Final Report 0001AC

Multidisciplinary Optimization of Naval Ship Design and Mission Effectiveness

#N03-T026

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Contract# N00014-03-M-0270

Period Covered: 7/1/03 – 2/2/04
Security Classification: Unclassified
Issuing Agency: Office of Naval Research
February 2, 2004

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **FEB 2004**	2. REPORT TYPE **Final**	3. DATES COVERED **01 Jul 2003 - 02 Feb 2004**

4. TITLE AND SUBTITLE **Multidisciplinary Optimization of Naval Ship Design and Mission Effectiveness**	5a. CONTRACT NUMBER **N00014-03-M-0270**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Justin Vianese**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Engineous Software 200 CentreGreen Way Suite 100 Cary, NC 27513**	8. PERFORMING ORGANIZATION REPORT NUMBER **Final Report 0001AC**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Office of Naval Research Katherine Drew ONR Code 334 Ballston Tower One 800 North Quincy Street Arlington, VA 22217-5660**	10. SPONSOR/MONITOR'S ACRONYM(S) **ONR**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **N00014**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

The Engineous Software STTR Team, including team members from Northrop Grumman, Naval Undersea Warfare Center (NUWC), Massachusetts Institute of Technology (MIT), and Elon University; proposed at the outset of the project that it could develop an integrated Multi-disciplinary Optimization (MDO) system of naval ship design and mission effectiveness. Specifically, the team intended to use a ship model of interest to the Navy in an effort to demonstrate that disparate ship analysis tools could be integrated under a single framework and automated. This integrated, automated system would allow its users to measure ship performance and effectiveness, as well as accounting for uncertainty in those measurements, through design exploration techniques, such as optimization, design of experiments (DOE), and quality engineering analysis (e.g. Monte Carlo analysis). The primary struggle on the project was acquiring analysis models to use in the MDO system. The time required to obtain the models, unfortunately, limited the amount of analysis the team was able to perform. However, once the models were obtained, the team was able to quickly integrate them and show the power and flexibility of the MDO system. The results showed that the system was able to quickly apply numerous exploration techniques, including the Multi-Objective Genetic Algorithm specifically developed for the STTR, to the integrated models. Hundreds of ship designs were evaluated in the pursuit of an optimum design; while taking into account uncertainty. A measured improvement of 6% in lifecycle cost was calculated for an optimization analysis. It was also found that while introducing uncertainty in the analysis that the lifecycle cost was perturbed by only a maximum variation of 1%. While these results are only first order analyses used to demonstrate the feasibility of developing such a system, they offer a compelling case for further exploration. The next phase of this project could bring enormous advances in the MDO ship system. By developing more robust models, tightly integrating the design integration components, including new analysis tools, and possibly pushing the integration capabilities across the internet to include geographically disperse design centers the system could move from the compelling demonstration to a user-friendly MDO naval design framework.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**83**	

1.0 Abstract

The Engineous Software STTR Team, including team members from Northrop Grumman, Naval Undersea Warfare Center (NUWC), Massachusetts Institute of Technology (MIT), and Elon University; proposed at the outset of the project that it could develop an integrated Multi-disciplinary Optimization (MDO) system of naval ship design and mission effectiveness. Specifically, the team intended to use a ship model of interest to the Navy in an effort to demonstrate that disparate ship analysis tools could be integrated under a single framework and automated. This integrated, automated system would allow its users to measure ship performance and effectiveness, as well as accounting for uncertainty in those measurements, through design exploration techniques, such as optimization, design of experiments (DOE), and quality engineering analysis (e.g. Monte Carlo analysis).

The primary struggle on the project was acquiring analysis models to use in the MDO system. The time required to obtain the models, unfortunately, limited the amount of analysis the team was able to perform. However, once the models were obtained, the team was able to quickly integrate them and show the power and flexibility of the MDO system.

The results showed that the system was able to quickly apply numerous exploration techniques, including the Multi-Objective Genetic Algorithm specifically developed for the STTR, to the integrated models. Hundreds of ship designs were evaluated in the pursuit of an optimum design; while taking into account uncertainty. A measured improvement of 6% in lifecycle cost was calculated for an optimization analysis. It was also found that while introducing uncertainty in the analysis that the lifecycle cost was perturbed by only a maximum variation of 1%. While these results are only first order analyses used to demonstrate the feasibility of developing such a system, they offer a compelling case for further exploration.

The next phase of this project could bring enormous advances in the MDO ship system. By developing more robust models, tightly integrating the design integration components, including new analysis tools, and possibly pushing the integration capabilities across the internet to include geographically disperse design centers the system could move from the compelling demonstration to a user-friendly MDO naval design framework.

2.0 Objectives

The objectives of Phase I outlined in the proposal addressed the following questions:

1. What codes are currently in use at naval ship design organizations? How are these codes used, and how do they interact with each other?

2. What codes are currently in use to evaluate mission effectiveness? How are these codes used? How do they interact with other mission analysis codes or ship design codes?

3. What is the feasibility of integrating the ship design analysis and mission effectiveness codes into a single design framework such as the Engineous Collaborative environment called FIPER?

4. How can integrated ship design/synthesis and mission effectiveness codes be applied to other organizations within the Center for Innovative Ship Design at NSWC-CD, the Navy, industry and universities?

5. What is the feasibility of integrating a pareto multidisciplinary optimization technique into a collaborative engineering environment (such as FIPER) including:
   - Parallel processing
   - Distributed Processing
   - Multiple operating systems

6. What are the costs and benefits of accounting for uncertainties in data inputs for ship design?

7. Demonstrate the feasibility of integrating at least one ship design code and one mission effectiveness code to assess a design currently being evaluated by the Center for Innovative Ship Design at NSWC-CD.

8. Generate a work plan for a Phase II proposal.

3.0 Team Members

The STTR team members included industry participants from Northrop Grumman Ship Systems in Pascagoula, Mississippi and the Naval Undersea Warfare Center in Newport, Rhode Island; Director of the Sea Grant College Program from MIT; a Multi-Disciplinary Optimization (MDO) consultant from Elon University; and participants from Engineous Software. A full list of team members is included in Appendix B of this document.

4.0 Analysis Tools

Based on recommendations from the team members, the following candidates for analysis tools were chosen:

1. ASSET – Ship design (e.g. dimensions, weight, etc.)
2. SMP – Seakeeping
3. MIT Cost model
4. SIMSmart – Piping/HVAC layout
5. Signatures – Stealth

The team soon realized that SIMsmart would provide too much detail design as compared to the other analysis tools. While optimization at the detailed design stage of ship design was still desirable, using SIMsmart was not inline with the team's proposal, which was to focus on the 80% of ship building costs locked in at conceptual design phase. Work on SIMsmart ceased in November.

Due to its classified status, Signatures was also removed from the team's tool list. It was determined that no unclassified analysis tool existed to effectively measure stealth capabilities of ships.

Thus, ASSET, SMP, and the MIT Cost model were used in the integrated analysis. Using these tools, the team would develop a generalized prototype solution to demonstrate the integrated MDO system.

5.0 Analysis Models

After identifying the analysis tools for our system, the team set out to find models for each analysis tool. However, identifying proper ship models to use in our MDO analysis was a source of struggle on the project.

As leaders in ship design, the members from Northrop Grumman oversaw the task of acquiring ship models for ASSET and SMP. The MIT cost model could be altered to suit any ship model relatively quickly, so no specific model was needed. At the beginning of the project, Northrop Grumman identified the LCS ship class as a good candidate for the integrated analysis. Unfortunately, it was later determined that the LCS models for SMP and ASSET would not be available, since Northrop Grumman was entering an unsolicited bid to the Navy on that project. At that point Northrop suggested using the Multipurpose Force Future (MPFF) model as a replacement (See Appendix C for details on the MPFF ship presented during our ONR briefing in November). Northrop was using a baseline of three classes of ships – LPD 17, LHD8, and LMSR – to develop the MPFF ship class. After unsuccessfully trying to acquire MPFF specific models, in late December Northrop suggested we use the LHD8 ship class as our baseline for the project as it would be a good starting point to the MPFF analysis.

ASSET included an LHD8 model within the databanks provided with its software, so only an SMP model was needed. It was determined that this model would be developed with the help of NUWC and MIT. By mid-January, the team had LHD8 models for ASSET, SMP, and the MIT cost models; and was ready to explore the ship design space.

6.0 Integration

Engineous Software's FIPER product was used as the system integration framework and for the design exploration analysis. [For a full background on FIPER and its history, please refer to Appendix D in this report.] By leveraging FIPER's ability to rapidly integrate disparate analysis tools, ASSET, SMP, and the MIT cost model could be tied together in a flexible and easily changeable way. FIPER provided not only that integration framework, but also techniques in design of experiments (DOE), optimization, and quality engineering. Thus, FIPER supplied a complete architecture for a MDO system for naval ship design and mission effectiveness.

Bringing together the ASSET, SMP, and cost model tools required using two types of FIPER integration components: the Microsoft/Excel FIPER component used for communicating directly with an Excel spreadsheet, and the Data Exchange component used to communicate with any program that can accept and return input and results as text files. The MIT cost model and ASSET were integrated using the Excel component; SMP using the Data Exchange component.

The MIT cost model component was a relatively straight forward integration using the Excel component. The component provides an editor that permits the user to select particular spreadsheet cells directly and give those cells parameter names. These parameters are how FIPER transfers information in and out of the spreadsheet. A picture of this editor is shown in Figure 1.

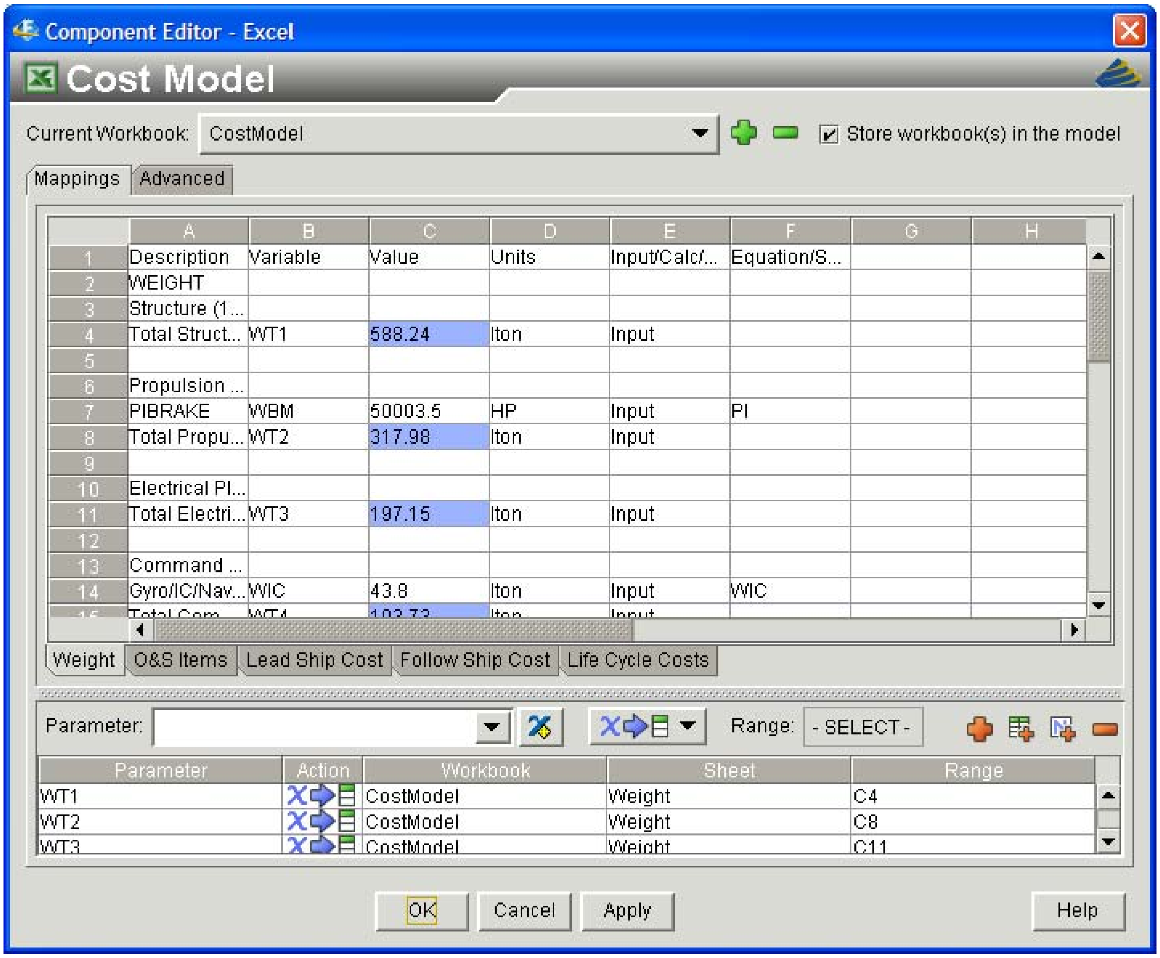


Figure 1 – FIPER Editor for MIT Cost Spreadsheet

Once the user has "mapped" all the input/output parameters of interest that he/she wishes to write/read to or from the spreadsheet, FIPER provides these parameters as input/outputs for the other integrated analysis tools (i.e. ASSET and SMP). Figure 2 shows the list of parameters that were input for the cost model and the resulting output generated by the spreadsheet.

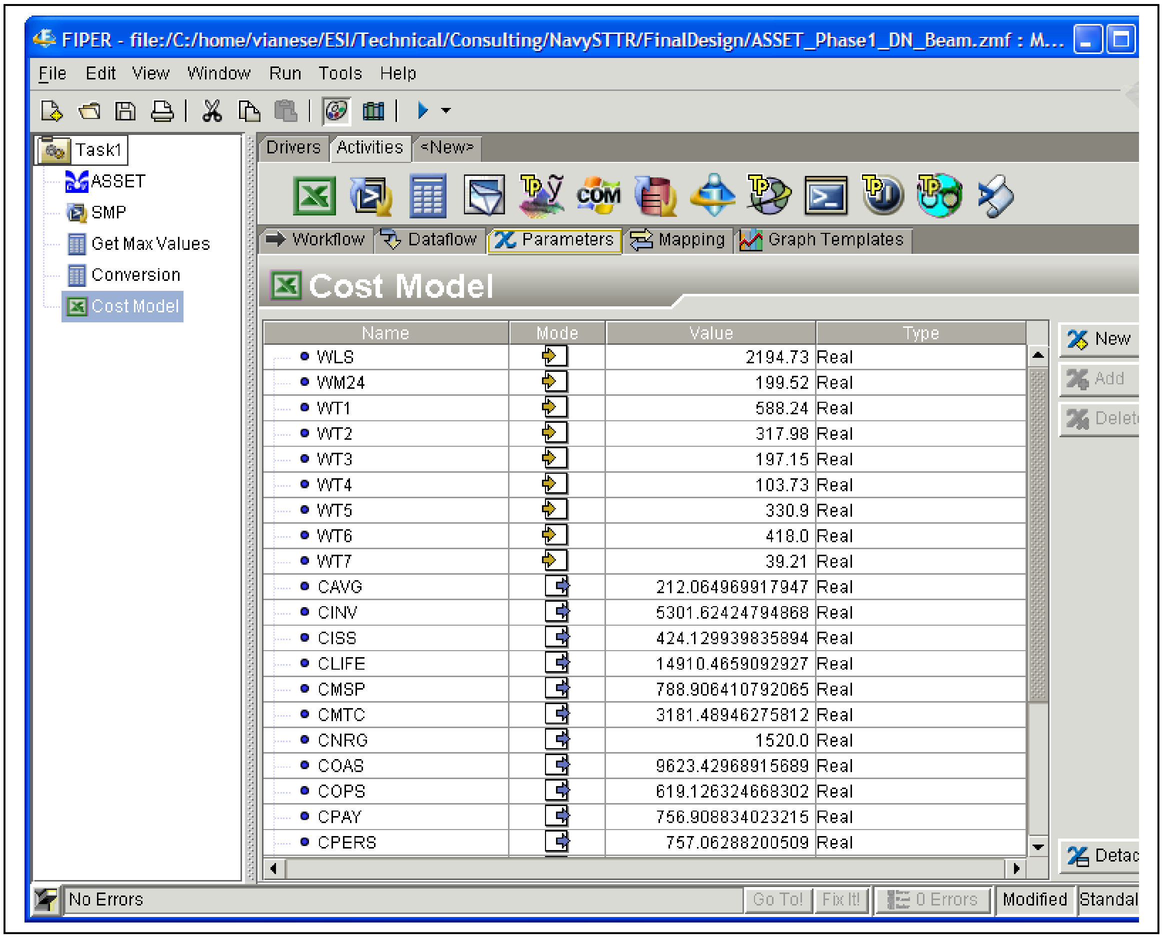
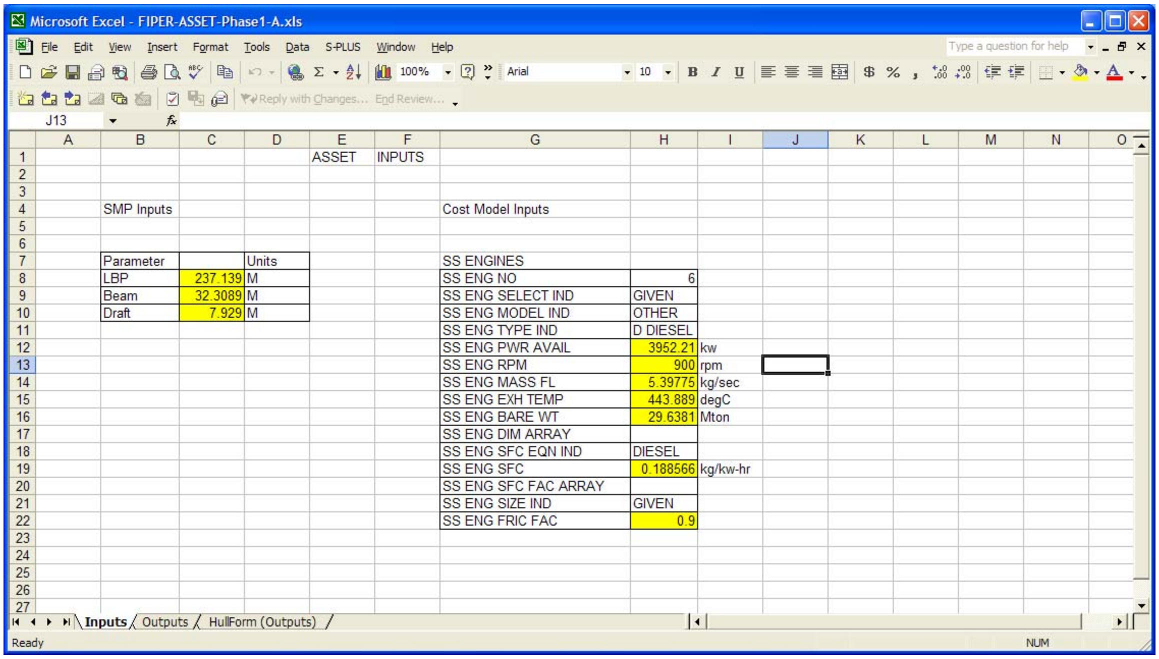


Figure 2 – Parameters for the MIT Cost Spreadsheet

The complete cost spreadsheet with full parameter descriptions can be seen in Appendix E.

The ASSET model used a similar integration scheme as the MIT model cost spreadsheet. One feature of ASSET is that editing parameters and retrieving results can be done through an Excel spreadsheet. Using a spreadsheet allows the user to identify key parameters and display them in a "dashboard" like manner instead of searching through an expansive graphical user interface. A spreadsheet was set up to communicate with ASSET. Figures 3-5 show those input and output parameters as they appear in the spreadsheet.



Microsoft Excel - FIPER-ASSET-Phase1-A.xls

ASSET INPUTS

SMP Inputs

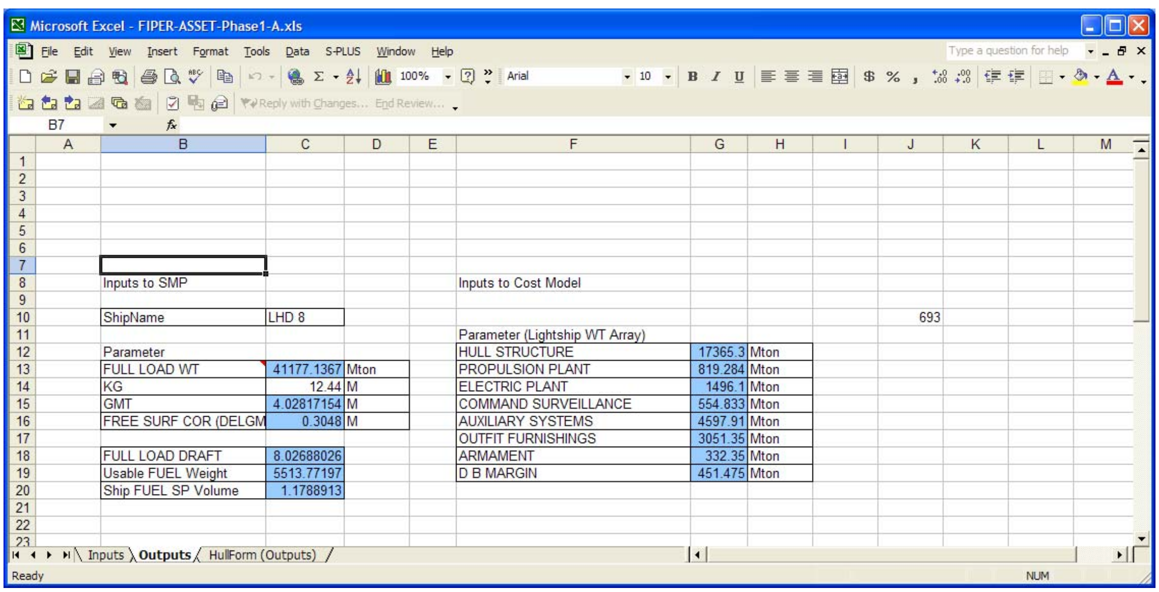
Parameter		Units
LBP	237.139	M
Beam	32.3089	M
Draft	7.929	M

Cost Model Inputs

SS ENGINES		
SS ENG NO	6	
SS ENG SELECT IND	GIVEN	
SS ENG MODEL IND	OTHER	
SS ENG TYPE IND	D DIESEL	
SS ENG PWR AVAIL	3952.21	kw
SS ENG RPM	900	rpm
SS ENG MASS FL	5.39775	kg/sec
SS ENG EXH TEMP	443.889	degC
SS ENG BARE WT	29.6381	Mton
SS ENG DIM ARRAY		
SS ENG SFC EQN IND	DIESEL	
SS ENG SFC	0.188566	kg/kw-hr
SS ENG SFC FAC ARRAY		
SS ENG SIZE IND	GIVEN	
SS ENG FRIC FAC	0.9	

Inputs | Outputs | HullForm (Outputs)

Figure 3 – ASSET Inputs



Microsoft Excel - FIPER-ASSET-Phase1-A.xls

Inputs to SMP

ShipName	LHD 8	
Parameter		
FULL LOAD WT	41177.1367	Mton
KG	12.44	M
GMT	4.02817154	M
FREE SURF COR (DELGM	0.3048	M
FULL LOAD DRAFT	8.02688026	
Usable FUEL Weight	5513.77197	
Ship FUEL SP Volume	1.1788913	

Inputs to Cost Model

Parameter (Lightship WT Array)		
HULL STRUCTURE	17365.3	Mton
PROPULSION PLANT	819.284	Mton
ELECTRIC PLANT	1496.1	Mton
COMMAND SURVEILLANCE	554.833	Mton
AUXILIARY SYSTEMS	4597.91	Mton
OUTFIT FURNISHINGS	3051.35	Mton
ARMAMENT	332.35	Mton
D B MARGIN	451.475	Mton

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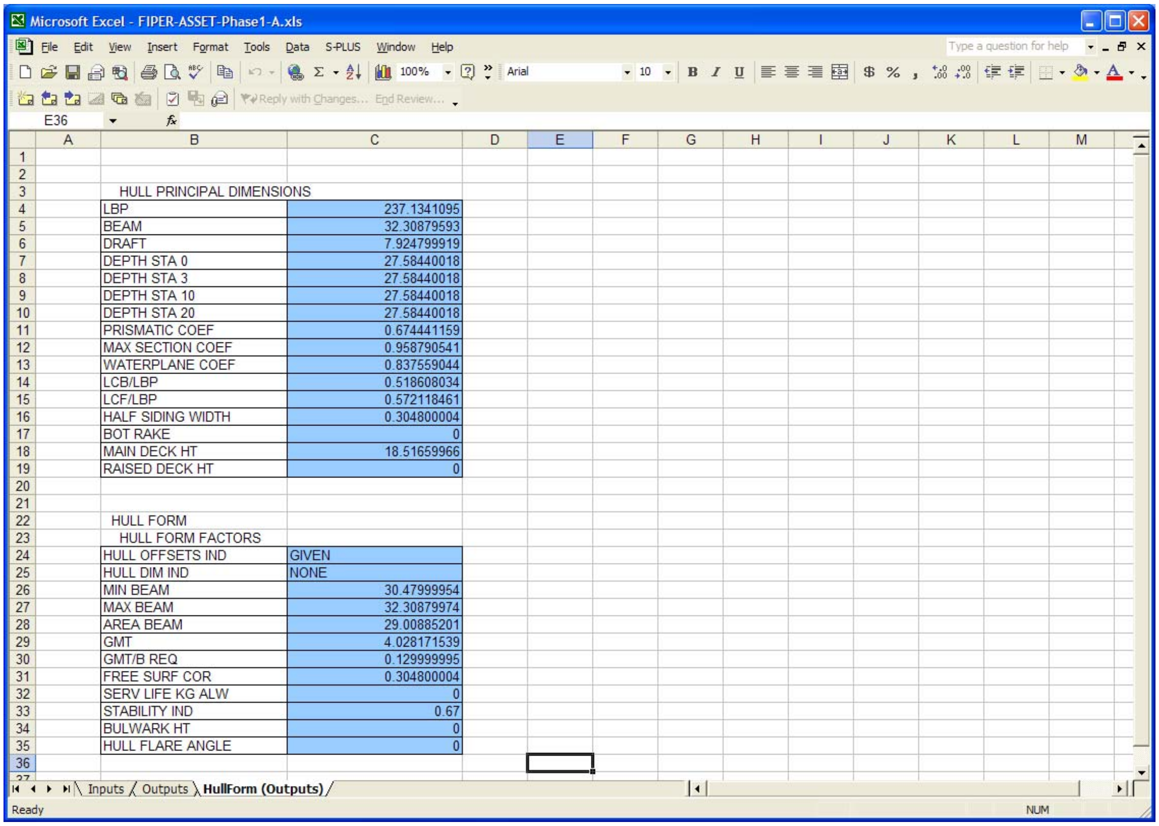
Inputs | Outputs | HullForm (Outputs)

Figure 4 – ASSET Outputs



HULL PRINCIPAL DIMENSIONS	
LBP	237.1341095
BEAM	32.30879593
DRAFT	7.924799919
DEPTH STA 0	27.58440018
DEPTH STA 3	27.58440018
DEPTH STA 10	27.58440018
DEPTH STA 20	27.58440018
PRISMATIC COEF	0.674441159
MAX SECTION COEF	0.958790541
WATERPLANE COEF	0.837559044
LCB/LBP	0.518608034
LCF/LBP	0.572118461
HALF SIDING WIDTH	0.304800004
BOT RAKE	0
MAIN DECK HT	18.51659966
RAISED DECK HT	0

HULL FORM	
HULL FORM FACTORS	
HULL OFFSETS IND	GIVEN
HULL DIM IND	NONE
MIN BEAM	30.47999954
MAX BEAM	32.30879974
AREA BEAM	29.00885201
GMT	4.028171539
GMT/B REQ	0.129999995
FREE SURF COR	0.304800004
SERV LIFE KG ALW	0
STABILITY IND	0.67
BULWARK HT	0
HULL FLARE ANGLE	0

Figure 5 – ASSET Hull Forms

Once parameters were set up in the spreadsheet, a set of Excel macros were executed to handle the transfer of data between Excel and ASSET. These macros were defined in an example Excel spreadsheet provided with the installation of ASSET, and were slightly altered to fit this particular problem.

