial step in each period in that it simulates with SEM using the current part and resource "solution" and determines if the target performance metric is met. The results represent the optimization progress of each period. Since there are multiple trials, the results are taken as an average across trials.

At this stage in the process we check the current performance metric against the target value. If the target has been reached, the solution refinement step will be skipped and the optimization will move on to the next period. Otherwise, the process moves on to the refinement step. While the optimizer does its best to reach the target metric, it cannot guarantee that the targets can be obtained in a timely manner. In this case, the user can accept the current solution if it is close but has not quite reached all target values. By applying the solution refinement methodology, we help ensure that the target performance will be reached.

The refinement mechanism generates an update of the recommended inventory levels for the optimization period. As with the heuristic and analytic approximation methods, it is necessary to validate whether the new levels achieve the required performance. Consequently, the Assess Solution mechanism is invoked after each refinement step.

6.5 Future Optimization Directions

One of the many challenges that remain is the development of techniques for quantifying solution robustness and algorithms for generating solutions with varying levels of robustness. As with most optimization schemes, the current SEM optimizer tends to produce solutions that are "brittle", meaning that even minor reductions of inventory and/or resource levels may lead to dramatic reductions in overall aircraft performance. While this behavior is consistent with the objective of minimizing solution cost, the utility of the resulting solutions is tied to the accuracy with which quantities such as component mean-time-between-failures can be estimated. For new systems in particular, estimates of these parameters are likely to be inaccurate, leading to the requirement that the SEM optimizer be modified to account for the associated uncertainties. Ultimately, the approach must be enhanced to provide a characterization of the trade-offs between solution robustness and cost, enabling end-users to quantify risk by understanding the impact of financial decisions. Methods for quantifying solution robustness are relatively immature, and little research has been devoted to developing algorithms to generate solutions with varying degrees of robustness.

ACKNOWLEDGMENTS

There were three different teams involved in the development of the SEM product. On the JSF Program, Richard Pound, Mike Alton, Lindsey Brown and Ebonii Bell have worked diligently to provide requirements and perform user acceptance testing to affirm conformance to requirements. At LM Aero, Kevin Abshire, Cathy Bixler, Mark Carter and Julie Seiber were the system development team who provided high level and detailed requirements to the design team, developed test cases and managed verification of SEM. Also at LM Aero, Doug Park, and Mike Naquin developed overall architecture and wrote code for user interfaces. At Sandia National Laboratories, Kimberly Paradeise, Laura Weiland, Hai Le, Rossitza Homan, Tom Swiler, Jean-Paul Watson, David Strip and Mike Collins were the design and development team for the simulation engine and optimization.

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