Since Excel was used as a front-end data entry tool, the FIPER Excel component was once again used for integration. Figure 6 shows the ASSET integration editor.

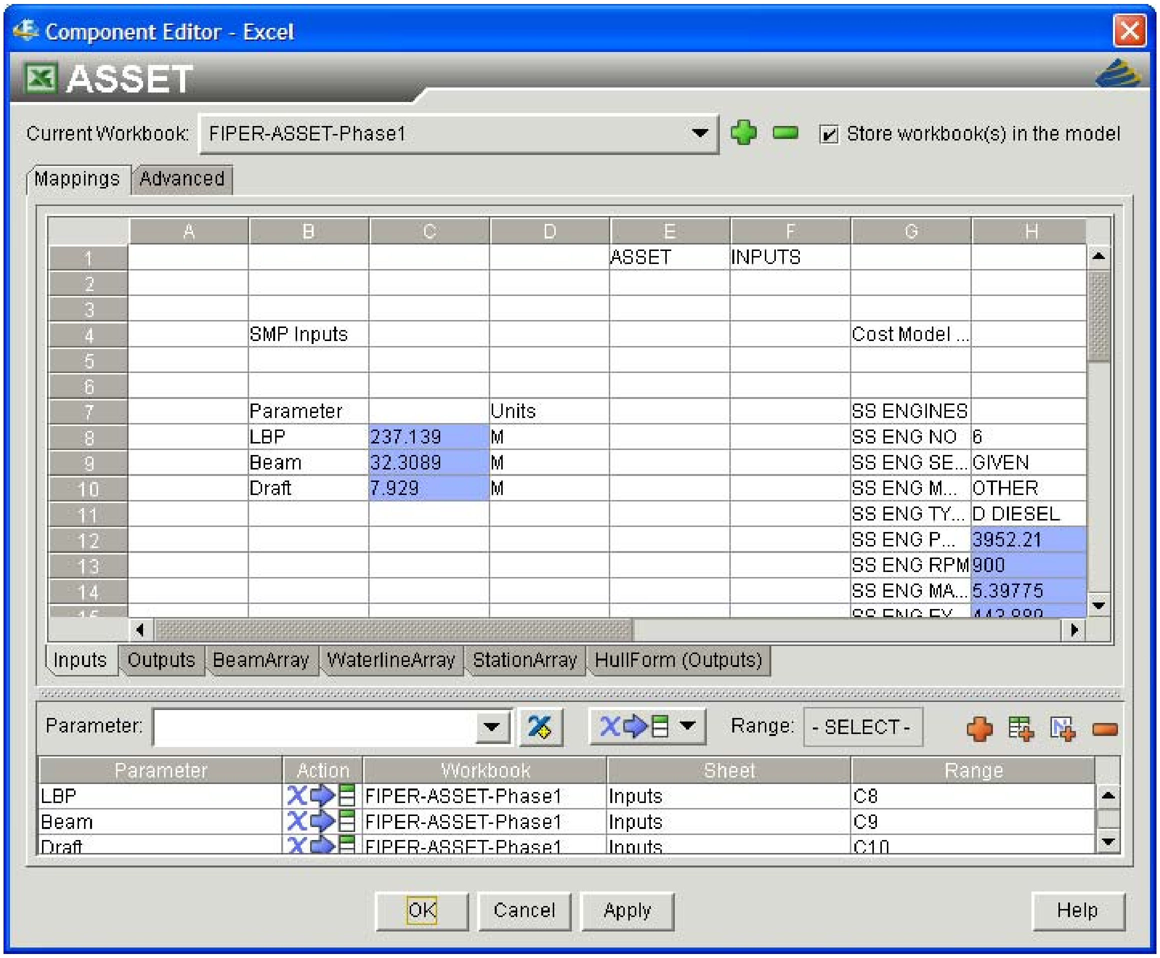
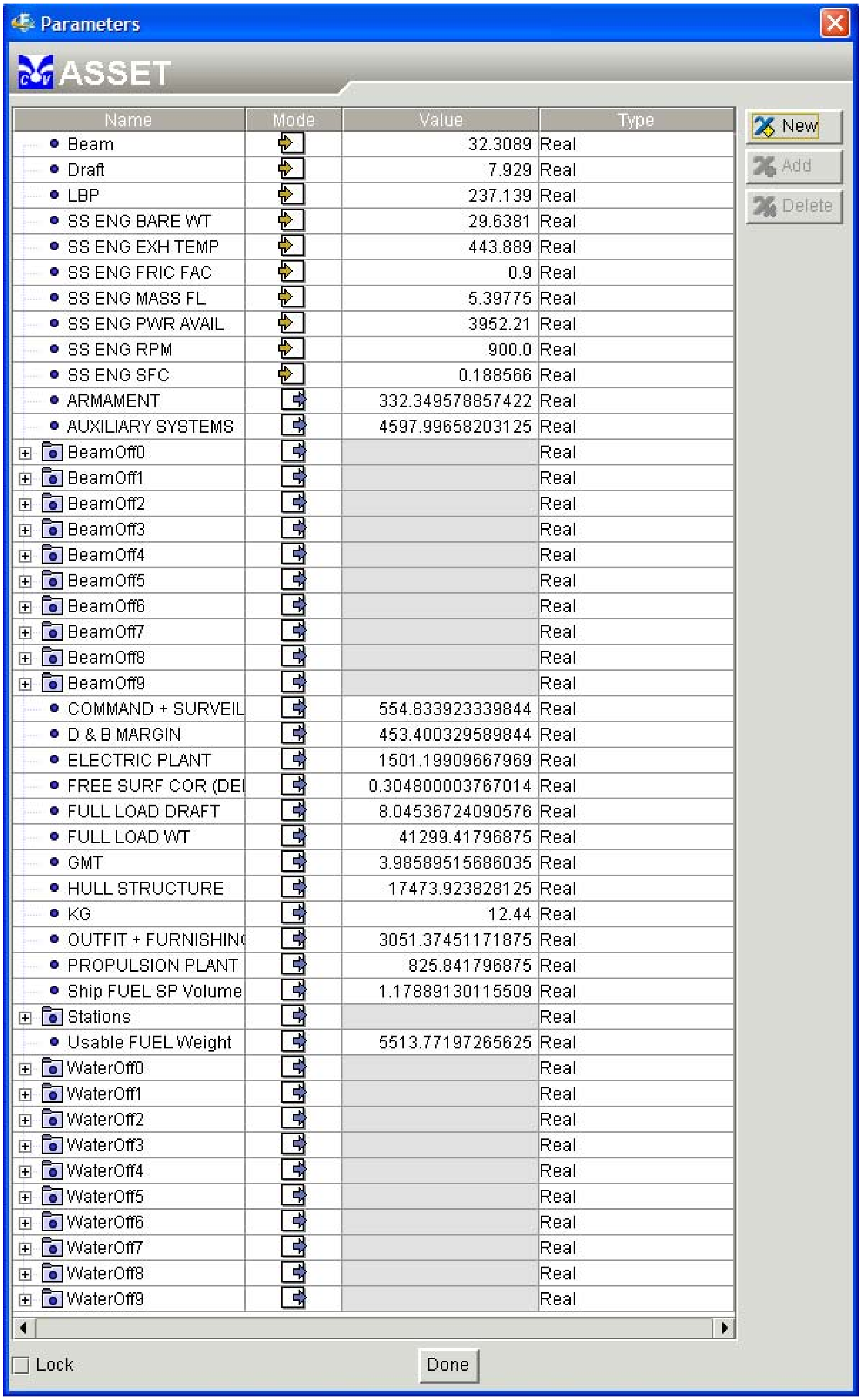


Figure 6 – FIPER Editor for ASSET-Excel Interface

Just like the MIT cost spreadsheet, the input and output parameters were communicated from/to FIPER, allowing those values to be shared with other integrated analysis tools. Figure 7 shows a list of those parameters.



Name	Mode	Value	Type
Beam		32.3089	Real
Draft		7.929	Real
LBP		237.139	Real
SS ENG BARE WT		29.6381	Real
SS ENG EXH TEMP		443.889	Real
SS ENG FRIC FAC		0.9	Real
SS ENG MASS FL		5.39775	Real
SS ENG PWR AVAIL		3952.21	Real
SS ENG RPM		900.0	Real
SS ENG SFC		0.188566	Real
ARMAMENT		332.349578857422	Real
AUXILIARY SYSTEMS		4597.99658203125	Real
BeamOff0			Real
BeamOff1			Real
BeamOff2			Real
BeamOff3			Real
BeamOff4			Real
BeamOff5			Real
BeamOff6			Real
BeamOff7			Real
BeamOff8			Real
BeamOff9			Real
COMMAND + SURVEIL		554.833923339844	Real
D & B MARGIN		453.400329589844	Real
ELECTRIC PLANT		1501.19909667969	Real
FREE SURF COR (DEI		0.304800003767014	Real
FULL LOAD DRAFT		8.04536724090576	Real
FULL LOAD WT		41299.41796875	Real
GMT		3.98589515686035	Real
HULL STRUCTURE		17473.923828125	Real
KG		12.44	Real
OUTFIT + FURNISHIN(		3051.37451171875	Real
PROPULSION PLANT		825.841796875	Real
Ship FUEL SP Volume		1.17889130115509	Real
Stations			Real
Usable FUEL Weight		5513.77197265625	Real
WaterOff0			Real
WaterOff1			Real
WaterOff2			Real
WaterOff3			Real
WaterOff4			Real
WaterOff5			Real
WaterOff6			Real
WaterOff7			Real
WaterOff8			Real
WaterOff9			Real

Figure 7 – ASSET parameters

SMP used FIPER’s Data Exchange component to communicate input and output parameter values. This component is FIPER’s most generic integration capability, allowing users to integrate any tool that provides model input/output via ASCII text files. Since SMP does use ASCII input models and ACSII results files, the Data Exchange component was the natural choice for integration into FIPER. The Data Exchange component editor was used to identify the input and output parameters of interest, allowing the user to highlight those parameters from SMP’s input and output text files. Figures 8-10 show examples of this ability to highlight values in order to identify them as parameters to FIPER.

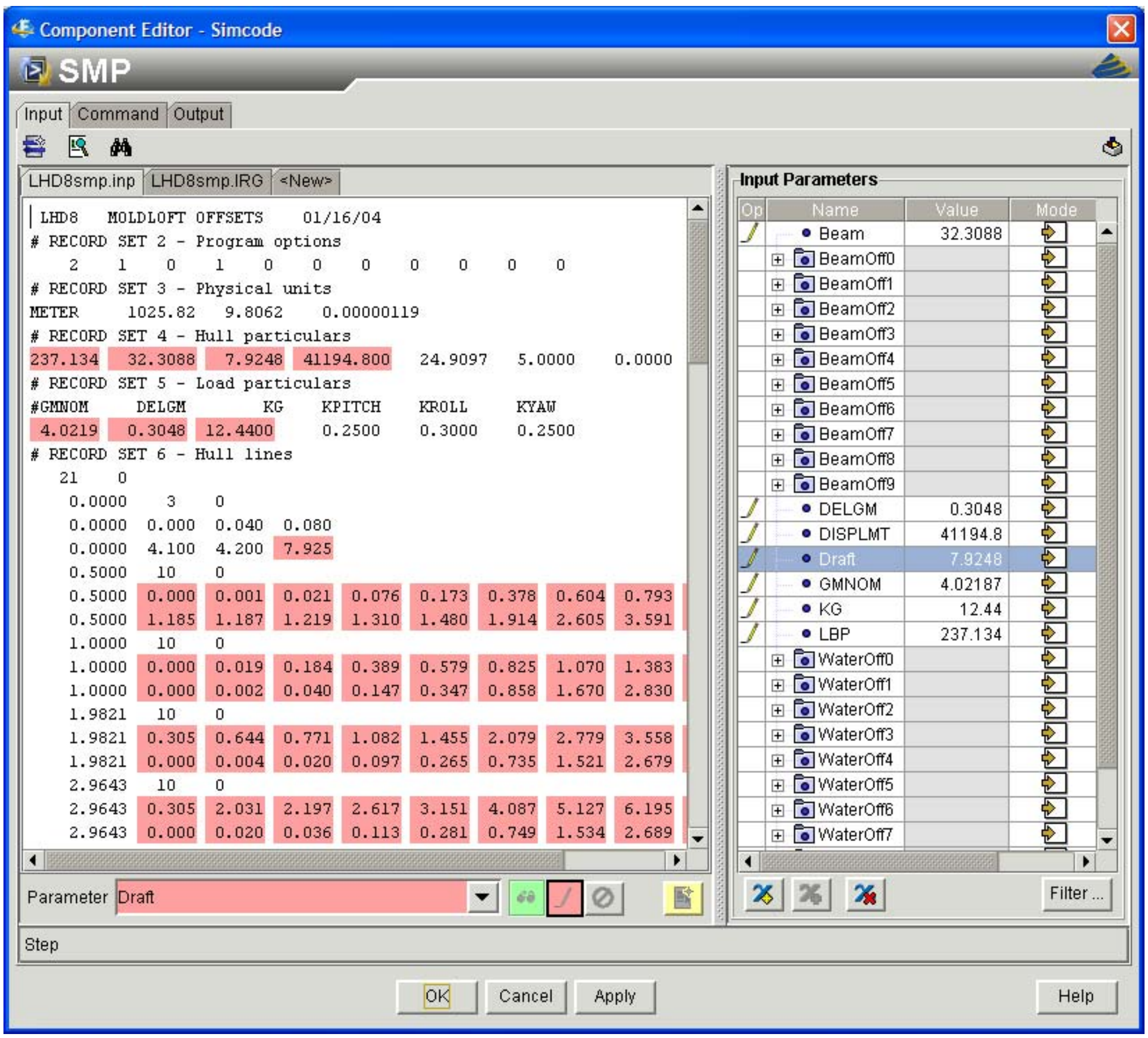


Figure 8 – SMP input file with parameters highlighted

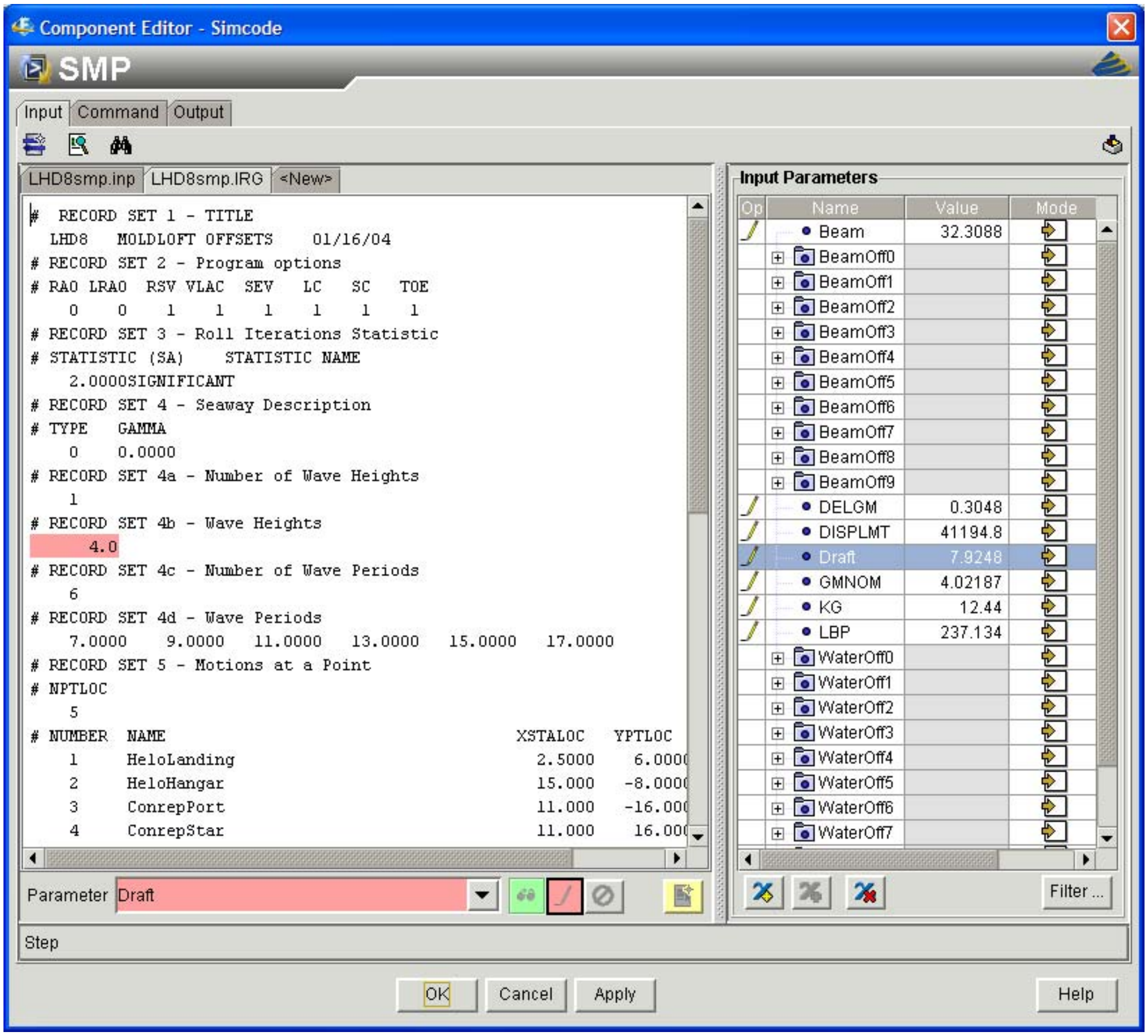


Figure 9 – SMP Irregular Wave input file with a parameter highlighted

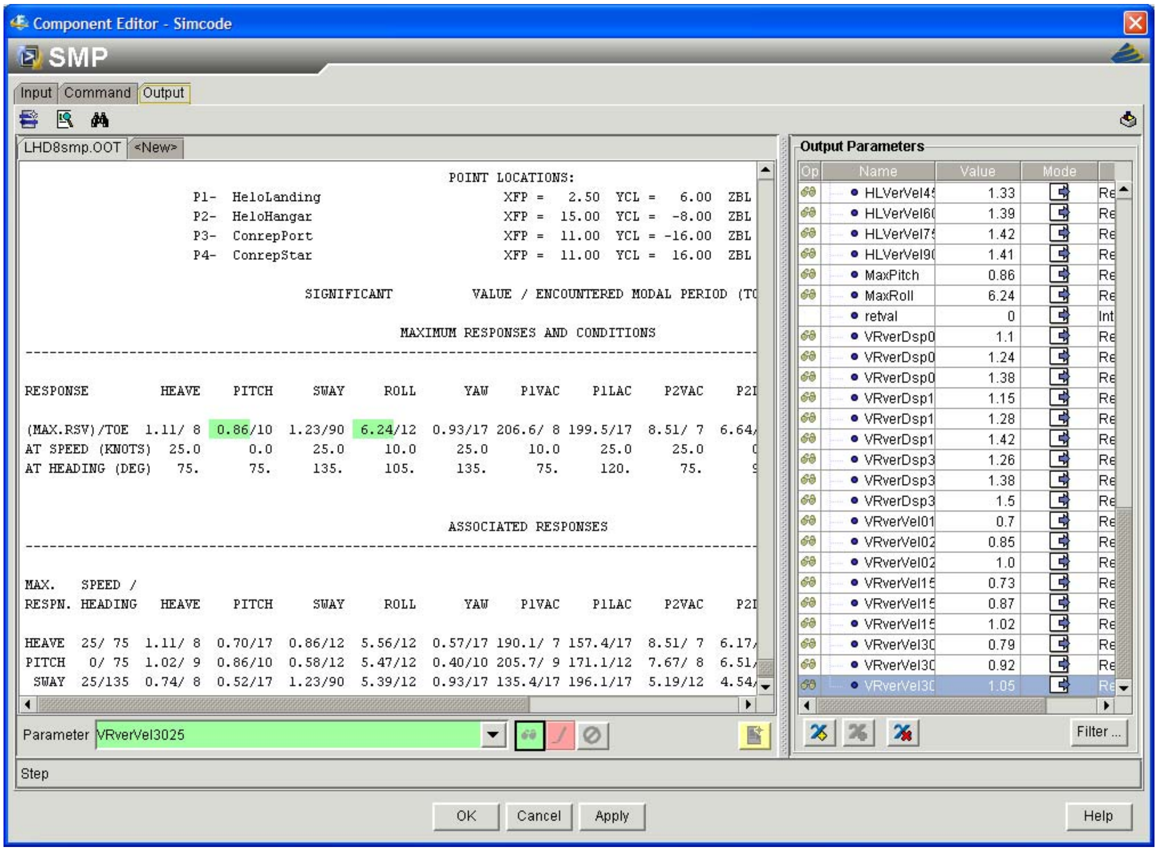
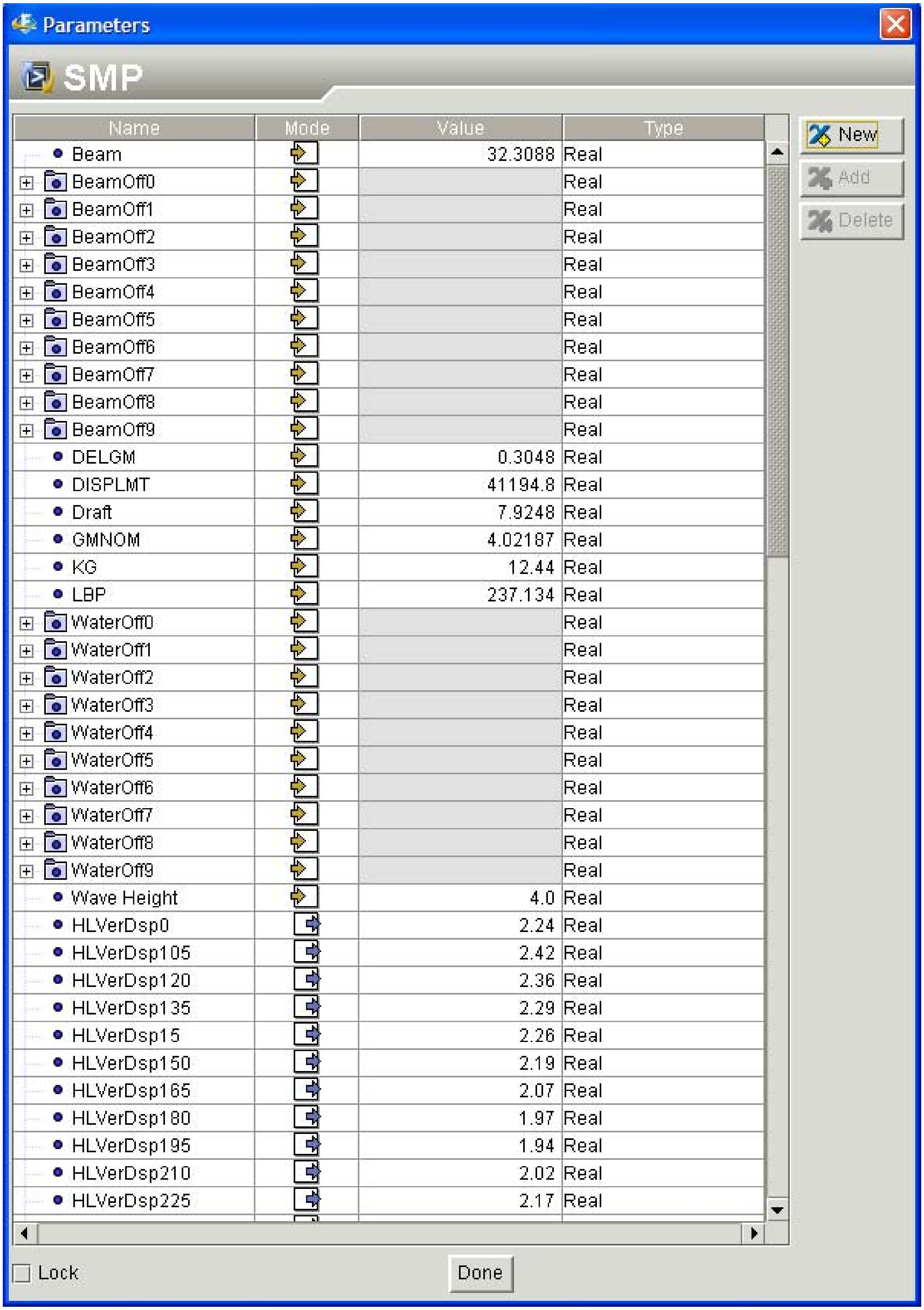


Figure 10 – SMP output file with parameters highlighted

As can be seen, the identification of parameters is done by simply highlighting the pertinent input/output values. The user is actually assigning a parameter name to the selected value of interest. Once FIPER starts iterating on different ship designs, these highlighted parameters have the current values substituted for the analysis.

Figure 11 and 12 show the parameters associated with the SMP model. As with the cost model and ASSET, these parameters are available to the other tools. This permits the mapping of same parameters between two different tools. For example, weight comes out of ASSET and gets mapped into the cost model spreadsheet.

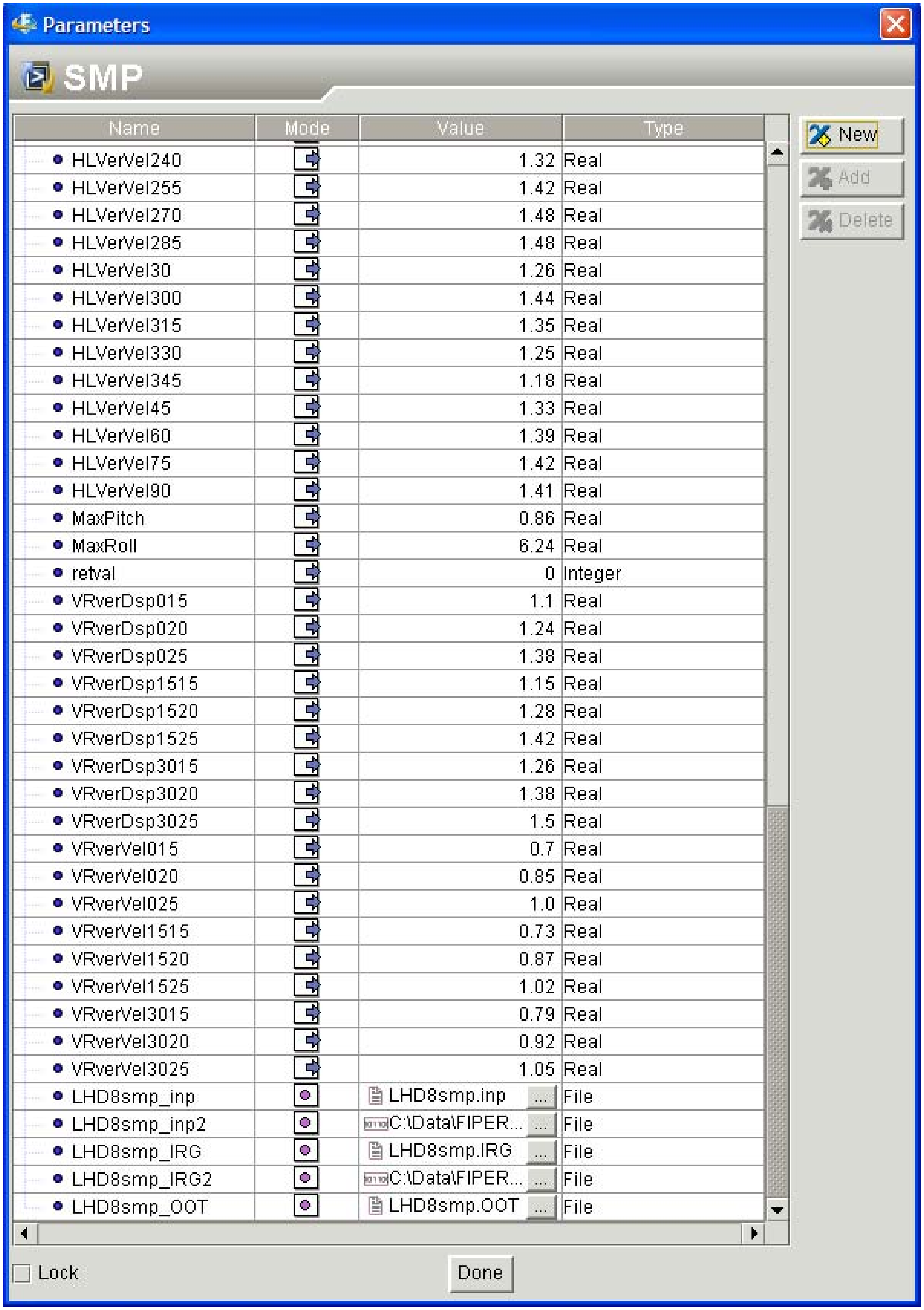


Parameters

SMP

Name	Mode	Value	Type
Beam		32.3088	Real
BeamOff0			Real
BeamOff1			Real
BeamOff2			Real
BeamOff3			Real
BeamOff4			Real
BeamOff5			Real
BeamOff6			Real
BeamOff7			Real
BeamOff8			Real
BeamOff9			Real
DELGM		0.3048	Real
DISPLMT		41194.8	Real
Draft		7.9248	Real
GMNOM		4.02187	Real
KG		12.44	Real
LBP		237.134	Real
WaterOff0			Real
WaterOff1			Real
WaterOff2			Real
WaterOff3			Real
WaterOff4			Real
WaterOff5			Real
WaterOff6			Real
WaterOff7			Real
WaterOff8			Real
WaterOff9			Real
Wave Height		4.0	Real
HLVerDsp0		2.24	Real
HLVerDsp105		2.42	Real
HLVerDsp120		2.36	Real
HLVerDsp135		2.29	Real
HLVerDsp15		2.26	Real
HLVerDsp150		2.19	Real
HLVerDsp165		2.07	Real
HLVerDsp180		1.97	Real
HLVerDsp195		1.94	Real
HLVerDsp210		2.02	Real
HLVerDsp225		2.17	Real

Figure 11 – SMP parameters (first half)


Parameters

SMP

Name	Mode	Value	Type
HLVerVel240		1.32	Real
HLVerVel255		1.42	Real
HLVerVel270		1.48	Real
HLVerVel285		1.48	Real
HLVerVel30		1.26	Real
HLVerVel300		1.44	Real
HLVerVel315		1.35	Real
HLVerVel330		1.25	Real
HLVerVel345		1.18	Real
HLVerVel45		1.33	Real
HLVerVel60		1.39	Real
HLVerVel75		1.42	Real
HLVerVel90		1.41	Real
MaxPitch		0.86	Real
MaxRoll		6.24	Real
retval		0	Integer
VRverDsp015		1.1	Real
VRverDsp020		1.24	Real
VRverDsp025		1.38	Real
VRverDsp1515		1.15	Real
VRverDsp1520		1.28	Real
VRverDsp1525		1.42	Real
VRverDsp3015		1.26	Real
VRverDsp3020		1.38	Real
VRverDsp3025		1.5	Real
VRverVel015		0.7	Real
VRverVel020		0.85	Real
VRverVel025		1.0	Real
VRverVel1515		0.73	Real
VRverVel1520		0.87	Real
VRverVel1525		1.02	Real
VRverVel3015		0.79	Real
VRverVel3020		0.92	Real
VRverVel3025		1.05	Real
LHD8smp_inp		LHD8smp.inp ...	File
LHD8smp_inp2		C:\Data\FIPER... ...	File
LHD8smp_IRG		LHD8smp.IRG ...	File
LHD8smp_IRG2		C:\Data\FIPER... ...	File
LHD8smp_OOT		LHD8smp.OOT ...	File

Figure 12 – SMP parameters (second half)

Besides the integration of ASSET, SMP, and the MIT cost model, two additional components were needed to complete the integrated analysis system. Two calculation blocks were developed to help with minor calculations. The first was used to convert parameters that were metric in the ASSET model, but in English units in the cost model. The calculation component is nothing more than a scientific calculator that can operate on FIPER parameters. Figure 13 shows the calculations done between ASSET and the cost model.

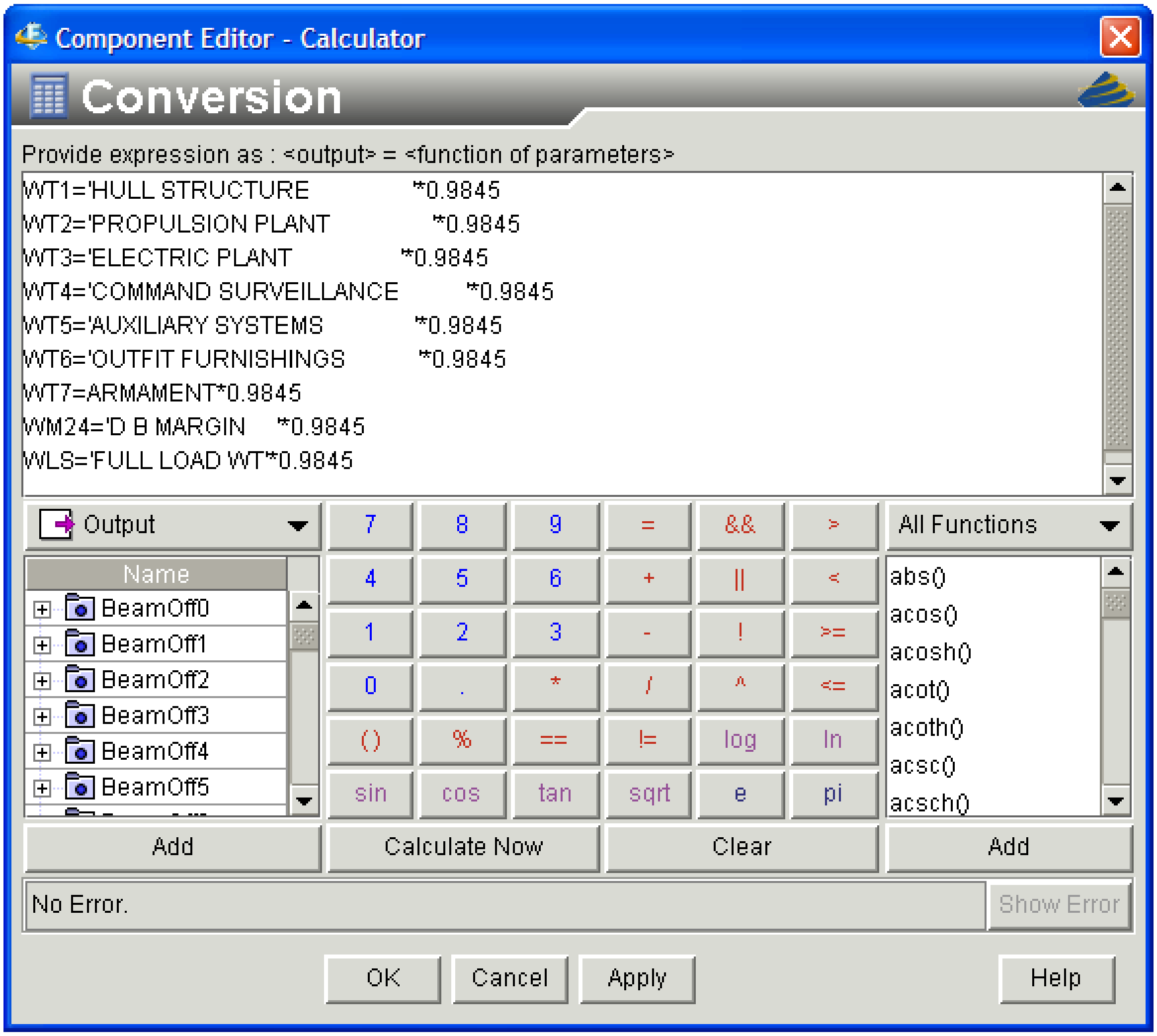


Figure 13 – Unit Conversion between ASSET and the cost model

The second calculation component was used to calculate maximum vertical displacement and velocity by examining several key points on the ship. The maximums were checked against constraints to insure that the ship design being evaluated was feasible. Figure 14 shows the calculations done.

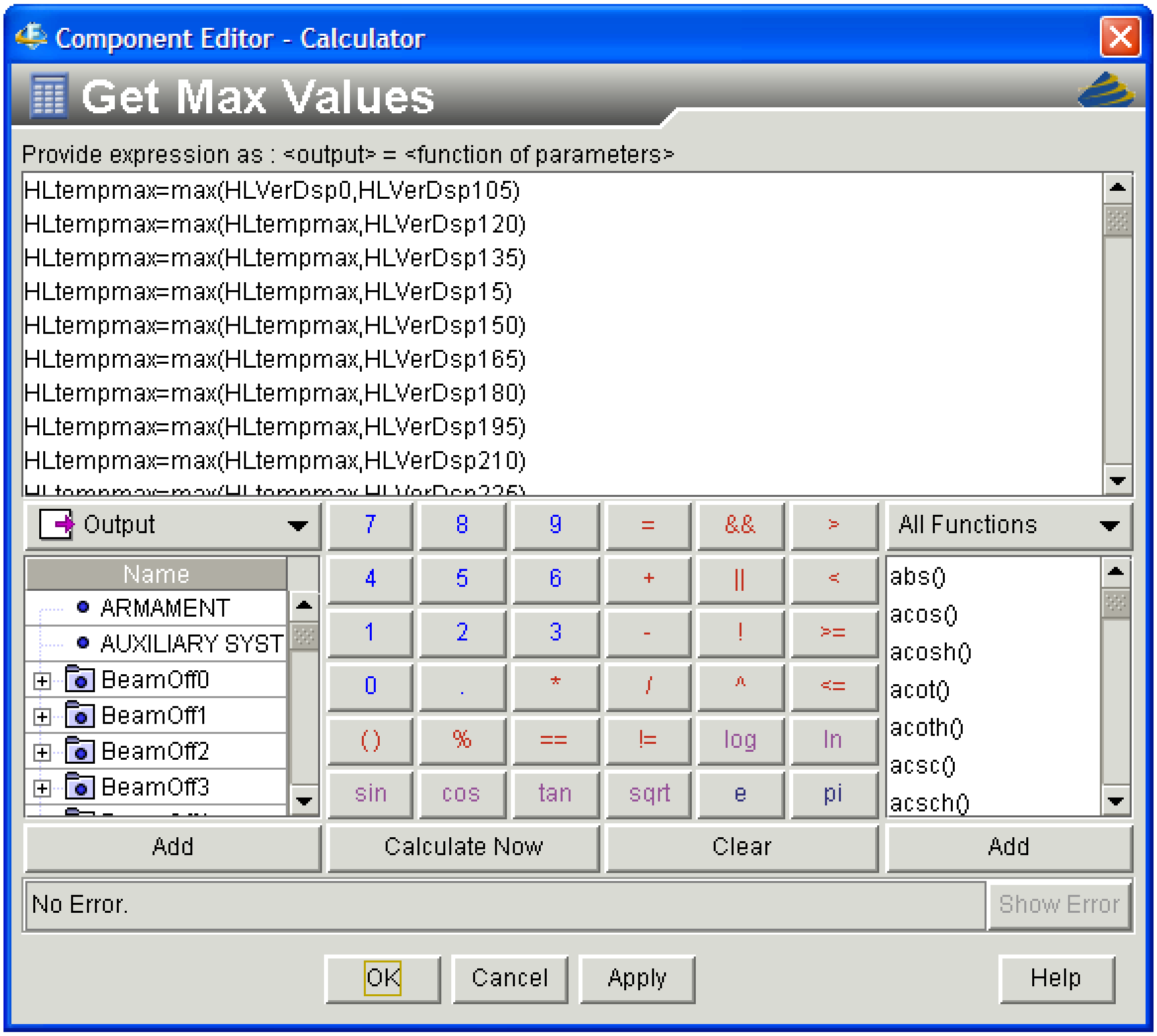


Figure 14 – Calculation for Maximum Vertical Displacement and Velocity

Finally, the overall integration of ASSET, SMP, the cost model, the unit conversion calculation, and the maximum displacement and velocity calculation is shown in Figure 15.

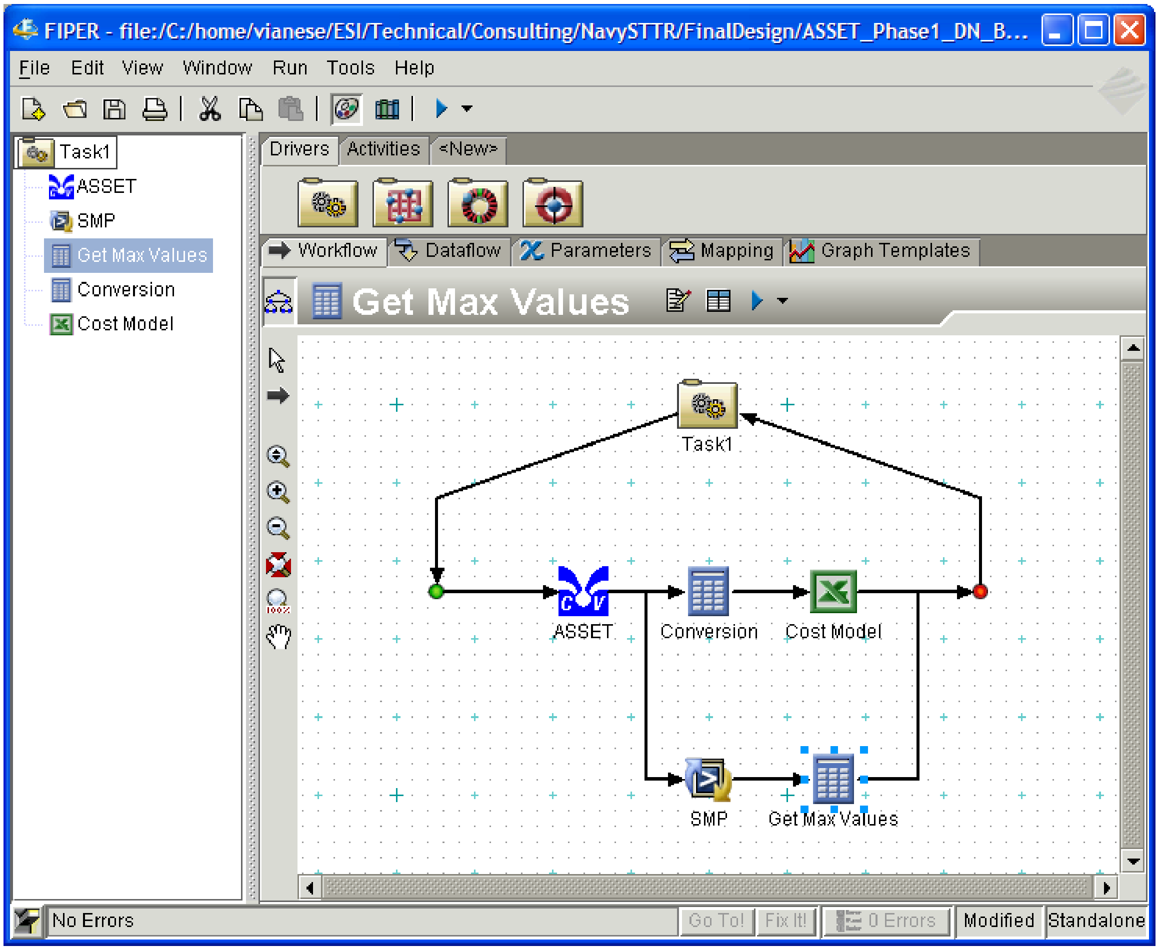


Figure 15 – Overall System Integration

The general flow of the system is as follows: the user provides input for ASSET; ASSET calculates the ship dimensions and weight and provides output, which is converted using the unit conversion calculation component; the ASSET output is also sent to SMP; the converted parameters from the calculation component are passed to the cost model; SMP calculates the seakeeping and passes the output to the second calculation component; the second calculation component determines the max displacement and velocity, which are measured against constraints. Figure 16-20 shows the mapping of parameters between the different analysis tools.

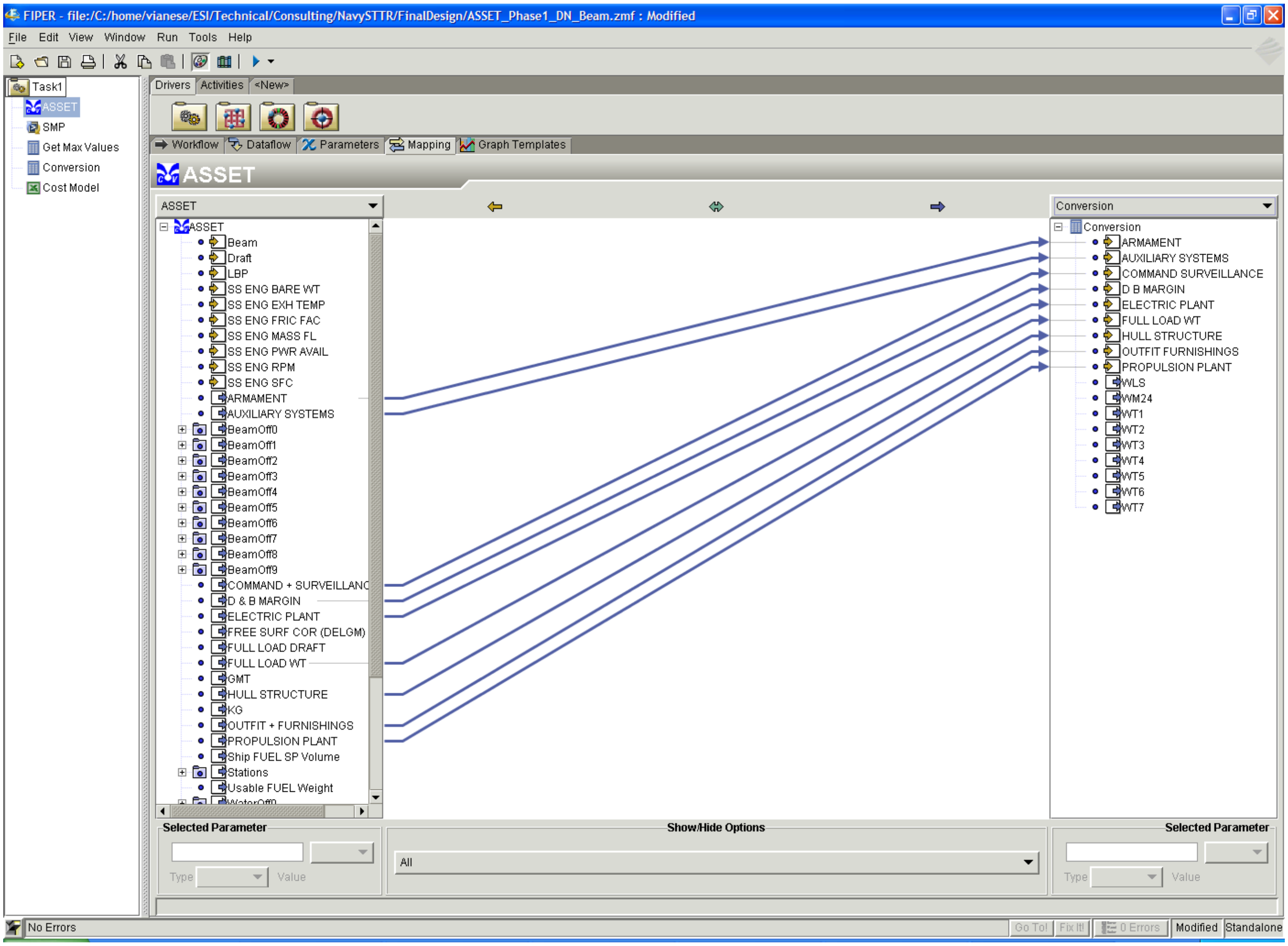


Figure 16 – Parameter Mapping between ASSET and the Unit Conversion Calculation

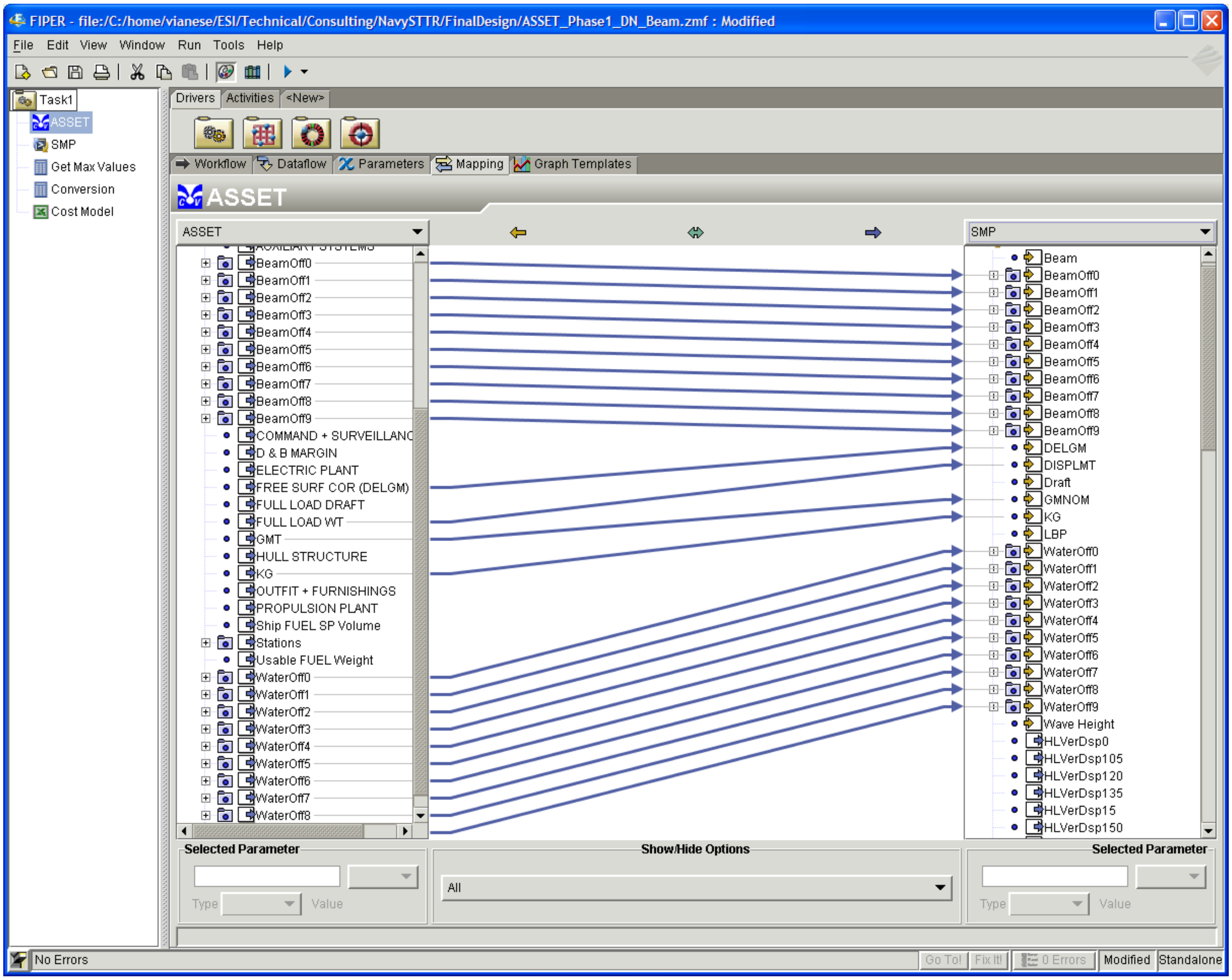


Figure 17 – Parameter Mapping between ASSET and SMP

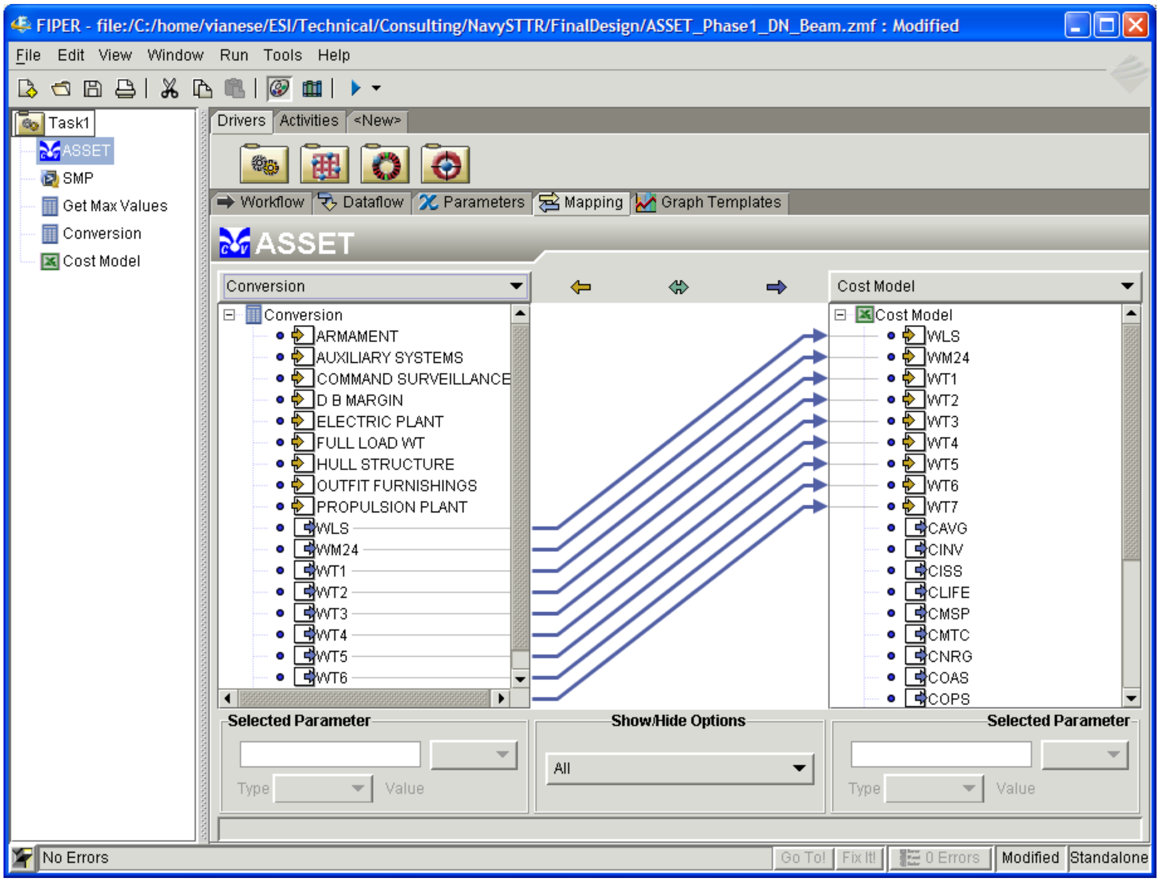


Figure 18 – Parameter Mapping between Unit Conversion Calculation and the Cost Model

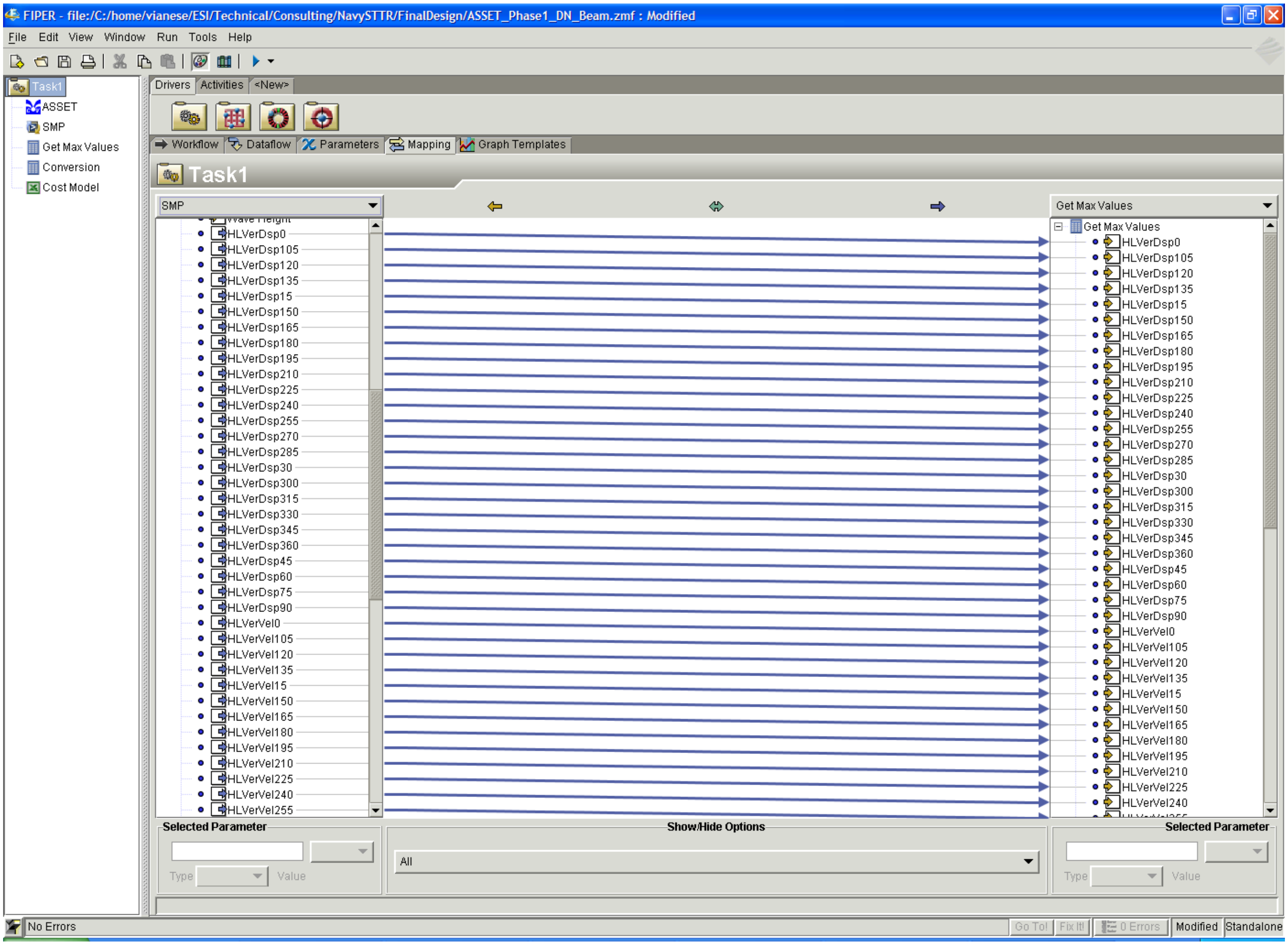


Figure 19 – Parameter Mapping between SMP and Maximum Velocity and Displacement Calculation (First Half)

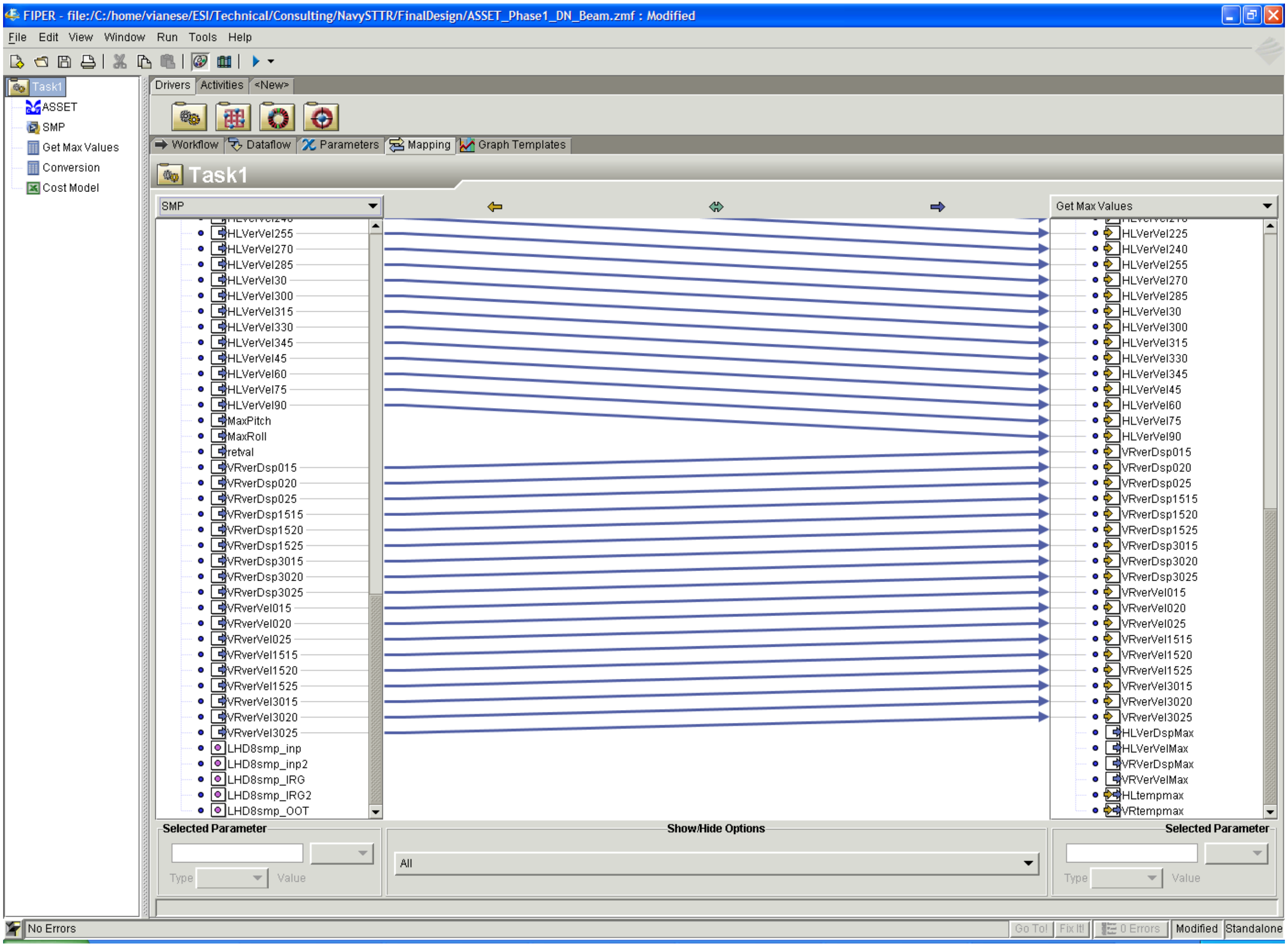


Figure 20 – Parameter Mapping between SMP and Maximum Velocity and Displacement Calculation (Second Half)

The integration was broken into two parts: one model that focused on variations in length without accounting for variations in the beam; and a second model that accounted for variation in beam with variations in length. The former was done as a first step to prove the concept of a functioning MDO ship system. The later was a more realistic evaluation system that accounted for variations in beam. Results for the later are shown in section 8.0 except where noted.

7.0 Multi-Objective Genetic Algorithm Optimization Technique

Anticipating a design space with many competing objectives of performance and effectiveness, it was decided early on we would need an optimization technique to incorporate into FIPER that was well suited to handle those competing objectives. A Multi-Objective Genetic Algorithm (MOGA) called Epsilon-MOEA was chosen as the ideal solution. Dr. David Powell from Elon University completed this integration in

FIPER. Appendix F outlines his integration work on the STTR project. An in-depth paper is available that describes the technique used. It is called “A Fast Multi-objective Evolutionary Algorithm for Finding Well-Spread Pareto-Optimal Solutions” and can be downloaded from http://www.iitk.ac.in/kangal/pub.htm .

8.0 Analysis

8.1 Analysis overview

Once integration of the entire MDO system was complete, design exploration techniques were added to the integrated process. These techniques were used to explore the design space in search of optimum ship designs. FIPER allows the user to quickly integrate design exploration techniques into any integrated process by dragging and dropping preloaded “design drivers” into the workflow. These design drivers act as engines to automate the execution of the integrated process by substituting values into the input parameters of interest. A user can set up a design driver to examine a set of predefined runs, search for an optimal answer, or measure uncertainties in the integrated process and/or models. Iterating through a sequence of runs chosen by the design driver, the integrated process returns results for each run. Once FIPER executes a predefined design driver, it continues until an optimal solution is obtained or the maximum number of allowed runs is reached.

8.2 Requirements

In order to measure performance and effectiveness, the MPFF ship class needed to meet certain requirements. John Covington from Northrop Grumman provided the requirement matrix shown in Figure 21.

Mission Subsystem	Heading and Speed Limits	Absolute Motions – Significant Single Amplitude (SSA) Values									
		Roll about CG (deg)	Pitch about CG (deg)	Yaw about CG (deg)	Vertical Displ. (m)	Lateral Displ. (m)	Vertical Velocity (m/s)	Vertical Accel. (g)	Lateral Accel. (g)	Long’l Accel. (g)	Acceleration Limit Locations
Mobility	-	8	3	-	-	-	-	0.4	0.2	0.2	@all regularly occupied spaces
Helo VTOL (No RAST)	Relative wind envelope	5	3	-	1.25 @Helo landing spot	-	2 @Helo landing spot	-	-	-	-
Helo Deck Handling (No RAST)	-	3.6	3.6	-	-	-	-	0.4	0.2	0.2	@helo hangar
CONREP	+/-30° off head/following seas	4.4	4.4	-	-	-	-	0.4	0.2	0.2	@CONREP Stations
VERTREP	+/-30° off head seas, 15-30 kt	4.4	4.4	-	1.4 @ VERTREP station	-	2.1 @ VERTREP station	0.4	0.2	0.2	@VERTREP Station
Strikedown	-	8	3	-	-	-	-	0.4	0.2	0.2	along UNREP route
RAS	+/-30° off head seas, 15-30 kt	4.4	3		1.4 @ VERTREP station		2.1 @ VERTREP station	0.4	0.2	0.2	@ all regularly occupied spaces and all RAS locations

VTOL-Vertical take off and landing

RAST-Recovery, Assist, Securing and Traversing system. Mechanical helo recovery and handling system.
CONREP- Connected Replenishment. Two ships steaming side by side transferring supplies
VERTREP- Vertical replenishment. Transfer of supplies between ships using helicopters.
Strikedown-Transfer of supplies from initial landing or laydown area to below decks.
RAS-Replenishment at sea, includes CONREP, VERTREP and Strikedown operations. Notice RAS requirements are the intersection of requirements for these operations.

Figure 21 – Requirements Matrix

In order to effectively evaluate the numerous requirement cases, many of the requirements were consolidated and enveloped to produce an overarching set of constraints. Constraints for vertical displacement and velocity at the Helo VTOL, VERTREP, and RAS points (see descriptions in Figure 21) were chosen, as well as the pitch and roll constraints at the Helo VTOL. The vertical, lateral, and longitudinal accelerations at each point were not included in the constraint list; it was verified that for all cases these parameters did not come close to violating the required maximum values.

While typical ship design analysis calls for examining a ship at several sea states, the team chose a sea state of about level 5 to run all the analysis. This provided a consistent, coherent set of results and demonstrated the process of the integrated MDO analysis. In phase II of the project, a more complete set of sea states, as well as a larger set of requirements, could be scrutinized.

8.3 Design of Experiments

A Design of Experiments (DOE) was executed on the integrated process. Figure 22 shows the integrated process with the DOE design driver added.

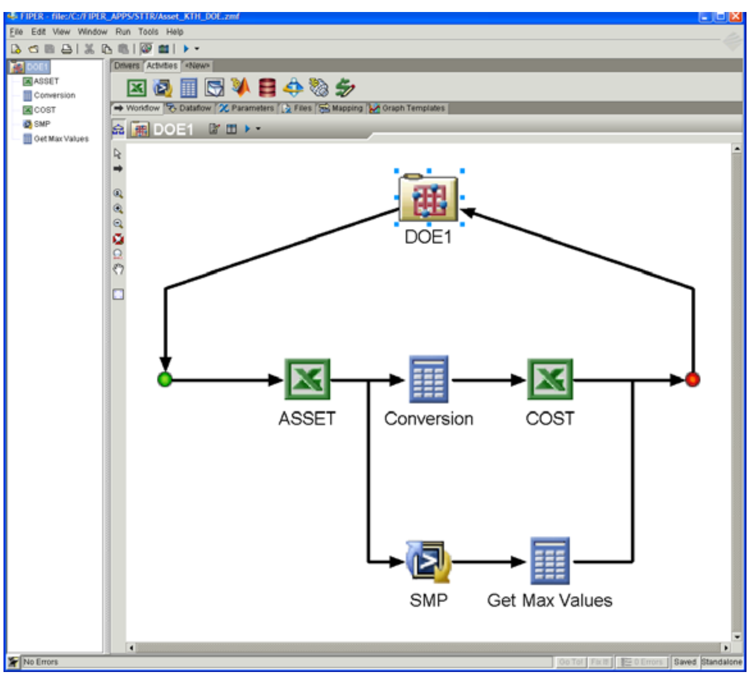


Figure 22 – Work Flow with DOE Added

The DOE was a Latin Hypercube analysis of 30 points. Figure 23 shows the design driver editor for the DOE.

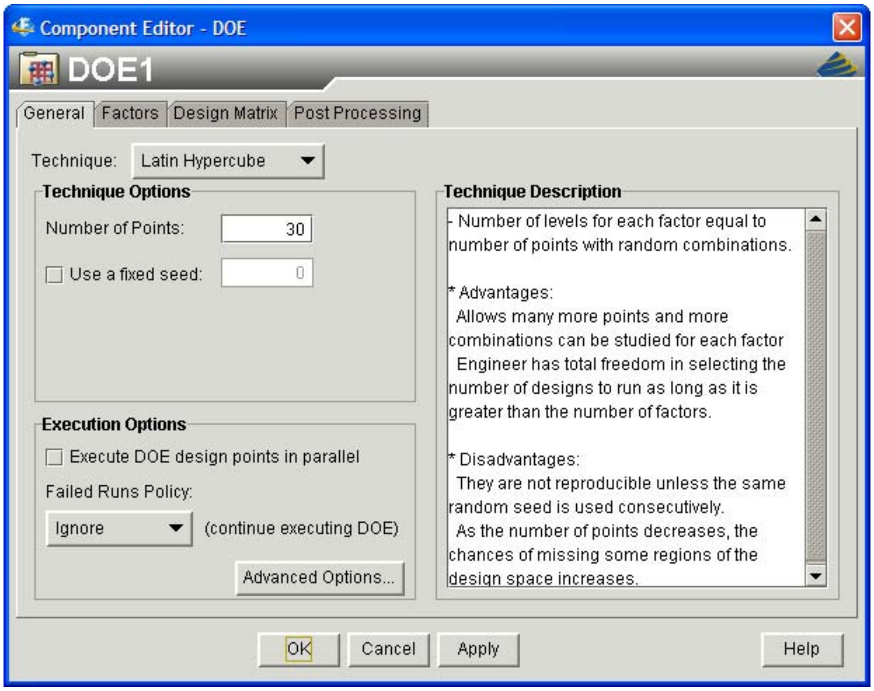


Figure 23 – DOE Editor

The DOE is used to quickly search the design space for optimum answers. By running a matrix of 30 different ship designs, we were able to evaluate ships of varying sizes and investigate their performance and effectiveness as measured against the requirements. Figure 24 shows the list of input parameters, or factors as they are termed in DOE, of interest in our design study.

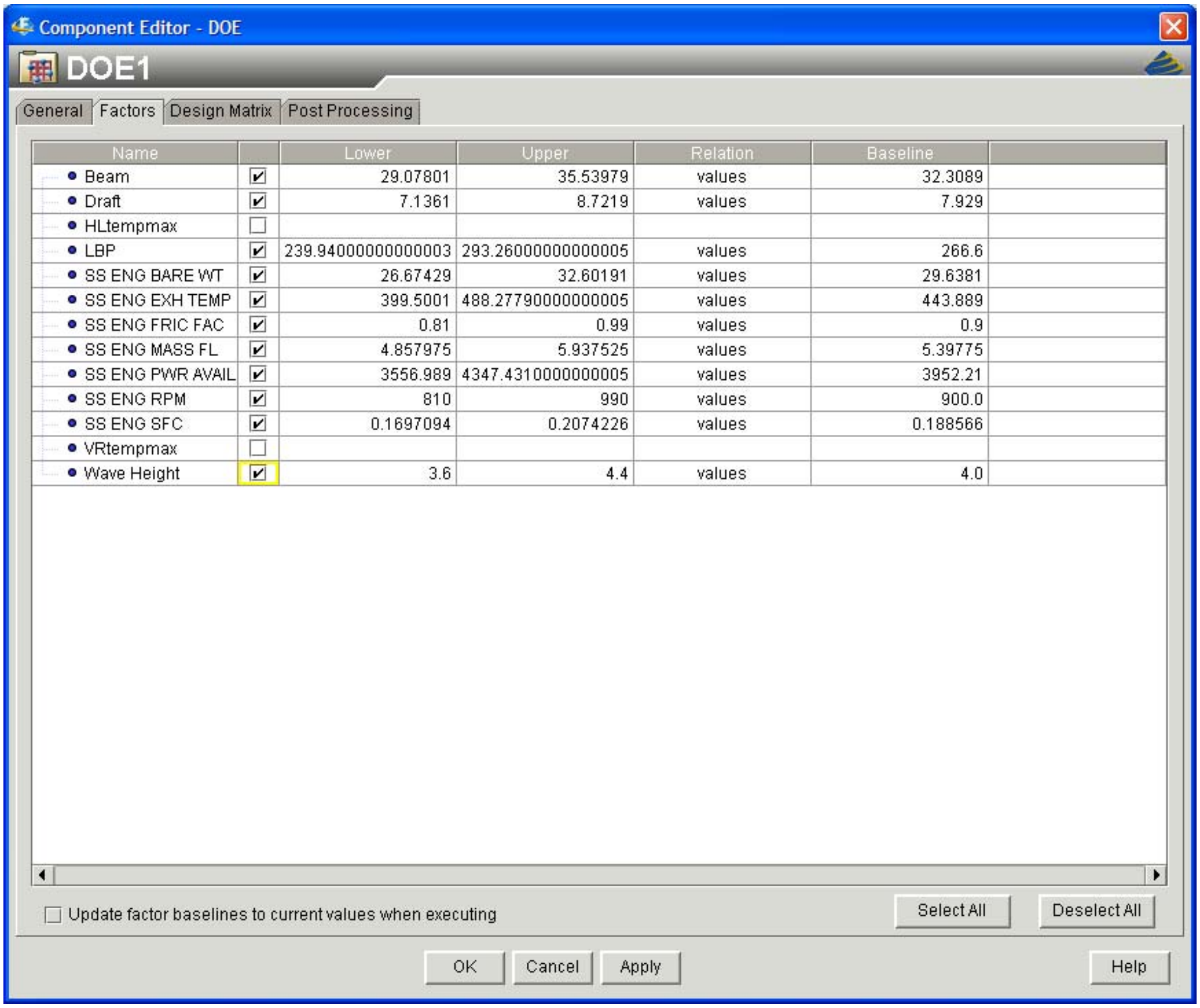


Figure 24 – DOE factors

Upon completing a DOE, the factors could be measured against key responses to determine their influence on that response. The Pareto chart effectively captures this metric as seen in Figures 25 and 26.

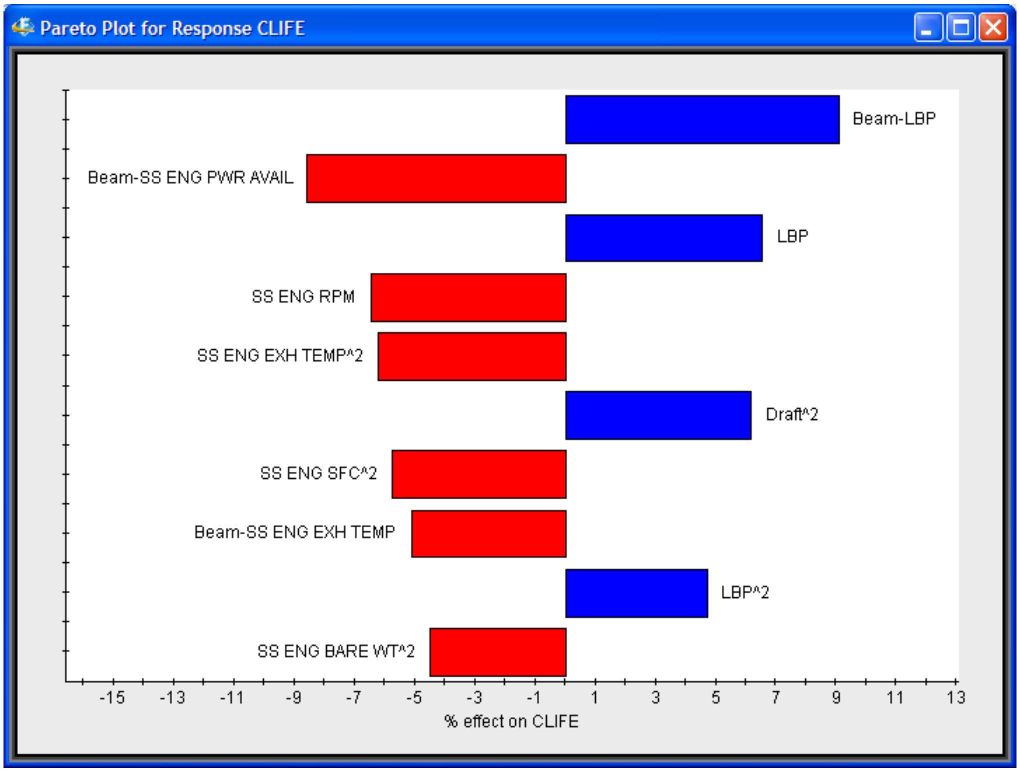


Figure 25 – Pareto Plot of factors % effect on Lifecycle Cost

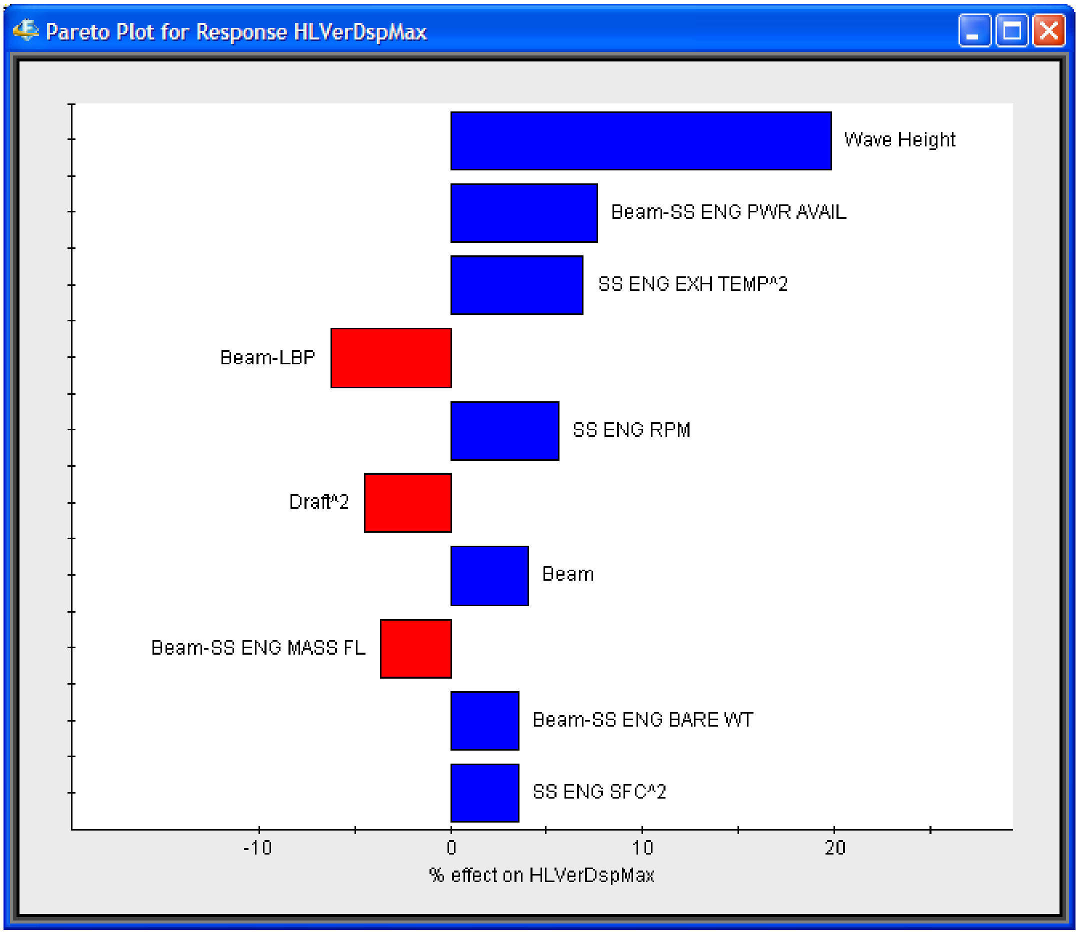


Figure 26 – Pareto Plot of factors % effect on Lifecycle Cost

As can be seen in Figure 25, the biggest influence on lifecycle cost is the size of the ship, or Beam-LPB, which is the interaction of the ship's length and beam. Likewise, Figure 26 shows the largest driver of the Helo Deck vertical displacement would be wave height, which is a fairly intuitive result if wave height is varied.

Finally, the Lifecycle cost and Helo deck vertical displacement as a function of Beam and Length were examined. Figure 27 and 28 show the results in a 3-D plot.

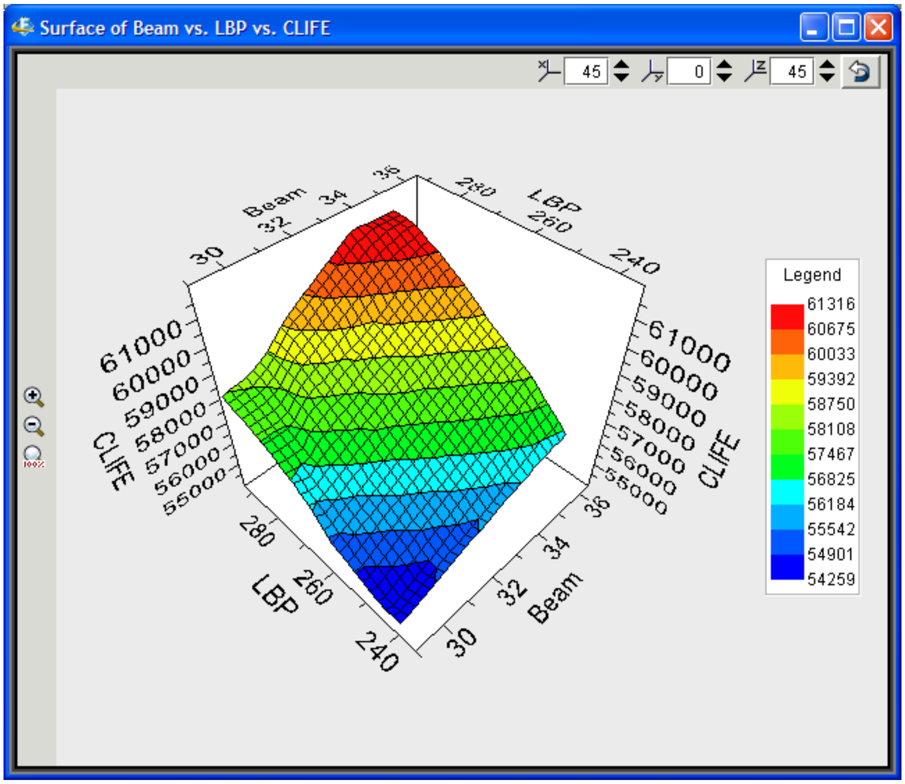


Figure 27 – Lifecycle Cost versus Ship Length and Beam

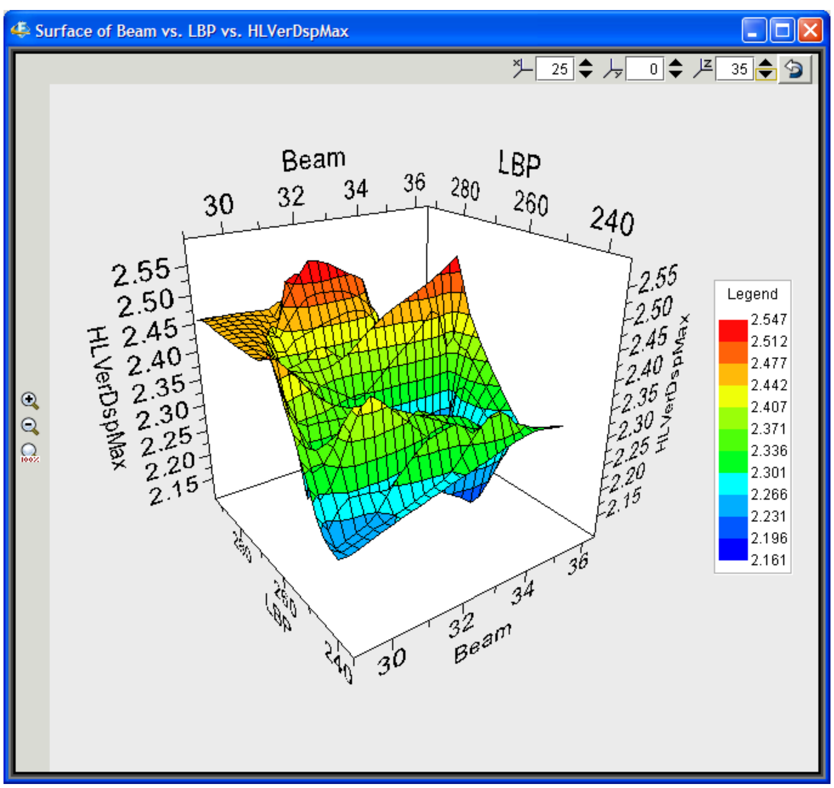


Figure 28 – Helo Deck Max Vertical Displacement versus Ship Length and Beam

Complete Results for all 30 DOE runs can be seen in Appendix G.

8.4 Optimization

Once a DOE analysis was run, a viable (i.e. best answer) starting point could be chosen for initialization of an optimization run. The table in Figure 29 shows the starting design point chosen and the associative starting constraint values.

Initial Design				
Design Variables	Lower Bound	Initial Value	Upper Bound	
SS ENG FRIC FAC	0.75	0.9	0.99	
SS ENG RPM	800	900	999	
SS ENG MASS FL	4	5.39775	6	
SS ENG PWR AVAIL	3500	3952.21	4500	
SS ENG SFC	0.1	0.188566	0.3	
SS ENG EXH TEMP	400	443.889	500	
SS ENG BARE WT	25	29.6381	50	
LBP	230	266.6	300	
Wave Height	3	4	5	
Responses	Lower Bound	Initial Value	Upper Bound	Violat
CLIFE		57845.64612		No
HLVerDspMax		2.36	2.6	No
HLVerVelMax		1.36	2.1	No
MaxPitch		0.73	3	No
MaxRoll		4.8	5.1	No
VRVerDspMax		1.32	2.1	No
VRVerVelMax		0.91	2.1	No

Figure 29 – Table of initial design parameters

Starting from this point, a first optimization was done using the Hooke-Jeeves technique. The table outlines the initial, upper, and lower bound values for each of the design parameters. Figure 30 shows the optimization design driver editor for this technique.

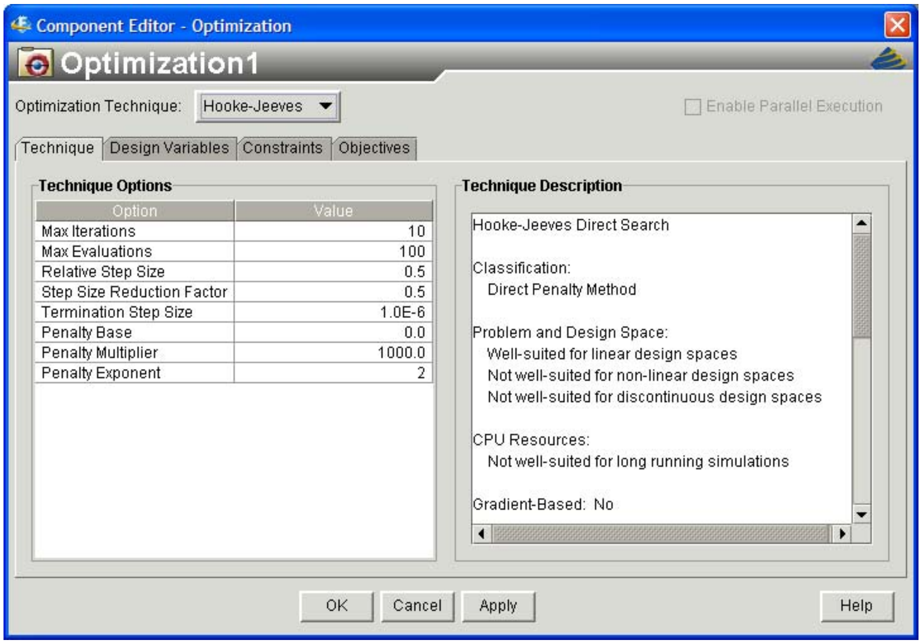


Figure 30 – Hooke-Jeeves Optimization Editor

A total of 101 design evaluations were completed by the optimizer, and a total of 97 feasible designs were found. Figures 31 and 32 show the history chart of the lifecycle cost and Helo Deck vertical displacement for all 101 designs.

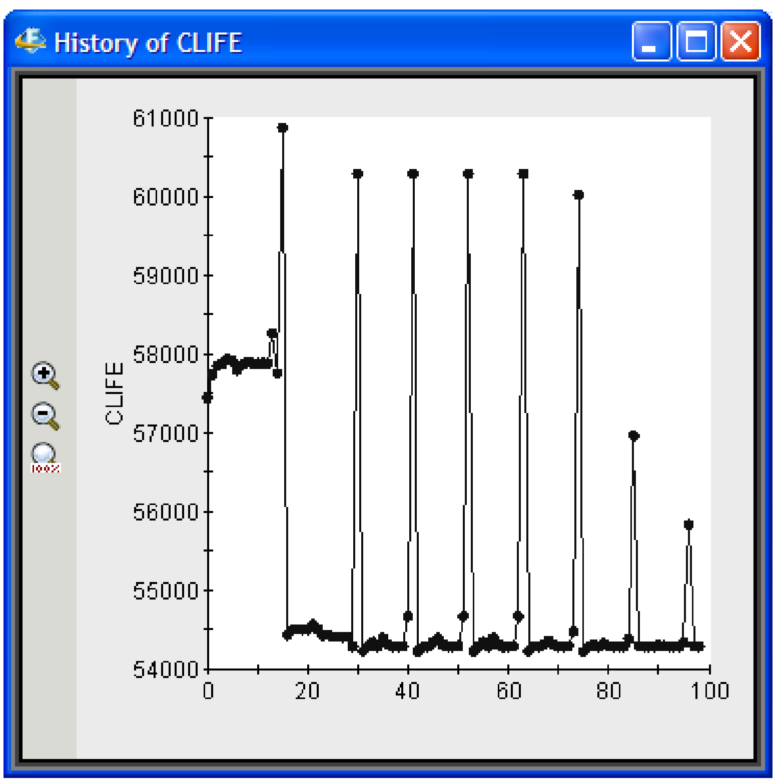


Figure 31 – Lifecycle Cost over 101 runs

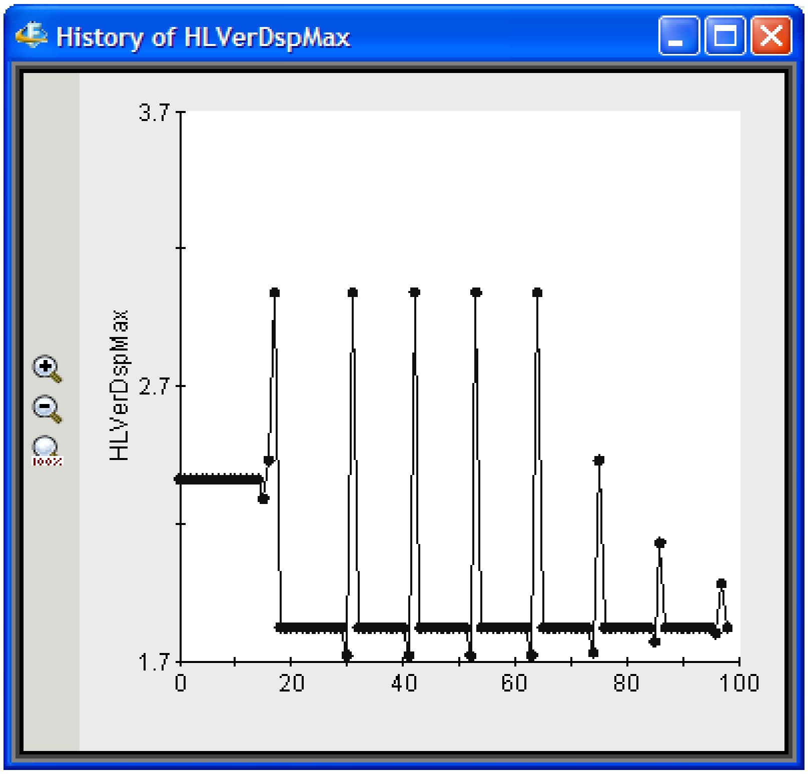


Figure 32 – Helo Deck Max Vertical Displacement over 101 runs

The table in Figure 33 shows the final optimum ship design, based on the given constraints, found by the Hooke-Jeeves technique.

Optimized Design				
Design Variables	Lower Bound	Initial Value	Upper Bound	
SS ENG FRIC FAC	0.75	0.99	0.99	
SS ENG RPM	800	999	999	
SS ENG MASS FL	4	4	6	
SS ENG PWR AVAIL	3500	4500	4500	
SS ENG SFC	0.1	0.1	0.3	
SS ENG EXH TEMP	400	400	500	
SS ENG BARE WT	25	25	50	
LBP	230	230	300	
Wave Height	3	3	5	
Responses	Lower Bound	Initial Value	Upper Bound	Violation
CLIFE		54275.22037		No
HLVerDspMax		1.82	2.6	No
HLVerVelMax		1.06	2.1	No
MaxPitch		0.67	3	No
MaxRoll		3.8	5.1	No
VRVerDspMax		1.14	2.1	No
VRVerVelMax		0.81	2.1	No

Figure 33 – Final Optimum Design found by the Hooke-Jeeves technique

Figure 34 shows the overall improvement for Lifecycle cost and Helo Deck maximum vertical displacement.

Objective component	Difference	Improvement
CLIFE	3570.425757	6%
HLVerDspMax	0.54	23%

Figure 34 – Measured Improvement between initial ship design and final ship design.

In addition to the Hooke-Jeeves optimization analysis, the newly integrated Multi-Objective Genetic Algorithm (MOGA) technique was also used to investigate the ship design space in search of an optimum. While the MOGA technique was integrated and applied to the integrated system, insufficient time remained to adequately evaluate the large number of runs usually required to execute an effective MOGA analysis. On a first order problem such as this, the results would be quite close to those found by the Hooke-Jeeves method. Further exploration of this technique could be done in subsequent phases.

8.5 Uncertainty Analysis

Expanding on the optimization analysis, a Monte Carlo analysis was performed to measure the effect of uncertainty on the weight, cost, vertical maximum displacement at the helo deck of the ship, etc. Below are the random variables (i.e. parameters with associative uncertainty) and those responses. Each random variable was given a normal distribution. The initial design point was taken as the mean, and an appropriate standard deviation was given. Two hundred design simulations were executed using a descriptive sampling technique. The descriptive sampling technique allowed the user to drastically reduce the number of Monte Carlo simulation needed to provide an accurate picture of uncertainty.

Monte Carlo Simulation Results

Sampling Technique:	Descriptive Sampling
Number of Simulations:	200

RANDOM VARIABLES:

SS ENG BARE WT

Distribution
Normal

Mean
25.0

Standard Deviation
2.96381

Coefficient of Variation
0.1185524

Fixed Parameter
Standard Deviation

Wave Height

Distribution
Normal

Mean
3.0

Standard Deviation
0.4

Coefficient of Variation

0.133333333333333

Fixed Parameter
Standard Deviation

LBP

Distribution
Normal

Mean
235.0

Standard Deviation
2.0

Coefficient of Variation
0.008510638297872

Fixed Parameter
Standard Deviation

Lower Truncation
230.0

SS ENG EXH TEMP

Distribution
Normal

Mean
400.0

Standard Deviation
44.38890000000001

Coefficient of Variation
0.11097225

Fixed Parameter
Standard Deviation

SS ENG SFC

Distribution
Normal

Mean
0.188566

Standard Deviation
0.0188566

Coefficient of Variation
0.1

Fixed Parameter
Standard Deviation

SS ENG MASS FL

Distribution
Normal

Mean
4.0

Standard Deviation
0.539775

Coefficient of Variation
0.13494375

Fixed Parameter
Standard Deviation

SS ENG PWR AVAIL

Distribution
Normal

Mean
4500.0

Standard Deviation
395.221

Coefficient of Variation
0.0878268888888889

Fixed Parameter
Standard Deviation

SS ENG FRIC FAC

Distribution
Normal

Mean
0.99

Standard Deviation
0.09

Coefficient of Variation
0.090909090909091

Fixed Parameter
Standard Deviation

SS ENG RPM

Distribution
Normal

Mean
999.0

Standard Deviation
90.0

Coefficient of Variation
0.09009009009009

Fixed Parameter
Standard Deviation

RESPONSES:

HLVerDspMax

Mean
1.8162999999999994

Standard Deviation
0.2420293391409915

Minimum
1.14

Maximum
2.5

Probability less than upper limit 2.6
1.0

MaxPitch

Mean
0.6550500000000001

Standard Deviation
0.09949620583155105

Minimum
0.41

Maximum
1.37

Probability less than upper limit 3.0
1.0

VRVerVelMax

Mean
0.7900999999999999

Standard Deviation
0.10606715422801799

Minimum
0.49

Maximum
1.1

Probability less than upper limit 2.1
1.0

CLIFE

Mean
54725.74988611083

Standard Deviation
207.12540937167617

Minimum
54214.3771529129

Maximum
55367.9184658241

VRVerDspMax

Mean
1.1192499999999996

Standard Deviation
0.14972315322977048

Minimum
0.7

Maximum
1.55

Probability less than upper limit 2.1
1.0

MaxRoll

Mean
3.7650500000000005

Standard Deviation
0.49018404655546205

Minimum
2.36

Maximum
4.96

Probability less than upper limit 5.1
1.0

HLVerVelMax

Mean
1.0544

Standard Deviation
0.14096095186167248

Minimum
0.66

Maximum
1.45

Probability less than upper limit 2.1
1.0

As can be seen in the tables above, based on the uncertainty given, all our constraints were satisfied with 100% probabilities; and our lifecycle cost ranged between a minimum of 54214 and a maximum of 55367 – a maximum variation of about 1%. Again, this was done as a first order analysis.

Figures 36-38 show the histogram plots of the some of those responses.

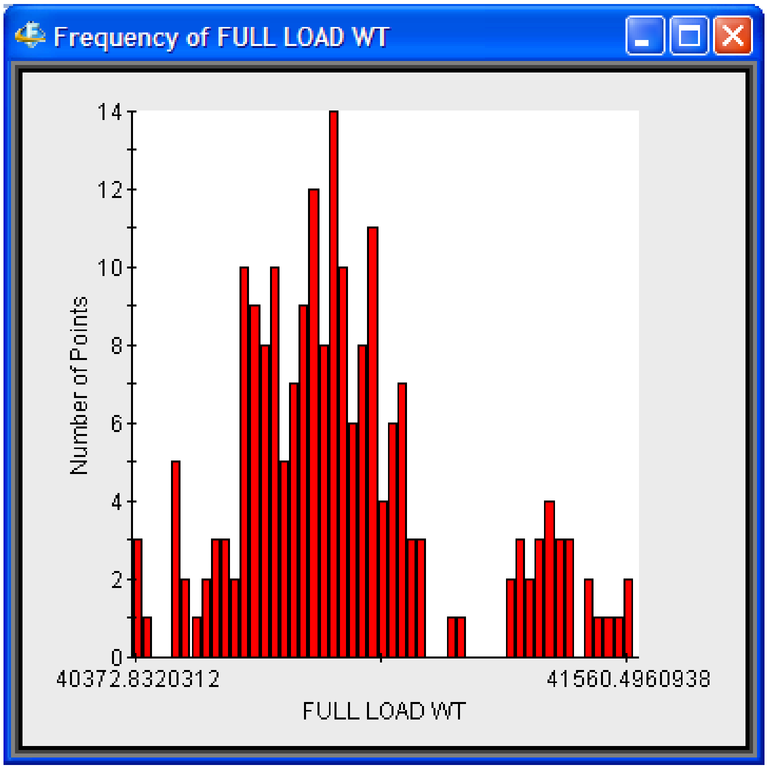


Figure 36 – Histogram of Monte Carlo Runs for the Weight Response

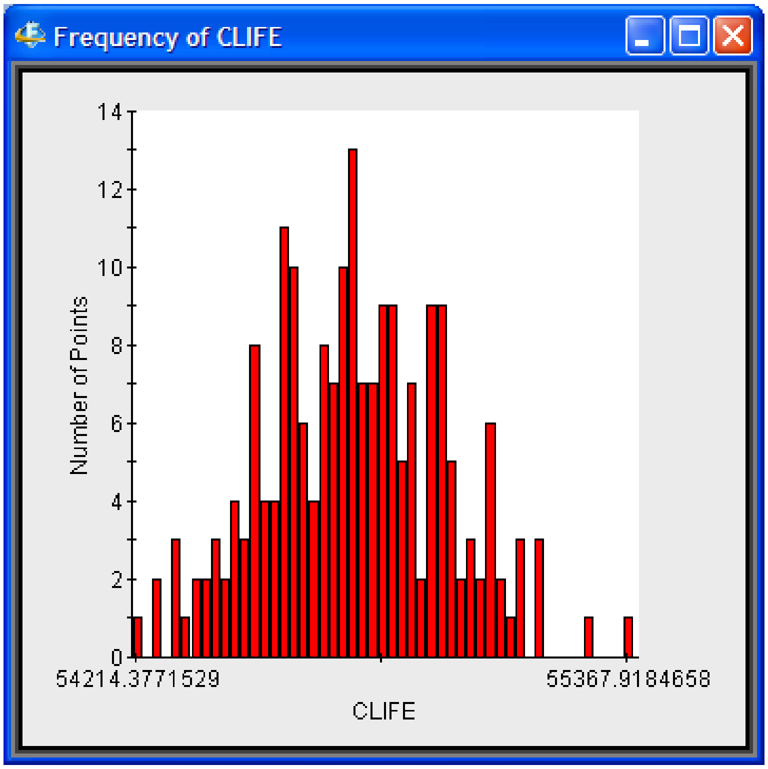


Figure 37 - Histogram of Monte Carlo Runs for the Lifecycle Cost Response

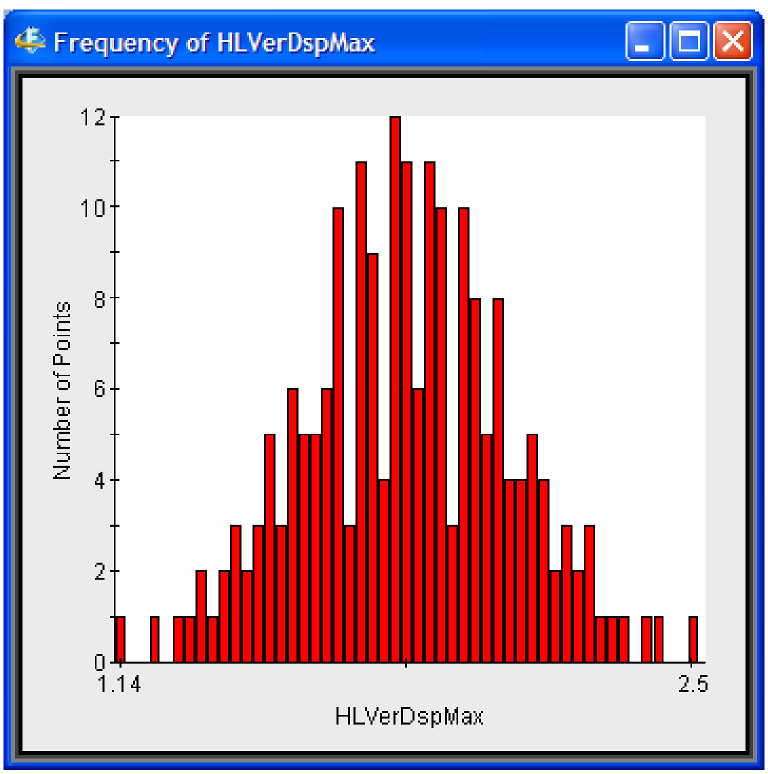


Figure 37 - Histogram of Monte Carlo Runs for the Helo Deck Max Vertical Displacement Response

9.0 Phase II

Phase II work will be discussed in the Phase II work plan to be delivered by February 4th, 2004.

10.0 Summary

The success of the work on this project can be measured in a couple different ways. If the accomplishments are measured against the objectives outlined in the section 2.0, the following results can be stated:

1. The team members identified three analysis tools: ASSET, SMP, and an Excel cost model to measure ship performance and effectiveness.
2. The MPFF ship class was verified as a program of interest to the Navy and MPFF models were obtained or developed for the project.
3. Each model was integrated into the FIPER framework under a single workflow.
4. The integrated workflow allowed the users to quickly apply design exploration techniques such as design of experiments, optimization, and quality engineering tools.
5. A Multi-Objective Genetic Algorithm (MOGA) was identified as an optimization technique of choice and integrated into the FIPER framework.
6. Uncertainty analysis using Monte Carlo technique was performed and measured against Lifecycle cost.
7. Northrop Grumman has stated that other classes of ships, such as DDX, are potential beneficiaries of an integrated MDO analysis ship design system implemented in FIPER. By taking the current system and enhancing and expanding it in future phases, a broader base of industry and institutional candidates could benefit from the possibilities.

Evaluating the project in terms of its overall usefulness and impact is another measure of the projects success. The team was able to take isolated ship design disciplines and bring them under a single framework. The models were able to communicate with each other through FIPER after their initial integration. And, it should be noted that this integration was not a "hard coded," single-use integration case. Due to FIPER's flexible framework, different models can be integrated without great pains. In addition, applying design exploration techniques was done in a simple drag and drop action. These capabilities allow the team to provide an integrated naval design environment one else can. It has the ability to integrate tools not only in the localized analysis environment (i.e. a single engineering group), but also across different design groups, departments, as well as outside vendors.

While the analysis performed under this project would not hold up to scrutiny under a true ship design effort, it did demonstrate the ease in which a system could be rapidly assembled and the ability to apply design exploration techniques to that process. Once integrated, all design driver capabilities in FIPER could be brought to bear on the design system. Optimization, DOE, quality engineer, etc. could all be used and would not require a separate integration.

Moving forward, the next phase of the project will lead to the development of more robust analysis models, integration of more analysis tools to measure ship performance and effectiveness, tight coupling of those analysis tools (i.e. integration component interfaces that are specific to the tools, like SMP, to allow even quicker integration and greater ease of use), and the demonstration of the ability to handle tool integration through the internet in a secure fashion.

Appendix A

11.0 Project Work Summary

11.1 Period Covering 7/1/03 – 9/30/03

Engineous Software received notification that we had been recommended for an award for STTR # N03-T026 by John Williams on June 11, 2003. We received a purchase order for this award on June 26, 2003. As soon as we received word of the recommendation, we immediately started implementing the required agreements with MIT to address intellectual property rights, confidentiality requirements, product licensing requirements and other matters pertaining to the subcontracting relationship between Engineous and MIT. Since Northrop Grumman was already a customer of Engineous, and since they would not be getting paid (except for expense reimbursement), no documents needed to be signed with them. Unfortunately, it took from 6/20 to 9/03 to get the referenced documents agreed upon and signed and this put us a little behind schedule. However, we did not expect any problems with completion of the outlined project by the scheduled due date.

On September 9th we officially kicked off the program with a conference call. During this call a lot of ground was covered. For example:

- We reviewed the objectives proposed in the STTR.
- A demonstration of the Engineous technology that would be used as a framework to integrate the different tools was given.
- A discussion was held on exactly which ship synthesis, mission effectiveness and ship design tools would be integrated.
- We discussed which design currently at NSWC-CD we would use.
- A date was set for a meeting at Engineous Headquarters for October 7th & 8th.

During September, the Northrop Grumman team received internal funding for two people to support the effort on the STTR. Aldo Kusmik from NUWC also received support from his management for participation and brought in another person to be trained on Engineous technology to support this program. See Appendix B for an updated team list.

In the months of October and November, each member of the team was trained on the FIPER framework and had it loaded on their computer. During this time, we accomplished the following items:

- Team members became proficient on the use and understanding of the FIPER technology.
- Developed a list of codes currently being used and how they interacted with each other at naval ship design locations. Codes for:
    - Mission effectiveness
    - Mission analysis
    - Ship design

- Determined the feasibility of integrating these codes.
- Identified the ship that would be used as an example.

11.2 Period Covering 10/1/03 – 12/31/03

A STTR team meeting was held at Engineous Software headquarters on October 7th and 8th (See Appendix B for a list of team members). This meeting brought together the team members from Northrop Grumman, MIT, NUWC and Elon University. Team members received training on Engineous's integration software FIPER. Meetings were also held to discuss the direction of the project including:

- Identifying ASSET, SMP, SIMSmart, Signatures and MIT's Excel cost model as the analysis tools of choice
- Identifying LCS as our model ship
- Identifying Multi-Objective Genetic Algorithm (MOGA) as the optimization technique of choice for ship analysis

Northrop Grumman was in charge of obtaining the ship models for the LCS program. Asset would be obtained directly from the ONR. SMP would be provided by NUWC. The MIT Excel cost model and Signatures would be provided by MIT. Finally, SIMSmart would be provided by Northrop Grumman. A weekly conference call was established for every Thursday at 10 am EST to communicate on the project progress among team members. Each team member returned home with a copy of FIPER for use on the project.

A working model of SIMSmart was readily available and integration of the model into FIPER was begun immediately. Justin Vianese from Engineous traveled to Northrop Grumman Ship Systems in Pascagoula, Mississippi November 12th-14th to assist in the integration of the SIMSmart into FIPER. During this visit, it was determined that the LCS models for SMP and ASSET would not be available, since Northrop Grumman was entering an unsolicited bid to the Navy on that project. Northrop suggested using the Multipurpose Force Future (MPFF) or Auxiliary Oilier Experiment (AEX) ship models instead.

In late November, the team determined that the SIMSmart model was a good detailed analysis, but would not integrate well with the SMP and ASSET models, which dealt with much higher level analysis. At that point, work with SIMSmart ceased. It was also determined that due to Signatures classified status; the team would not be able to obtain a copy. MIT found that no unclassified software existed that could provide the stealth analysis needed. Therefore, stealth analysis was dropped from the list of tools. Northrop identified MPFF as the best replacement ship candidate for the STTR project.

On November 21st Rick Recuparo and Justin Vianese from Engineous gave a project update to ONR in Washington D.C. Attending the update from ONR were

Katherine Drew, Bruce Wintersteen, and Luise Couchman. The team's progress to date and future program goals were presented. The presentation included:

- A review of the proposed objectives
- Overview of the FIPER integration software
- Identification of the analysis tools
- Overview of the MPFF ship class (operation roles)
- MDO analysis technique
- Identification of requirements and measures of effectiveness
- Cost analysis
- Integration scheme
- Summary of work done and future work

Due to a last minute conflict of schedules, Northrop Grumman was not able to attend the meeting to present the MPFF overview. A follow up web presentation for ONR was done on December 10th to present this portion. The full presentation is included in Appendix B of this report.

At the end of December Northrop Grumman determined that the LHD8 ASSET model, one of the three classes of ships Northrop was combining as a baseline for their MPFF project, was to be used for our analysis. Northrop also determined that the SMP model would need to be created for LHD8, as no model was currently available. With the help of MIT and NUWC, Engineous would need to create this model and integrate it with the ASSET LHD8 model and MIT Excel cost model.

There was also a change in the team as well in December. Rick Recuparo left Engineous Software to pursue another opportunity. He left on amicable terms on December 12th. Justin Vianese took over as the Principal Investigator at that time.

The team spent the remainder of the project period:

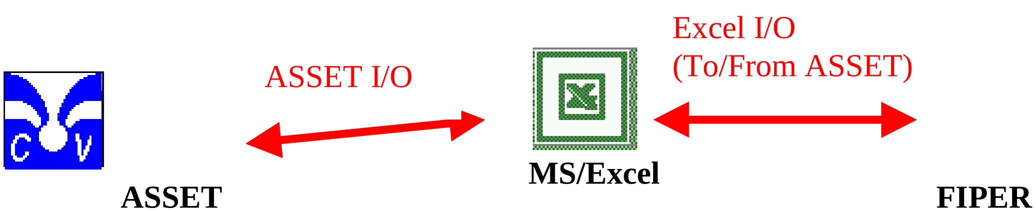
- Developing a LHD8 SMP model
- Integrating the LHD8 ASSET, SMP, and Cost models into the FIPER
- Running optimization analysis on the integrated process
- Writing a Final Report documenting complete project effort
- Developing a 5 page Phase II plan

11.3 Period Covering 1/1/04 – 2/2/04

At the end of December, Northrop Grumman determined that the LHD8 ship was to be used in our MDO analysis. The LHD8 model was provided in ASSET, but the LHD8 model needed to be created in SMP; and the spreadsheet needed to be adjusted for LHD8 as well.

Engineous did a preliminary integration of ASSET, SMP, and the MIT cost spreadsheet into FIPER. While the LHD8 model was available for the ASSET, example models were used for the preliminary integration until the actual models were built. The MIT cost model was integrated into the FIPER framework using FIPER's Excel integration component. This component allows the user to specify which data he/she would like to change in the spreadsheet via cell locations, and which results he/she would like to read after those changes are made. Thus, the user could manipulate spreadsheet cells of interest (e.g. weight, length, crew size, etc.) and see the effect on output results, such as overall lifecycle cost.

ASSET was integrated in a similar manner, by taking advantage of ASSET's ability to communicate directly with Excel. ASSET allows a user to develop an Excel spreadsheet of pertinent ASSET input parameters and key results, and communicate changes to ASSET via the spreadsheet. The results are returned to the spreadsheet once ASSET is finished executing its analysis. Execution of ASSET can be controlled from within Excel by leveraging specific Excel macros provided by ASSET. By leveraging this interface capability, Engineous was able to again use FIPER's Excel component to make substitutions in an Excel spreadsheet. All parameters of interest, inputs (e.g. length, etc.) and outputs (e.g. weight, etc.) were stored in the Excel spreadsheet, which communicated directly with FIPER. Below is a diagram of that communication.



While ASSET and the cost model took advantage of FIPER's Excel component, SMP was integrated using FIPER's data exchange component. The data exchange component allows information stored in text input and output files for SMP to be written and read in and out of FIPER. The data exchange component editor is used to identify the input and output parameters of interest by allowing the user to highlight input and output parameters from SMP's input and output files.

SMP Input File Data Exchange Example:

RECORD SET 4 - Hull particulars
237.134   32.3088   7.9248 41194.800   24.9097   5.0000   0.0000

The above highlighted parameter, Ship Length, could be identified in the data exchange parameter so FIPER could manipulate this parameter to produce ships of varying length. Similarly, highlighting a parameter in the data exchange editor from a sample SMP output file provides FIPER with a template on how to read parameters from SMP as they are generated after each analysis. So, for each ship analysis run, say with varying length, FIPER can read weight, heave, pitch, sway, roll, yaw, etc.

SMP Output File Data Exchange Example:

MAXIMUM RESPONSES AND CONDITIONS

RESPONSE	HEAVE	PITCH	SWAY	ROLL	YAW	P1VAC	P1LAC	P2VAC	P2LAC	P3VAC	P3LAC	P4VAC	P4LAC
(MAX.RSV)/TOE	1.11/ 8	0.86/10	1.23/90	6.24/12	0.93/17	206.6/ 8	199.5/17	8.51/ 7	6.64/10	9.72/12	3.78/ 9	9.72/12	3.78/ 9
AT SPEED (KNOTS)	25.0	0.0	25.0	10.0	25.0	10.0	25.0	25.0	0.0	25.0	0.0	25.0	0.0
AT HEADING (DEG)	75.	75.	135.	105.	135.	75.	120.	75.	90.	90.	90.	270.	90.

The above highlighted parameters provide FIPER with the results of pitch and roll for the ship. After each analysis of a different ship configuration is run, these parameters are communicated back to FIPER; and used to evaluate the performance and effectiveness of the ship in combination with all the other parameters coming out of ASSET and the cost model.

After linking the demonstration models, Engineous worked with NUWC and MIT to build the proper LHD8 models for SMP and the cost models. On January 15th, Dave Naehring and Justin Vianese from Engineous met with Dr. Chryssostomos Chryssostomidis at MIT in Cambridge, Massachusetts. During the meeting Dr. Chryssostomidis reviewed the ASSET, SMP, and cost model's input and output parameters of interest with Dave and Justin. The data flow to/from ASSET, SMP, and the MIT cost model were identified.

After meeting with Dr. Chryssostomidis, and with significant help from William Krol at NUWC, Engineous was able to complete the development of uniform LHD8 models for ASSET, SMP, and the cost model.

After completing the models, the new SMP model and cost model were integrated into FIPER in place of the example models that were used in the initial integration. Once the new models were integrated, FIPER's design exploration techniques were used to investigate the design space. At first, length was examined and a Design of Experiments (DOE) analysis was run. By its nature, the DOE allows the user to quickly scan the design space to identify areas that might provide significant improvements in ship design. After running a DOE, a user can employ an optimization technique and/or a quality engineering technique, such as Monte Carlo analysis, to look for deterministic and/or stochastic optimums.

By trying multiple optimization techniques, including the Multi-objective Genetic Algorithm developed by Elon University, "optimum" ship designs were obtained. The word “optimum” must be qualified because the optimum design obtained was based on certain assumptions and a limited parameter set in which to explore the design space. Fewer assumptions and greater parameter sets would provide a superior optimum (i.e. closer to the true optimum).

A Monte Carlo analysis was also performed to investigate the effect of uncertainty on performance and effectiveness. FIPER used a descriptive sampling Monte Carlo technique to determine the reliability of the ship design measured against its constraints. That is, what happens to key measures of performance/effectiveness (e.g. overall lifecycle cost) when uncertainties are introduced into the ship design (e.g. ship weight).

A complete overview of all results and further descriptions of integration can be found in the appropriate sections of the Final Report.

After completion of the analysis, information and results were complied in a final report. A review of the project and the results will be presented to ONR on February 3rd in Washington, DC. As required, the Phase II work plan will be provided to ONR by February 4th.

Appendix B

STTR Team Contact List

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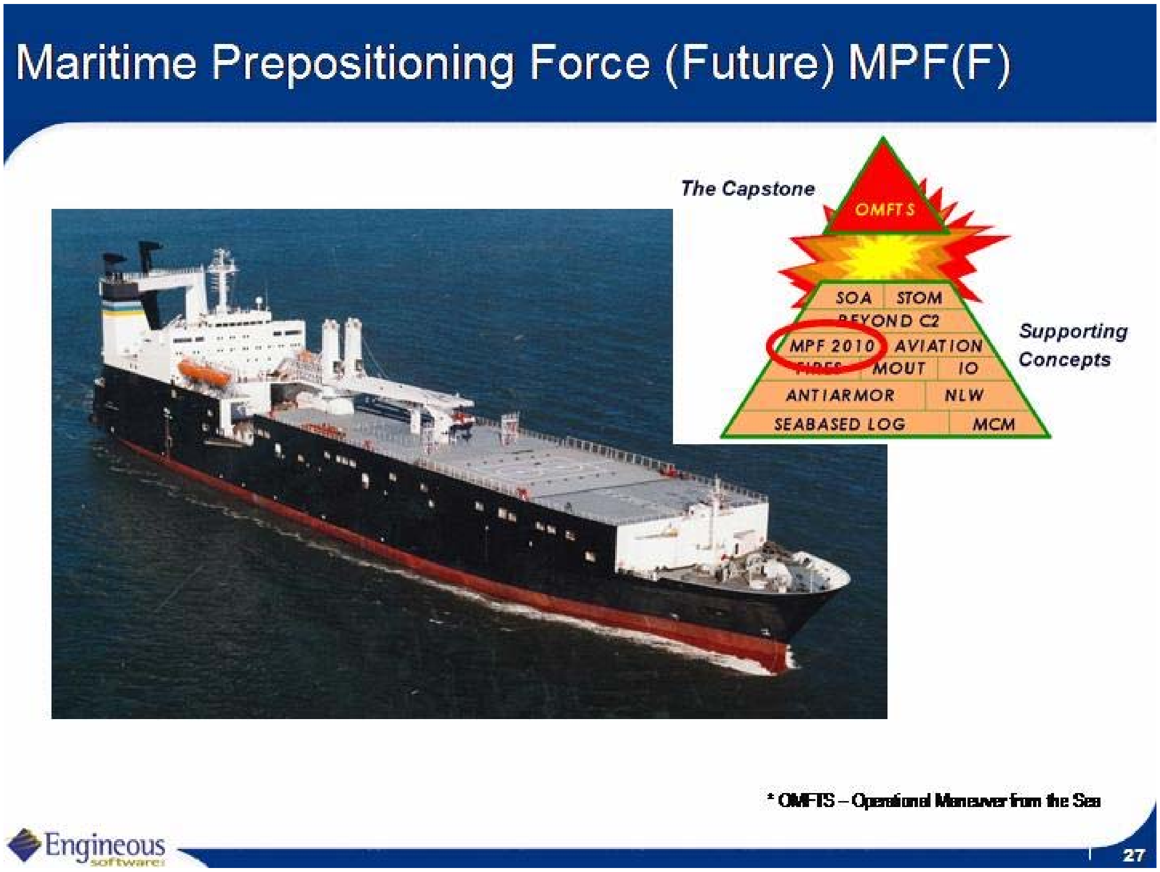
Appendix C

The MPFF Ship Class Presentation by Northrop Grumman



MPF - Current

- **MPF established in 1979.**
- **3 Forward Deployed Squadrons**

MPSRONs

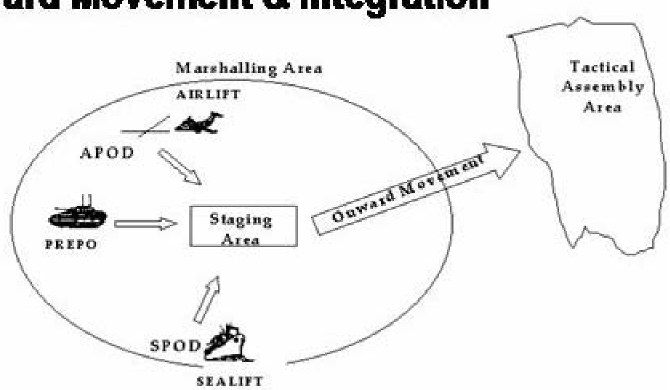
- (1) Mediterranean Sea
- (2) Diego Garcia
- (3) Guam/Siapan

13 Ships Organized to:

- 7 day response time
- Supports a Marine Expeditionary Brigade (MEB) of approx. 17,000 Marines for 30 days

MPF - Current Doctrine

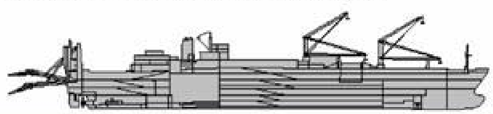
- **Reception, Staging, Onward Movement & Integration (RSO&I)**
  - Reception
  - Staging
  - Onward Movement
  - Integration



- **Provides:**
  - Mobility
  - Limited in-stream offload
    - At Sea

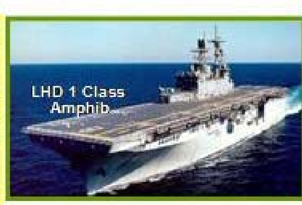
MPF(F) – Future Mission

- **A Family of ships that provide:**
  - At-sea arrival and assembly / reconstitution & redeployment of units
  - Direct support of the assault echelon of the MAGTF
  - Indefinite sea based sustainment of the Landing Force
- **Unload cargo**
  - Unimproved ports
  - Over the Beach by Joint Logistics Over The Shore (JLOTS)
- **Supports**
  - Operational Maneuver From The Sea (OMFTS)
  - Ship To Objective Maneuver (STOM)
- **Supports 5 Tenants of Sea Basina**



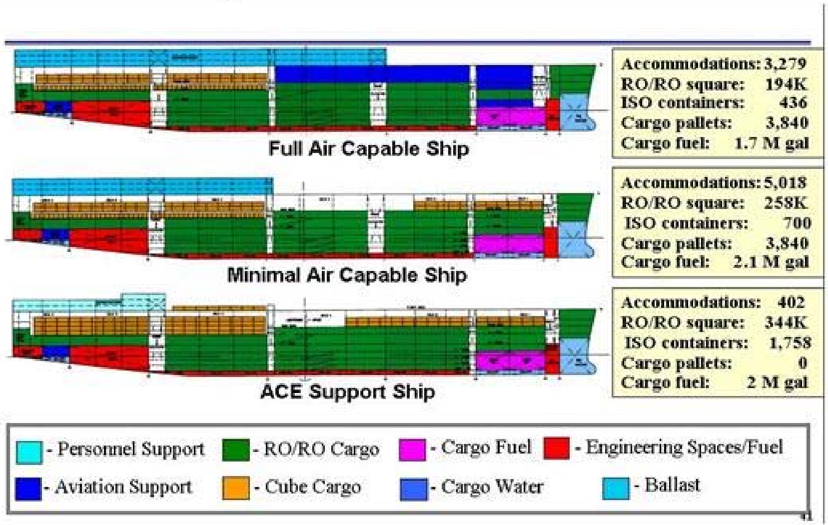
MPF(F) –Future Benefits

- **Projects Joint Operational Independence**
- **Allows the Joint Force Commander**
  - Accelerated Deployment & Employment Times
  - Enhances Seaborne Positioning of Joint Assets
- **Minimizes Logistics Stockpile ashore** (Iron Mountain)
- **Minimizes Force Protection issues ashore**
  - (Uses the *Safety* of the open ocean)



MPF(Future) Challenges & Needs

- **3 Separate but integrated functions**



Joint Logistics Functions

- **6 Logistical Functions**
  - **Supply**
  - **Maintenance**
  - **Health Services**
  - **Transportation**
  - **Service**
  - **General Engineering**
- **Keeps deployed forces:**
  - **Manned**
  - **Armed**
  - **Fueled**
  - **Sustained**
  - **Moving**
- **Combat Service Support (CSS) provides the Logistical functions to the Joint Task Force**

MPF(Future) Challenges & Needs

- **Interface with Legacy Transportation Systems**
  - CH 46
  - AAV
  - LCU 1600
  - LCAC

- **Interface with Future Transportation Systems**
  - MV 22
  - AAAV
  - LCU(R)
  - HLCAC

Conclusion

- **MPF(F) must interface with Legacy and Future Transportation Systems (JITL facilitators)**
- **Will support:**
  - Sea Power 21
  - EMW
  - OMFTS
  - STOM
- **Platform to provide:**
  - Force Closure
  - Joint Task Force Interoperability
  - Sustainment
  - Reconstitution and Redeployment
- **MPF(F) is the string that ties Sea Power 21 and Sea Basing together**

Design Assumptions

- Personnel - 8320 Within the MPF (F) MEB
- Aircraft – Broad system operational & support role
- Equipment – Extended support and handling function
- Hospital Capability – new extended location & role
- Modularity
  - Joint Command and Control
  - Fleet Hospital

Aircraft: MPF(F) ACE & Distribution

AoA MPF(F) ACE Requirements

- MV-22: 48
- CH-53E: 20
- UH-1Y: 9
- AH-1Z: 18
- F-35B: 30
- Total: 125

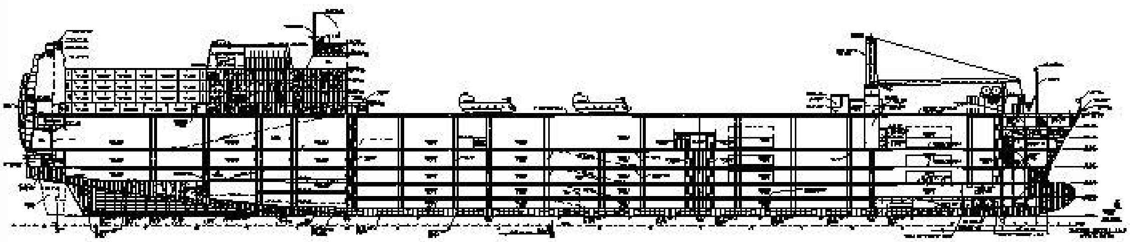
- F-35B Deleted From MPSRON Operated From Grey Hulls.
- MH-60 Added for "Plane Guard" Duties.
- LHD-8 MPSRON Requires 2xCH-53E on Each LMSR Variant. 56'x8' and Larger Variants Split the ACE Between 2 Hulls.

Straight 8 LHD MPSRON--Option 1						
	LHD #1	LHD #2	LMSR #1	LMSR #2	LMSR #3	
MV-22	24	24	0	0	0	48
CH-53E	7	7	2	2	2	20
UH-1Y	6	3	0	0	0	9
AH-1Z	9	9	0	0	0	18
MH-60R	1	1	0	0	0	2
JSF	0	0	0	0	0	0
					Total	97

56'-8' LHD MPSRON--Option 2						
	LHD #1	LHD #2	LMSR #1	LMSR #2	LMSR #3	
MV-22	24	24	0	0	0	48
CH-53E	10	10	0	0	0	20
UH-1Y	4	5	0	0	0	9
AH-1Z	11	7	0	0	0	18
MH-60R	2	2	0	0	0	4
JSF	0	0	0	0	0	0
					Total	99

77'-10' LHD MPSRON--Option 3						
	LHD #1	LHD #2	LMSR #1	LMSR #2	LMSR #3	
MV-22	24	24	0	0	0	48
CH-53E	10	10	0	0	0	20
UH-1Y	4	5	0	0	0	9
AH-1Z	11	7	0	0	0	18
MH-60R	2	2	0	0	0	4
JSF	0	0	0	0	0	0
					Total	99

LMSR 2-Spot Variant IV-A

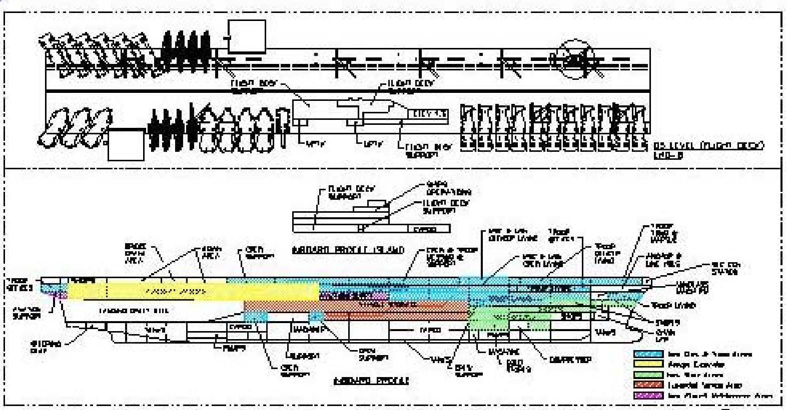


Key Changes from Baseline

- Removed Crane
- Expanded Flight Deck
- Extended Deckhouse
- Increased Berthing

Option IVA LMSR w/ Expanded Helo Deck/Troop Berthing/Vehicle Square	LMSR #1	LMSR #2	LMSR #3
MV-22	1	2	0
CH-53E	1	0	2
LCAC	0	0	0
Marine Compliment	400	400	400
Cargo Cube	4,497,928	4,497,928	4,497,928
Vehicle Square	331,700	331,700	331,700

LHD-8 2-LCAC Variant I-B

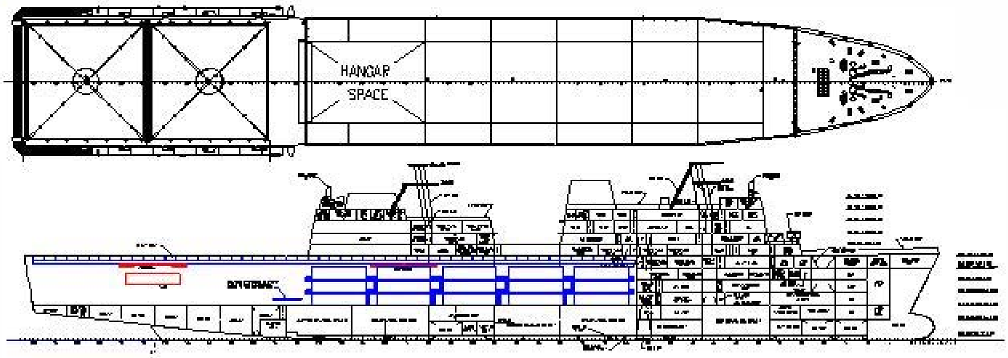


Option IB LHD-8 w/ Wet Well, 2 LCAC Spots, Expanded ACE/ Vehicle Decks/Troop Berthing	LHD #1	LHD #2
MV-22	24	24
CH-53E	7	7
UH-1Y	6	3
AH-1Z	9	9
MH-60R	1	1
LCAC	3	3
Marine Complement	3438	3438
Cargo Cube	117815	117815
Vehicle Square	24935	24935

Key Changes from Baseline

- Increased Vehicle Square by Reducing Number of LCAC's Carried.
- Accommodating Aircraft Arrangement 2 (LHD # 2).
- Lengthened Hangar Deck and Rearranged Support Facilities.

LPD Variant V-A



Option VA LPD w/ Revised Internals for Modular Reconfigurability	
V-22 Spots	2
LCAC	2
Marine Complement	826
Cargo Cube	487,727
Vehicle Square	33,891

Key Changes

- Eliminated 2nd Deck and 1st Platform
- Added cell guides
- Added bridge cranes for container handling

MPF(F) Variant Option Characteristic Matrix

Description	Baseline LHD-8	Option IB LHD-8	Option IIB 56' Longer 8' Wider	Option IIIB 77' Longer 10' Wider	Baseline LMSR	Option IVA LMSR	Option IVB LMSR w/ LCAC well	Baseline LPD	Option VA LPD
Displacement	42,300	42,300	48,700	49,000	62,809	62,809	54,945	25,390	25,390
Speed	24 knots	24 knots	24 knots	20 kts	24 kts	24 kts	24 kts	22 kts	22 kts
Number of helo spots	9	9	10	11	1	2	2	2	2
Vehicle stowage area	21,044	24,935	29,437	35,968	391,100	331,700	76,700	33,900	22,100
Cargo hold volume	118,324	118,324	134,260	144,367	4,818,000	4,497,900	[illegible]81,900	357,100	209,800
LCAC well	3 LCACs	2 LCACs	2 LCACs	2 LCACs			1 LCAC	2 LCACs	2 LCACs
MV-22	12	24	24	24				1 or	1 or
CH-53E	4	7	10	10	1	2		1 or	1 or
AH-1Z	4	9	7	7				3 or	3 or
UH-1Y	3	3	5	5					
MH-60 or CH-46	2	1	2	2				2	2
Ship endurance @ 20 knots	10,000 nm @ 20 knots	10,000 nm @ 20 knots	10,000 nm @ 20 knots	10,000 nm @ 20 knots	12,000 nm @ 24 kts	12,000 nm @ 24 kts	9,000nm @ 24 kts	13,000 nm @ 10 kts	13,000 nm @ 10 kts
Number of USMC berths	1871	3438	3762	4178	0	400	400	TBD	826
Crew size	1135	261	261	261	95	170	170	186	186
MSC	0	51	51	51	50	45	45	51	51
Navy/Marine	1135	210	210	210	45	125	125	135	135

Aviation

Cargo Area and Cube

BEYOND TODAY - IMPLICATIONS ON THE PLATFORM

NORTHROP GRUMMAN
Ship Systems

Appendix D

A Distributed, Component-Based Integration Environment for Multidisciplinary Optimal and Quality Design

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Technological advancements over the last decade have progressed to the point where the expectations of the consumer for the performance and quality of products are manifesting themselves as expectations of engineers developing these products for the capabilities of their design environments. Design is becoming an ever-increasingly complex activity involving numerous software tools, communication/transformation of data, and collaboration among design teams both within and among corporations. Engineers are now expecting to be provided with software tools that are intuitive, easy to use, and that can interact with the other tools involved in their process fairly seamlessly. In reality, most engineering design environments fall short of meeting the expectations of the engineers, leaving many obstacles to overcome in their effort to design and develop the quality products demanded by the customers. There are numerous developments underway by various companies and organizations trying to provide this ideal environment; the problem with most of them is that they continue to focus on the all-in-one solution, attempting to provide the complete solution as opposed to a *framework* that makes the complete solution possible through incorporation of best-of-breed analysis and design tools. This paper describes the Federated Intelligent Product EnviRonment (FIPER), an environment that has been developed to serve as a plug-and-play framework for engineers to incorporate their tools of choice to provide services within the environment, to define a process mapping of the usage of these services (even across enterprise boundaries), and to take advantage of all available computing resources in the execution of these services to continually improve the products offered to consumers.

I. Introduction

The past decade has witnessed an obvious proliferation of software tools available for the various activities involved in multidisciplinary analysis and design. While this has resulted in greater accuracy and finer detail in the level of modeling of physical phenomena, it has also added to the complexity of the process overall. The mere existence of these tools does not mean they are improving the productivity of the engineer; in fact, the opposite may very well be true. The reason for this is that there is usually no single entry point to these tools or a common way to interact with them, making it difficult for them to be used in a coordinated fashion. Moreover, once an ultimate design is arrived at, it is often very difficult, if not impossible, to determine what

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* Member AIAA

specific tools were used (in particular, what *versions* of those tools), in what combination, and what were the sources of the data supplied to them. The problem becomes even more overbearing if part of the design process involves contributions from design teams in geographically disparate locations (possibly even other corporations altogether), when firewalls create barriers, security is of utmost concern, and data transfer among tools becomes cumbersome and error-prone. Considering all of these obstacles, engineers are also under strict time constraints to meet the deadlines governed by product release cycles, a frustrating predicament given that numerous design evaluations are typically required to achieve significant design improvement, even using the latest intelligent optimization and reliability/robustness algorithms available. The mere availability of an abundance of expensive, high-powered computing hardware does not ensure that it can be employed effectively during the design process. All of these aforementioned problems serve to counteract the ultimate goal of the designer in trying to continually improve the product by incorporating the latest technologies so that the expectations of the customer are met or even exceeded. The solution is not more or even better design tools – the solution is a framework that provides a solid foundation for overcoming these problems. The requirements for this type of framework continue to be established as the problems and obstacles become more clearly understood[1-3].

Recognizing the need for such a framework, Engineous Software has teamed with General Electric, Goodrich, Parker Hannifin, Ohio University, the Ohio Aerospace Institute, and Stanford University in a four-year collaborative effort to develop a Federated Intelligent Product EnviRonment (FIPER)[4], a project sponsored by the National Institute for Standards and Technology (NIST) Advanced Technology Program (ATP). The FIPER joint venture team is beginning its third year of work, with the various team members (and additional sub-contractors) investigating different aspects of the environment and/or services to be provided in the environment. The ultimate outcome of the project is a commercially developed and supported product development environment from Engineous Software. The remainder of this paper provides a high-level overview of this environment, with particular focus on the use of this environment for optimal and quality design. Programs in place for the early application of this environment in industry are also discussed.

II. FIPER

FIPER has been developed to provide a framework to overcome the aforementioned problems in existing design environments. For continuity, we will consider each of the issues and describe how FIPER addresses them.

a) *"no single entry point to these tools or a common way to interact with them"*

FIPER is a <u>component-based</u> framework that offers a common Java-based wrapping mechanism and uses XML descriptors to allow components to express the services they provide, information required to define how to use those services (*properties*), and the inputs/outputs (*parameters*) they expose to the environment (for other services to interact through). One of the fundamental aspects of FIPER is that anyone can develop his/her own components (i.e. wrapped tools) to populate the FIPER environment with services geared toward their specific problems. (Consequently, FIPER is not limited to the engineering design domain, but can theoretically be applied in other domains such as manufacturing or finance – it is all a matter of the components incorporated and the types of services they provide. To this point the emphasis has been on the engineering design domain). For example, Ohio University has developed a Cost Modeling component to provide a cost estimation service within the environment[5]. Other FIPER team members, including Engineous Software, are developing various components to provide different services in the FIPER environment, including but not limited to:

Engineering Analysis Components	**Design Driver Components**
CAD CAE Data Exchange Excel Cost Estimation Statistical Analysis	Design Of Experiments Optimization Design for Six Sigma (Reliability/Robustness) MDO Algorithms Knowledge-Based Engineering (KBE)

Again, the independence of components from the framework must be emphasized. It is critical that engineers have the freedom to incorporate their own preferred tools not only for the analysis aspects of the process, but also for the design improvement functionality. The philosophy is that if you have it and you like it, you can use it – if not, you can find it from somewhere else and it will still work.

FIPER serves as a "host" for the components providing these services through the concept of a Library. The FIPER Library is a virtually centralized and physically distributed repository for publishing (storing), searching for, and retrieving components, essentially providing the capability to collaborate by sharing the services offered by the components (even among different business divisions or independent organizations). One of the primary aspects of the Library is that it is version controlled, a critical capability to ensure that as components are updated, references to the use of these components do not become "stale" and invalid.

b) *"very difficult, if not impossible, to determine what specific tools were used (in particular, what versions of those tools), in what combination, and what were the sources of the data supplied to them"*

FIPER allows an engineer to assemble components together into a workflow that models his/her design process. Workflow is, in general, a very powerful and flexible way of expressing what needs to be done, in what sequence, and what the data requirements are; its application to engineering design is natural and has tremendous potential[6]. In FIPER, a simple Desktop interface provides a means for building these *FIPER models* through a drag-and-drop mechanism, with convenient ways to specify the properties and parameters for each of the components in the model, essentially defining both control flow and data flow (through parameter mapping). The components referenced in the model being developed can reside in the FIPER Library or in a file system, with accessibility limited by whatever access permissions were supplied when the component was published. Just as components are published for others to use and extend, so too can model be published to the FIPER Library (with access permissions) for others to use if desired.

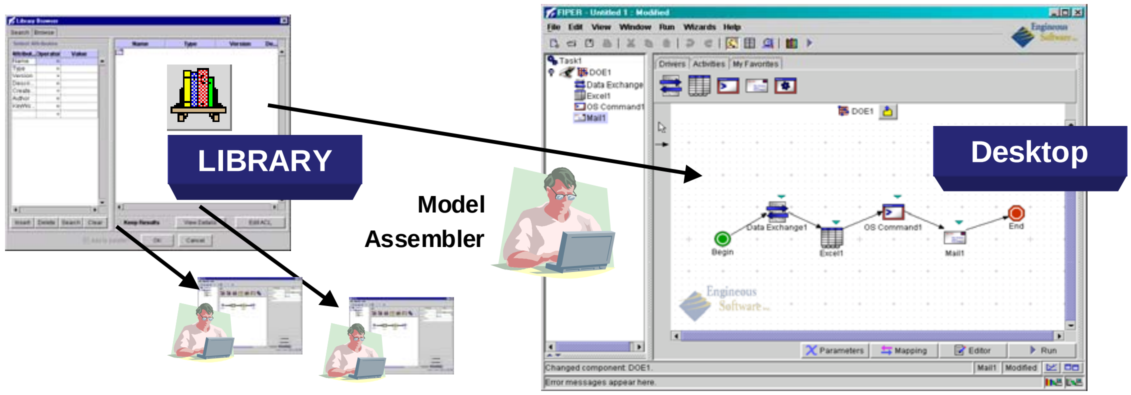


Figure 2: Building Models in FIPER

c) *"design process involves contributions from design teams in geographically disparate locations (possibly even other corporations altogether)"*

As described above, the FIPER Library provides a means for people to publish components and models to make them available for use by anyone who has access to that Library. It is envisioned that FIPER will provide inter-organization collaboration by allowing organizations to establish connections among their Libraries. Thus, models could actually contain references to components (or other models) which reside in a remote Library, again with accessibility limited by whatever access permissions were supplied when the component was published (or by stricter permissions established by the Library relationships). These so-called Business-to-Business (B2B) relationships are becoming evermore common, and thus this capability is a primary ultimate goal of FIPER, with prototype capabilities currently being tested.

d) *"mere availability of an abundance of expensive, high-powered computing hardware does not ensure that it can be employed effectively during the design process"*

The FIPER infrastructure includes all of the necessary modules for handling data communication and storage and process management. Built on the Java 2 Enterprise Edition (J2EE) platform as a solid foundation[7,8], the FIPER infrastructure is embodied by the combination of a *Problem Solving Environment (PSE)* and *FIPER Stations*.

The PSE is essentially an application server that provides:

- a Workflow Engine for interpreting and managing process flow to create work items
- a Context Manager for assembling the necessary input data for each work item
- a Dispatcher for determining which FIPER Station the work item should be sent to

- a Results Manager for processing results from the work items

Any organization with a PSE can collaborate, or share services, with any other organization with a PSE (i.e. B2B collaboration).

The FIPER Stations are computers in the network that have been registered with the PSE to handle the execution of work items, essentially consisting of a lightweight framework for receiving work items, communicating with the Library, executing components (likely launching corresponding back-end software applications), and returning results. The PSE dispatches work items to FIPER Stations based on a defined load-balancing scheme, distribution strategy, and/or *affinities* (i.e. operating system information, third party software licenses supported, machine name, etc.) defined for the item being executed. In this way, an organization can make the best use of its computing resources by making them available to do work within the FIPER environment.

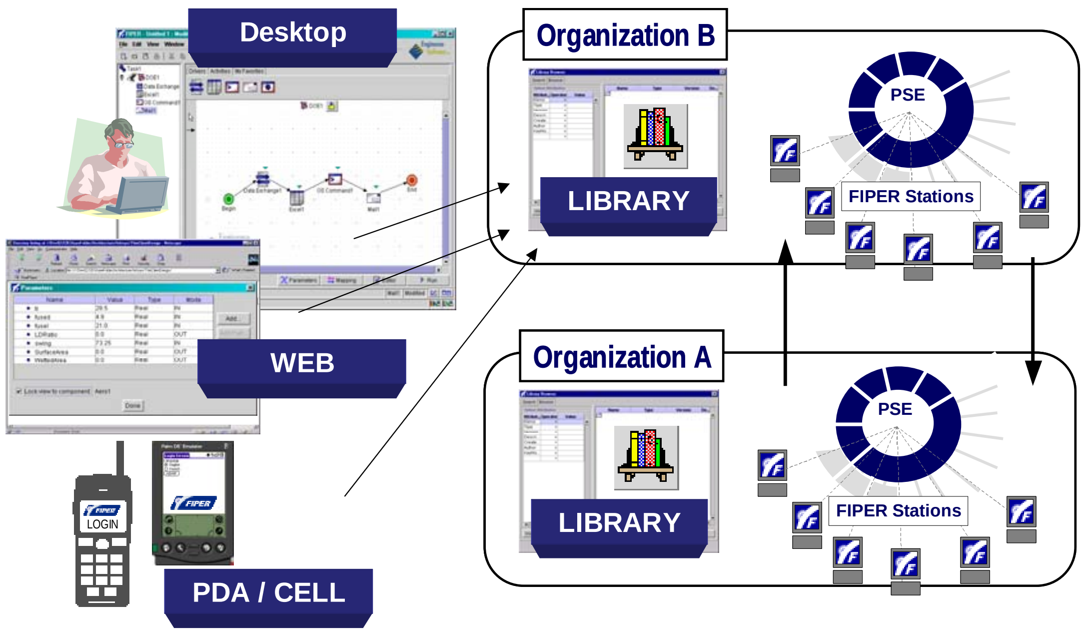


Figure 3: The Execution of a Model in the FIPER Environment

It is important to note that jobs can be submitted to the PSE to execute from any client. The only requirement is that the client be able to pass the XML description of the model to the PSE. Thus, thin clients such as custom web interfaces or even PDA devices can load a model from a FIPER Library, possibly provide new input values, submit it to the PSE, and receive results of that execution. Moreover, since the PSE handles all aspects of the execution, the submitter could actually exit the client from which the job was submitted and at a later time use another interface to query the status of the job or retrieve the results.

III. Applications

The component-based nature of FIPER is perfectly suited for application to engineering design problems. By applying “design driver” components such as optimization, DOE, and quality engineering techniques to an integrated collection of components for various analysis tools (CAD, finite elements, performance, etc.), a designer can more readily achieve the ultimate goal of an optimal and high-quality design. Within this process, there are many opportunities to take advantage of the true parallel and distributed nature of the FIPER framework because many design techniques require numerous independent design evaluations (which FIPER simply treats as multiple work items).

Various FIPER joint venture team members are currently beginning to deploy the FIPER environment for testing and validation. In addition, Engineous Software has established an Industrial Participants Program to involve key industry-leading organizations from the aerospace, turbomachinery, and automotive sectors. Projects stemming from these deployments will serve to provide valuable early input to direct the development and maturation of the environment.

At this point it is not certain what applications can be disclosed and to what level of detail. As an alternative, the final paper will report on in-house problems solved with this framework as an example of the mode of usage and the achievable benefits.

IV. Concluding Remarks

Due to the rapid advancement in technology, more and more is expected of the products that companies develop, which in turn results in greater expectations of engineers on the tools they use and the environment in which they design these products. FIPER is being developed to fill a void that currently exists between the integration needs of engineering design organizations and the capabilities that state-of-the-art computer science technology, hardware, and the Internet have to offer. Still in its formative stages, the true test of FIPER’s ability to accommodate those needs will be carried out through the applications of the involved organizations from industry. Early feedback will provide the opportunity to make necessary modifications and enhancements to allow a first commercial release to be robust and functionally complete.

Acknowledgements

This research is funded in part by the National Institute for Standards and Technology-Advanced Technology Program (NIST-ATPTM). The authors would like to acknowledge this support, the efforts of the entire development team at Engineous Software, and valuable input from the entire FIPER joint venture team.

References

1. Sobieszczanski-Sobieski, J., and Haftka, R., “Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments,” AIAA 96-0711, *34th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 15-18, 1996.
2. Wujek, B.A., *Automation Enhancements in Multidisciplinary Design Optimization*, Doctoral Thesis, University of Notre Dame, Notre Dame, IN, 1997.

3. Salas, A.O., and Townsend, J.C., "Framework Requirements for MDO Application Development," AIAA-98-4740, , 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 2-4, 1998.
4. *Federated Intelligent Product Environment (FIPER), Technical Proposal*, Ohio Aerospace Institute, General Electric, BFGoodrich, Parker Hannifin, Engineous Software, Ohio University, Stanford University, April 1999.
5. Koonce, D. and Judd, R. P., "A Cost Estimation Tool Integrated into FIPER", 4th International Conference on Design of Information Infrastructure Systems for Manufacturing, Melbourne, Australia, August 15-17, 2000
6. Wujek, B., Koch, P. N., Chiang, W. S., "A Workflow Paradigm for flexible design process Configuration in FIPER", AIAA-2000-4868, 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.
7. Allamaraju, Avedal, Browett, et all, *Java Server Programming J2EE Edition*, Wrox Press Ltd., Birmingham, UK, 2000.
8. Kassem, Nicholas, Designing Enterprise Applications with the Java 2 Platform, Enterprise Edition, Sun Microsystems, Addison-Wesley, 2000.

Appendix E

MIT Cost Model

Weight:

	A	B	C	D	E	F	G
1	Description	Variable	Value	Units	Input/Calc /Constant	Equation/Source	
2	**WEIGHT**						
3	Structure (100)						
4	Total Structural Weight	WT1	17367.1	lton	Input		
5							
6	Propulsion (200)						
7	PIBRAKE	WBM	50003.5	HP	Input	P_I	
8	Total Propulsion Plant Weight	WT2	819.3	lton	Input		
9							
10	Electrical Plant (300)						
11	Total Electrical Plant Weight	WT3	1509.3	lton	Input		
12							
13	Command and Surveillance (400)						
14	Gyro/IC/Navigation (420,430)	WIC	43.8	lton	Input	W_{IC}	
15	Total Command and Surveillance	WT4	554.8	lton	Input		
16							
17	Auxiliary Systems (500)						
18	Total Auxiliary Systems Weight	WT5	4597.9	lton	Input		
19							
20	Outfit and Furnishings (600)						
21	Total Outfit and Furnishings Weight	WT6	3051.4	lton	Input		
22							
23	Armament (700)						
24	Total Armament Weight	WT7	332.3	lton	Input		
25							
26	Future Growth Weight Margin	WM24	451.7	lton	Input		
27	Margined Lightship Weight	WLS	28683.8	lton	Input		
28							
29	Average Deck Height	HDK	8.05		Input		
30							
31		WF20	28.36		Input		
32		WF23	0		Input		
33		NHELO	0		Input		
34							

O&S Items:

	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc/Constant	Equation/Source
2						
3	Manning					
4	Officer	NO	264		Input	
5	CPO	NCPO	134		Input	
6	Enlisted	NE	2581		Input	
7	Total Crew	NC	2979		Input	
8						
9						
10						

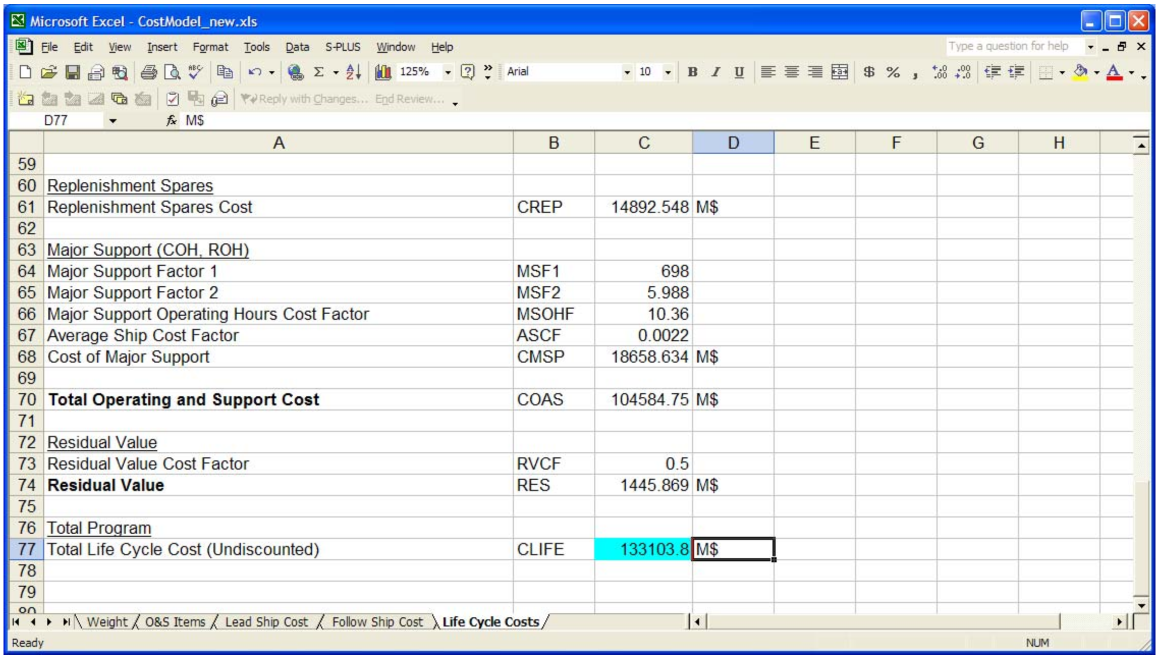
Lead Ship Cost:

	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc /Constant	Equation/Source
52	Program Manager's Growth Factor	PMGF	0.1			
53	Program Manager's Growth	CLPMG	91.496226	M$		
54	Weight of Costed Military Payload	WMP	871.66	lton		WT4+WT7+WF20-WIC-WF23
55	Combat System GFE CER	CSCER	0.321073	M$/lton	Input	
56	Helo cost	HC	18.71	M$		
57	Ordinance and Electrical GFE (Military Payload GFE)	CLMPG	476.49061	M$		
58	HM&E GFE Factor	HMEGFEF	0.03		Input	
59	HM&E GFE (Boats, IC)	CLHMEG	27.448868	M$		
60	Outfitting Cost Factor	OCF	0.04		Input	
61	Outfitting Cost	CLOUT	36.598491	M$		
62						
63	**Total Government Cost**	CLGOV	654.90825	M$		
64						
65	**Total End Cost**	CLEND	1679.666	M$		Must always be less than SCN appropriation
66						
67	**Total Lead Ship Acquisition Cost**					
68	Post Delivery Cost (PSA) Factor	PSACF	0.05			
69	PSA Cost	PSAC	45.748113	M$		
70	Total Lead Ship Acquisition Cost	TLSAC	1725.4141	M$		
71						
72						
73						

Follow Ship Cost:

	Description	Variable	Value	Units	Input/Calc /Constant	Equation/ Source
2	Follow Ship Cost					
3	Learning Rate Factor	LRF	0.9443333			
4	Learning Rate	LR	0.8886667			
5						
6	Follow Ship Cost - Shipbuilder Portion					
7	Follow Ship Basic Construction Cost	CFBCC	421.37166	M$		
8	Follow Ship Margin Cost	CFM	6.7417436	M$		
9	Integration/Engineering Follow Ship Factor	CF800F	0.104			
10	Integration/Engineering Follow Ship Exponent	CF800E	1.099			
11	Integration/Engineering	CF800C	81.117861	M$		
12	Ship Assembly and Support	CF900C	42.755164	M$		
13	Total Follow Ship Construction Cost	CFCC	551.98643	M$		
14	Profit	FPROFIT	0.1			From Profit Input Above
15	Total Follow Ship Price	PF	607.18507	M$		
16	Follow Ship Change Order Factor	FSCOF	0.08			
17	Change Order Cost	COC	48.574806	M$		
18	Total Follow Ship Cost Shipbuilder Portion	CFSB	655.75988	M$		
19						
20	Follow Ship Cost - Government Portion					
21	Follow Ship Other Cost Factor	FSOCF	0.0258333			
22	Follow Ship Other Cost	FSOC	15.685614	M$		
23	Follow Ship Program Manager's Growth Factor	FPMGF	0.05			
24	Follow Ship Program Manager's Growth	FPMG	30.359254	M$		
25	Follow Ship Combat System GFE CER	FSCSCEF	0.3566667	M$/lton		
26	Follow Ship Ordinance and Electrical GFE (Military Payload GFE)	FCMPG	529.31361	M$		
27	Follow Ship HM&E GFE Factor	FHMEGFE	0.03			
28	HM&E GFE (Boats, IC)	FCHMEG	18.215552	M$		
29	Outfitting Cost Factor	FOCF	0.04			
30	Outfitting Cost	FCOUT	24.287403	M$		
31						
32	**Total Follow Ship Government Cost**	FCGOV	617.86143	M$		
33						
34	**Total Follow Ship End Cost**	CFEND	1273.6213	M$		Must always be less than SCN appropriation
35						
36	Follow Ship PSA Cost Factor	CFPSAF	0.05			
37	Follow Ship PSA Cost	CFPSA	30.359254	M$		
38	**Total Follow Ship Acquisition Cost**	CFA	1303.9806	M$		

Lifecycle Costs:



	A	B	C	D
59				
60	Replenishment Spares			
61	Replenishment Spares Cost	CREP	14892.548	M$
62				
63	Major Support (COH, ROH)			
64	Major Support Factor 1	MSF1	698	
65	Major Support Factor 2	MSF2	5.988	
66	Major Support Operating Hours Cost Factor	MSOHF	10.36	
67	Average Ship Cost Factor	ASCF	0.0022	
68	Cost of Major Support	CMSP	18658.634	M$
69				
70	**Total Operating and Support Cost**	COAS	104584.75	M$
71				
72	Residual Value			
73	Residual Value Cost Factor	RVCF	0.5	
74	**Residual Value**	RES	1445.869	M$
75				
76	Total Program			
77	Total Life Cycle Cost (Undiscounted)	CLIFE	133103.8	M$
78				
79				

Appendix F

Subject: Coupling Status of Epsilon-MOEA to Fiper

From: Dave Powell, Elon University
Last Updated: December 23, 2003

This work was funded by the Navy STTR project led by Justin Vianese of Engineous Software. Special thanks are given to Oleg Golovidov of Engineous Software for his help and timely support.

In 2003, Kalyanmoy Deb published a new version of a genetic algorithm for multiobjective optimization. The code is called Epsilon-MOEA in C++ and in freely available from http://www.iitk.ac.in/kangal/soft.htm . There is one paper describing the approach, "A Fast Multi-objective Evolutionary Algorithm for Finding Well-Spread Pareto-Optimal Solutions" and can be downloaded from http://www.iitk.ac.in/kangal/pub.htm .

Fiper is written in Java. I ported the Epsilon-MOEA to Fiper to insure that the algorithm would be portable and be able to be run on any platform that supports fiper. This proved to be a wise decision. By porting to Java, I could use the JBuilder debugging environment to run both Fiper and the Epsilon-MOEA code.

I enhanced the original code to support:

1. initial seed of population.
2. user specifiable output file with format defined to support ggobi and also to provide the actual names of the fiper variables and objectives. I also add a penalty value so the user can see if the archive point violates constraints
3. user specifiable population size.
4. penalty is based on fiper penalty base, penalty multiplier and penalty exponent.

I validated the correctness of the code by running it on 4 well known test problems.

I wanted to display and analyze the pareto optimal set. I am using ggobi which is freely downloadable and provides a scatterplot matrix and a parallel coordinate plots. This program will run with the xml file that I generate to show values of variables at all points that the user clicks on. The ggobi is freely downloadable from www.ggobi.org

Fiper Version

The code was integrated with version 1.2.0 built on October 29, 2003.

Installation

1. Publish epsmoga.jar file to library. It will then be one of the optimization techniques.

2. Download and install ggobi from www.ggobi.org . After running an optimization, run ggobi. Under file open, select the xml file generated with pareto optimal set for analysis. There are three great views in ggobi for analyzing the pareto optimal set. These are scatterplot, scatterplot matix and parallel coordinates plot. With all three the user should try the Identify option. This option will show all of the coordinate values for a particular selected value. The parallel coordinates plot is vital when the user has more than two objectives for analysis.

Test Problems from Deb

I validated the port by running 5 constrained test problems from Deb's book. The test problems are defined on pages 348-370. These example problems were implemented as Calculations and in some cases as Excel spreadsheets. The example problems are provided in examples.zip.

Example	**# of Design Vars**	**# of Objectives**	**# of Constraints**
BNH	2	2	2
OSY	6	2	6
SRN	2	2	2
TNK	2	2	2
Water	3	5	7

Tuning Parameters

The main tuning parameters that the user needs to set on each formulation are the mutation rate and the epsilon for each objective. The other settings are robust.

- Population Size: Default is 100
- Number of Generations: Default is 1000. This is a steady state genetic algorithm with 2 new designs for each generation. This will result in 100 + 1000*2 = 2,100 evaluations. Note: Deb typically uses 25,000 or 50,000 total evaluations in the test cases listed above.
- Crossover rate: Default is 1.0. The allowed interval is .5 – 1.0.
- Mutation rate: Default is 0.5. The recommended interval is 0 – 1/#dv where #dv is the number of design variables.
- Distribution Index of Crossover. Default is 20. The allowable range is 0.5 – 100.
- Distribution Index of Mutation. Default is 100. The allowable range is 0.5-500.
- Seed. Default is .123. The allowable range is 0.0 – 1.0.
- Output File Base Name
- Penalty base. The default is 10. The recommended value is so that infeasible design always has a higher value then a feasible design.

- Penalty multiplier. The default is 1.0
- Penalty exponent. The default is 2.0

Coupling Documentation for iSIGHT Users

Oleg Golovido and the entire fiper team have done a fantastic job at allowing 3rd party developers to extend the optimization

- JBuilder Debugging is fantastic. This allows the 3rd party developer to step through coupling logic to see what is being returned from calls to fiper application programming interfaces.
- Optimization Formulation is different. In iSight, there is a delta for equality constraints and a delta for inequality constraints. Fiper assumes that these two quantities are zero and cannot be overridden by developer.
- Jar file needs to contain the properly formatted code along with a manifest that is hand generated. The contents and format of the file can be easily determined by looking at the fiper/lib/components/hookejeeves.jar

Bugs

- Lower and Upper bound GUI does not work for optimization techniques in v1.2 for design variables (unless one hits apply after each entry). This is also true for entering lower and upper bounds on constraints.

Suggested Enhancements to Fiper

- Delta for inequality constraints and equality constraints can not be specified. This prevents one from running code outside of fiper on examples provided by author to validate coupling.
- No ability to capture log of coupled organization techniques for diagnostics. For example, this gives capability to get Lagrange multipliers from Grg.
- Need ability to prematurely stop code gracefully when you have achieved enough gain. Need an exception that developer can catch and handle when this happens so they can set best design point.
- Need a defined exception thrown when the simulation code, spreadsheet or calculation aborts.
- Need a mechanism for setting a set of design points in the summary when one calculates a pareto optimal solution. Fiper currently considers only a single point.
- Filters need to be supported for pareto set analysis. I am currently supplying a ggobi analysis but this functionality could be reproduced in fiper. For example, for each pareto point, a weight could be generated for each objective to show its relative importance to the others.

- On GUI there is a Help button. It is not clear how 3rd party developer would add help to it.
- Need tooltips in xml file for each gui attribute that will display when mouse is over GUI component.
- Need a file naming and directory naming convention for developers that want to write a file of data for subsequent analysis and post processing.

Suggested Enhancements to Epsilon MOEA coupling to fiper

- Modify generateReplace to generate more than two designs per generation and allow fiper to evaluate these in parallel.
- Develop post processing graphics to simulate ggobi.
- Write out pareto set every xxx generations instead of only at the end of the entire run. The value of xxx could be user settable. This would allow the user to have a set of designs in case the user decides to prematurely abort. Even better would be to support a stop/abort exception in fiper that could be caught and handled.

Appendix G

Analysis Results

1. DOE Results

Technique:	Latin Hypercube
Number of experiments:	30

Normalized Effects (0-100%)

This table lists the *estimated* relative effects that the various factors had on each response:

Sources	HLVerDspMax	CLIFE
Beam-Draft	-2.8880309382788347	-3.598920073340587
SS ENG EXH TEMP^2	0.6427018558703073	-5.237650306944958
Beam-SS ENG EXH TEMP	0.29849550787444495	2.351064084689636
Wave Height	62.446623052754816	-1.7072969582039548
SS ENG RPM^2	-0.7395997497099356	-4.608648049474885
SS ENG RPM	-0.8388599155727484	-2.0133219458620135
SS ENG MASS FL^2	0.6776274786032248	-0.6238238798722826
Beam	3.481173374043034	11.761648162511312
Beam^2	2.505857107220773	7.188900535677539
Beam-LBP	1.4373471945759349	9.934920669378482
Beam-SS ENG MASS FL	0.574500142591674	-0.1890376680588
SS ENG MASS FL	-0.943741623232769	1.024160844691652
SS ENG SFC	-0.08899001191494972	1.749882228366007
SS ENG PWR AVAIL^2	0.38735635408047464	4.534295508007856
SS ENG EXH TEMP	-0.3506572880410876	0.3063452391585458
Draft^2	2.3329584859665213	0.30289673744417246
Beam-SS ENG BARE WT	0.2770249610679022	5.778494219937501
Beam-SS ENG FRIC FAC	-0.531692981533656	-0.6784131468228056
LBP	-13.132199098843742	16.274475139709647
SS ENG BARE WT	0.0341377588280527	-2.7915714325794143
SS ENG PWR AVAIL	-0.7857367533016233	-1.565128242027612
SS ENG BARE WT^2	-0.2018551269917933	-2.1837828013035367
Draft	0.3177126465104519	-2.270190421775744
Wave Height^2	0.5345829348927597	-3.468930050426585
SS ENG FRIC FAC	-0.7840864580946142	-1.9286672247994543
LBP^2	0.26378283381960577	3.907052936494184
SS ENG SFC^2	-0.6424253693557525	-0.4460637743048006

SS ENG FRIC FAC^2	1.8602429964285003	1.5744177181384966

All Results for the 30 Runs:

```
RunCounter  KG    "AUXILIARY SYSTEMS"     "COMMAND + SURVEILLANCE"
      "HULL STRUCTURE"  "FREE SURF COR (DELGM)" Draft "FULL LOAD DRAFT"
      "FULL LOAD WT"    "ELECTRIC PLANT"  "SS ENG RPM"      ARMAMENT
      Beam  "Ship FUEL SP Volume"   "PROPULSION PLANT"      "Usable
FUEL Weight"      "D & B MARGIN"    "SS ENG MASS FL"  "SS ENG SFC"
      GMT   "SS ENG EXH TEMP" LBP   "SS ENG BARE WT"  "SS ENG PWR
AVAIL"      "OUTFIT + FURNISHINGS"  "SS ENG FRIC FAC"
1     12.44 5195.779296875    593.654602050781  20632.39453125
      0.304800003767014 8.55785172413793  7.71546459197998  45744.59375
      1717.36853027344  909.310344827587  332.349578857422
      31.08338999999999 1.17889130115509  811.886535644531
      5513.77197265625  523.403137207031  5.82584741379311
      0.19571850344828  2.86233353614807  466.8487758620687
      287.7441379310344 30.96670448275864 3556.989    3429.26245117188
      0.98379310344828
2     12.44 4617.6328125      553.961181640625  17995.99609375
      0.304800003767014 8.01102413793103  8.75601387023926
      42137.8515625     1584.9765625      847.2413793103451
      332.349578857422  29.52365    1.17889130115509  1023.65191650391
      5513.77197265625  466.604064941406  5.56526637931035
      0.18531486206897  1.9445708990097   454.6035620689653
      258.32620689655187      30.35350241379312 3584.2456206896554
      3054.18090820313  0.99
3     12.44 5094.2490234375   590.94775390625   19429.044921875
      0.304800003767014 7.84697586206896  7.26959228515625
      44263.8203125     1592.88708496094  828.6206896551726
      332.349578857422  35.31696999999996 1.17889130115509
      826.3818359375    5513.77197265625  500.083862304688
      4.9696525862069   0.17100985517241  6.97415447235107
      436.2357413793102 250.97172413793115      31.78430724137934
      3611.502241379311 3389.3779296875   0.82241379310345
4     12.44 4579.5302734375   552.413635253906  17698.326171875
      0.304800003767014 7.40951379310345  8.44564723968506
      41606.0390625     1556.90502929688  958.9655172413804
      332.349578857422  29.96928999999999 1.17889130115509
      880.315002441406  5513.77197265625  458.228942871094
      5.11855603448276  0.19181713793103  2.2022922039032
      414.80661724137923      252.81034482758633      30.14910172413795
      3638.758862068966 3039.4677734375   0.91551724137931
5     12.44 4826.31591796875  571.1826171875    18132.11328125
      0.304800003767014 8.44848620689655  7.78080224990845
      42423.7421875     1524.45959472656  965.1724137931046
      332.349578857422  34.20286999999997 1.17889130115509
      857.122314453125  5513.77197265625  471.106201171875
      4.89520086206897  0.1697094   5.44892311096191  460.726168965517
      239.94000000000003      29.33149896551726 3666.0154827586216
      3200.59375  0.84724137931034
6     12.44 5309.7373046875   603.590148925781  20161.9375
      0.304800003767014 8.1750724137931   7.13365507125854
      45488.67578125    1695.25024414063  915.5172413793111
      332.349578857422  33.08876999999998 1.17889130115509
```

897.0869140625   5513.77197265625 519.372863769531
5.34191120689656 0.20352123448276 4.82242298126221
439.29704482758603   280.38965517241377   31.17110517241382
3693.272103448277 3460.85717773438 0.97137931034483
7   12.44 4858.86474609375 573.824829101563 19023.232421875
0.304800003767014 7.6282448275862   8.07769775390625
43452.53515625   1557.30456542969 977.586206896553
332.349578857422 33.53440999999997 1.17889130115509
879.285522460938 5513.77197265625 487.307708740234
5.26745948275862 0.17491122068966 5.11851644515991
445.41965172413774   247.29448275862077   29.7403003448276
3720.5287241379324   3231.87182617188 0.94655172413793
8   12.44 4606.98583984375 554.0712890625   17765.841796875
0.304800003767014 8.06570689655172 8.4149923324585
41692.03515625   1564.2265625   865.8620689655177
332.349578857422 30.63774999999999 1.17889130115509
850.094970703125 5513.77197265625 459.583343505859
5.75139568965518 0.18271395172414 2.69808077812195 399.5001
249.13310344827596   31.37550586206899 3747.785344827588
3050.38671875   0.89689655172414
9   12.44 5475.02099609375 616.286499023438 21214.369140625
0.304800003767014 8.61253448275862 6.87179756164551
46853.68359375   1653.31091308594 990.0 332.349578857422
35.53979   1.17889130115509 884.800109863281 5513.77197265625
540.869079589844 5.15578189655173 0.17751213103448
6.32268381118774 457.66486551724114   273.03517241379313
27.49189275862069 3775.041965517243 3628.18017578125
0.82862068965517
10   12.44 4858.38037109375 574.694641113281 18539.29296875
0.304800003767014 7.35483103448276 8.1856050491333   42966.34375
1535.74340820313 940.3448275862079 332.349578857422
34.42568999999997 1.17889130115509 899.530029296875
5513.77197265625 479.651184082031 5.04410431034483
0.18661531724138 6.04006719589233 463.78747241379284
241.7786206896552 29.53589965517243 3802.2985862068986
3238.20776367188 0.81
11   12.44 4614.1650390625   554.0322265625   17830.580078125
0.304800003767014 7.90165862068965 8.30792236328125
41782.87890625   1589.53735351563 816.2068965517242
332.349578857422 29.74647   1.17889130115509 838.37744140625
5513.77197265625 461.013885498047 5.67694396551725
0.17361076551724 2.06761908531189 402.5614034482758
256.4875862068967 31.98870793103451 3829.555206896554
3054.322265625   0.85344827586207
12   12.44 4597.80322265625 552.129211425781 17885.125
0.304800003767014 8.12038965517241 8.23913764953613
41814.25390625   1571.29064941406 921.7241379310353
332.349578857422 29.07801   1.17889130115509 867.603393554688
5513.77197265625 461.507995605469 5.71416982758621
0.1788125862069   1.57782459259033 451.54225862068944
260.164827586207 27.90069413793104 3856.8118275862093
3037.9501953125   0.89068965517241
13   12.44 4712.35009765625 563.598205566406 18290.3203125
0.304800003767014 7.24546551724138 7.72704219818115
42451.1328125   1544.61242675781 927.9310344827595
332.349578857422 32.64312999999998 1.17889130115509
889.961059570313 5513.77197265625 471.537658691406

5.30468534482759 0.17231031034483 4.26348876953125
472.9713827586204 243.6172413793104 30.76230379310347
3884.0684482758647 3137.908203125 0.90931034482759
14 12.44 5345.416015625 607.074768066406 20923.6171875
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46308.76953125 1642.82470703125 841.0344827586209
332.349578857422 34.64850999999997 1.17889130115509
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4.93242672413793 0.19051668275862 5.84754085540771
488.27790000000005 271.196551724138 28.51389620689656
3911.32506896552 3544.49633789063 0.87206896551724
15 12.44 5468.1865234375 616.536926269531 21787.97265625
0.304800003767014 7.73761034482758 7.27793788909912 47480.78125
1675.91943359375 946.5517241379321 332.349578857422
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5513.77197265625 550.744689941406 5.23023362068966
0.20092032413793 6.88289260864258 442.3583482758619
276.71241379310345 29.12709827586208 3938.5816896551755
3636.70141601563 0.92172413793103
16 12.44 4910.14501953125 576.172485351563 19543.515625
0.304800003767014 8.22975517241379 8.43145656585693
44080.4609375 1569.86853027344 884.4827586206902
332.349578857422 32.86594999999998 1.17889130115509
888.273010253906 5513.77197265625 497.1962890625
5.63971810344828 0.18401440689655 4.46784353256226
408.6840103448275 254.64896551724152 27.69629344827587
3965.838310344831 3254.4443359375 0.87827586206897
17 12.44 5214.974609375 595.889038085938 21313.216796875
0.304800003767014 8.28443793103448 7.52596521377563 46547.9375
1691.78125 822.4137931034484 332.349578857422 31.75184999999998
1.17889130115509 906.135986328125 5513.77197265625
536.05419921875 5.60249224137932 0.2074226 3.53749108314514
411.7453137931034 284.0668965517241 29.94470103448278
3993.0949310344863 3449.04052734375 0.92793103448276
18 12.44 5399.9912109375 611.00927734375 22395.779296875
0.304800003767014 7.30014827586207 7.31313848495483 47990.71875
1708.15295410156 934.1379310344837 332.349578857422
33.31158999999997 1.17889130115509 883.443298339844
5513.77197265625 558.775207519531 5.90029913793104
0.18921622758621 5.17909908294678 485.2165965517238
285.90551724137924 28.92269758620691 4020.3515517241417
3592.72436523438 0.85965517241379
19 12.44 5006.13720703125 581.804077148438 20312.916015625
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45096.20703125 1639.78247070313 896.8965517241386
332.349578857422 31.97466999999998 1.17889130115509
889.902404785156 5513.77197265625 513.192321777344
5.19300775862069 0.17621167586207 3.66694474220276
427.05183103448263 267.51931034482766 32.39750931034486
4047.608172413797 3311.62353515625 0.81620689655172
20 12.44 5377.2392578125 606.977172851563 22064.013671875
0.304800003767014 8.66721724137931 7.50102376937866
47608.015625 1726.8486328125 952.7586206896563
332.349578857422 32.42030999999998 1.17889130115509
888.069152832031 5513.77197265625 552.748413085938
5.00687844827586 0.20482168965517 3.69260144233704

423.9905275862068 289.58275862068956 32.60191
4074.8647931034525 3551.27416992188 0.86586206896552
21 12.44 5404.71337890625 611.077880859375 22335.115234375
0.304800003767014 7.79229310344827 7.54861354827881 47947.25
1690.23278808594 834.8275862068967 332.349578857422
33.75722999999997 1.17889130115509 917.923034667969
5513.77197265625 558.090637207031 5.86307327586208
0.19701895862069 5.53142261505127 420.92922413793093
282.2282758620689 28.30949551724139 4102.121413793107
3589.25244140625 0.97758620689655
22 12.44 4726.52392578125 562.48828125 18320.318359375
0.304800003767014 7.46419655172414 8.70150279998779
42541.4140625 1579.00268554688 971.3793103448288
332.349578857422 30.19210999999999 1.17889130115509
903.219848632813 5513.77197265625 472.959381103516
5.41636293103449 0.20222077931034 2.51600575447083
433.17443793103433 262.0034482758622 28.10509482758621
4129.378034482763 3136.05615234375 0.8348275862069
23 12.44 5593.583984375 624.278015136719 22948.875
0.304800003767014 7.6829275862069 6.66272163391113
48955.55859375 1741.69189453125 810.0 332.349578857422
33.98004999999997 1.17889130115509 916.317321777344
5513.77197265625 573.969482421875 5.49081465517242
0.18011304137931 5.83670425415039 482.15529310344795
293.26000000000005 28.71829689655174 4156.634655172418
3715.99658203125 0.9651724137931
24 12.44 4992.87744140625 579.444702148438 20388.908203125
0.304800003767014 8.50316896551724 8.61931896209717
45090.5703125 1668.26867675781 872.0689655172418
332.349578857422 30.41492999999999 1.17889130115509
811.966918945313 5513.77197265625 513.103515625
5.78862155172415 0.20612214482759 2.51228141784668
479.0939896551721 278.5510344827586 30.5579031034483
4183.891275862074 3295.15356445313 0.93413793103448
25 12.44 5040.01708984375 585.237609863281 20451.658203125
0.304800003767014 7.1361 7.62921762466431 45393.1171875
1632.04479980469 890.6896551724144 332.349578857422
31.52902999999998 1.17889130115509 973.5087890625
5513.77197265625 517.868041992188 5.52804051724138
0.19311759310345 3.50541400909424 448.4809551724136
274.8737931034483 27.08309137931035 4211.147896551729
3351.93603515625 0.95896551724138
26 12.44 4823.13037109375 569.448364257813 19208.1171875
0.304800003767014 7.57356206896552 8.16314506530762
43633.26953125 1609.40808105469 878.275862068966
332.349578857422 30.86056999999999 1.17889130115509
891.911926269531 5513.77197265625 490.153930664063 4.857975
0.18791577241379 2.91711950302124 405.6227068965517
263.84206896551734 32.19310862068968 4238.404517241384
3200.2509765625 0.88448275862069
27 12.44 4412.76318359375 540.838256835938 16932.974609375
0.304800003767014 7.19078275862069 8.64876461029053
40479.04296875 1500.22277832031 983.7931034482772
332.349578857422 29.30083 1.17889130115509 880.380676269531
5513.77197265625 440.481018066406 5.45358879310345
0.19961986896552 1.61885702610016 417.8679206896551
245.4558620689656 26.67429 4265.66113793104 2930.53393554688

0.95275862068966

28 12.44 4988.4150390625 581.801513671875 19752.966796875
0.304800003767014 7.51887931034483 7.18027639389038
44466.19140625 1637.65747070313 853.4482758620693
332.349578857422 32.19748999999998 1.17889130115509
846.799133300781 5513.77197265625 503.270751953125 5.937525
0.18141349655172 4.03816652297974 430.1131344827585
265.6806896551725 31.57990655172416 4292.917758620695
3314.42919921875 0.90310344827586
29 12.44 5261.47802734375 599.052795410156 21718.93359375
0.304800003767014 7.95634137931034 7.44995450973511
46979.01953125 1690.06127929688 903.1034482758628
332.349578857422 31.30620999999999 1.17889130115509
842.680114746094 5513.77197265625 542.842956542969
5.37913706896552 0.19441804827586 3.34599232673645
476.03268620689624 291.4213793103447 26.87869068965517
4320.174379310351 3483.12646484375 0.84103448275862
30 12.44 5347.71728515625 606.949462890625 20913.009765625
0.304800003767014 8.7219 7.75766706466675 46456.7734375
1626.72863769531 859.6551724137935 332.349578857422
34.87132999999996 1.17889130115509 1046.30786132813
5513.77197265625 534.618530273438 5.0813301724138
0.1983194137931 5.69662570953369 469.91007931034454
269.3579310344828 27.28749206896552 4347.4310000000005
3540.59130859375 0.94034482758621

2. Optimization Summary

```
Optimization technique: "Hooke-Jeeves"
  Max Iterations                                = 10
  Max Evaluations                               = 100
  Relative Step Size                            = 0.5
  Step Size Reduction Factor                    = 0.5
  Termination Step Size                         = 1.0E-6
  Penalty Base                                  = 0.0
  Penalty Multiplier                            = 1000.0
  Penalty Exponent                              = 2

Starting design point:
  SS ENG FRIC FAC                               = 0.9 [0.75...0.99]
  SS ENG RPM                                    = 900.0 [800.0...999.0]
  SS ENG MASS FL                                = 5.39775 [4.0...6.0]
  SS ENG PWR AVAIL                              = 3952.21
[3500.0...4500.0]
  SS ENG SFC                                    = 0.188566 [0.1...0.3]
  SS ENG EXH TEMP                               = 443.889 [400.0...500.0]
  SS ENG BARE WT                                = 29.6381 [25.0...50.0]
  LBP                                           = 266.6 [230.0...300.0]
  Wave Height                                   = 4.0 [3.0...5.0]

OPTIMIZATION RUN completed on Thu Jan 29 19:23:14 EST 2004

  Total design evaluations                      = 101
  Number of feasible designs                    = 97

Optimum design point:
  SS ENG FRIC FAC                               = 0.99
  SS ENG RPM                                    = 999.0
  SS ENG MASS FL                                = 4.0
  SS ENG PWR AVAIL                              = 4500.0
  SS ENG SFC                                    = 0.1
  SS ENG EXH TEMP                               = 400.0
  SS ENG BARE WT                                = 25.0
  LBP                                           = 230.0
  Wave Height                                   = 3.0
  VRVerDspMax                                   = 1.14
  HLVerDspMax                                   = 1.82
  MaxRoll                                       = 3.8
  MaxPitch                                      = 0.67
  HLVerVelMax                                   = 1.06
  VRVerVelMax                                   = 0.81
  CLIFE                                         = 54275.22036581
  Objective Function                            = 1.4495044073162

Calculated constraint values at the optimum:
  VRVerDspMax Upper Bound                       = -0.9600000000000002
  HLVerDspMax Upper Bound                       = -0.78
  MaxRoll Upper Bound                           = -1.2999999999999998
  MaxPitch Upper Bound                          = -2.33
  HLVerVelMax Upper Bound                       = -1.04
  VRVerVelMax Upper Bound                       = -1.29
```

3. Monte Carlo Summary

All Monte Carlo results are provided in the main report.