Project Final Report and Project Results Summary

Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization

TASK ORDER AGREEMENT #2022-328-001

NSRP MISSION

- Manage and focus national shipbuilding and ship repair research and development funding on technologies that will reduce the cost of ships to the U.S. Navy, other national security customers and the commercial sector, and develop and leverage best commercial and naval practices to improve the efficiency of the U.S. shipbuilding and ship repair industry.
- Provide a collaborative framework to improve shipbuilding-related technical and business processes.

INTRODUCTION

This project's goals were to implement into design and production planning software the accomplishments of NSRP RA Project 2017-443 and develop a new generation of ship structural design optimization tools for early-stage design that will result in:

- Assurance that structural design criteria are met while improving structural producibility and reducing design-build cycle time.
- Improving structural design and service-life assessment to reduce service-life corrosion, heavy weather damage, and structural fatigue cracking while mitigating excessive structural repair and maintenance costs and increasing ship availability.
- A comprehensive structural design space exploration capability for U.S. Navy and shipbuilder early-stage ship design processes resulting in robust structures with reduced Total Ownership Costs (TOC) of ships for the U.S. Navy and U.S. Coast Guard.

This NSRP RA Project addresses the problems of inadequate structural performance in-service, and of unsustainable structural maintenance costs and lost ship availability.

National Shipbuilding Research Program

FINAL REPORT AND PROJECT RESULTS SUMMARY

Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization

TASK ORDER AGREEMENT #2022-328-001

MAESTRO Marine LLC

Austal USA

NSWC Carderock Division, Code 65

U.S. Coast Guard, Surface Forces Logistics Center

American Bureau of Shipping

Robert Keane – Ship Design USA, Inc.

P. Jaquith & Associates

SPAR Associates, Inc.

January 29, 2024

TABLE OF CONTENTS

INTRODUCTION 2

FINAL REPORT 5

PROJECT PROBLEM STATEMENT AND OBJECTIVES 9

PROJECT WORK SCOPE AND TASKING 12

PROJECT TASK 1 REVIEW 16

PROJECT TASK 2 REVIEW 17

PROJECT TASK 3 REVIEW 23

PROJECT TASK 4 REVIEW 24

PROJECT RETURN ON INVESTMENT (ROI) 44

PROJECT FINAL REPORT SUMMARY 47

Appendix A. PROJECT RESULTS SUMMARY 50

Appendix B. RHINO-MAESTRO PLUGIN FUNCTIONALITY 59

Appendix C. WORK CONTENT & COST OPTIMIZATION METRICS 66

Appendix D. TASK 3 EARLY-STAGE DESIGN OPTIMIZATION APPROACH 68

Appendix E. RETURN ON INVESTMENT (ROI) DETAILS 73

FINAL REPORT

The NSRP Research Announcement Project being reported on is titled: "Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization". The project's synopsis is to develop a new generation of ship structural design optimization tools for early-stage design that will result in:

- Assurance that structural design criteria are met while improving structural producibility and reducing design-build cycle time.
- Improving structural design and service-life assessment to reduce service-life corrosion, heavy weather damage, and structural fatigue cracking while mitigating excessive structural repair and maintenance costs and increasing ship availability.
- Providing comprehensive structural design space exploration capability for U.S. Navy and shipbuilder early-stage ship design processes resulting in robust structures with reduced Total Ownership Costs (TOC) of ships for the U.S. Navy and U.S. Coast Guard.

This Final Report summarizes the work completed through the two-year project.

PROJECT TEAM

The Project Team consists of MAESTRO Marine as the project lead, with team members: Austal USA; NSWC Carderock Division, Code 65; U.S. Coast Guard, Surface Forces Logistics Center (SFLC); American Bureau of Shipping (ABS); Robert Keane – Ship Design USA, Inc.; P. Jaquith & Associates; and SPAR Associates, Inc. The Project Team brings a full spectrum of stakeholder interests, backgrounds and expertise to the project.

- Austal USA is a major U.S. shipbuilder with a significant design and construction portfolio. Austal brings the real-world experience and knowledge of shipbuilder design and construction to the project.
- NSWC Carderock Division, Code 65 supports Navy ship structures including development of tools for CREATE (Computational Research & Engineering Acquisition Tools & Environments) Ships, Rapid Ship Design Environment (RSDE) and Integrated Structural Design Environment (ISDE).
- U.S. Coast Guard, Surface Forces Logistics Center (SFLC) provides structural engineering design and analysis services to the U.S. Coast Guard fleet. SFLC has used the MAESTRO tools for in-service engineering and has sponsored one of the toolsets being used under the NSRP project to establish a structural digital twin capability.
- American Bureau of Shipping (ABS) brings the commitment to safety and service to ship design standards and in-service safety of operations to the team. ABS brings specialized technical depth and expertise to support the project's objectives for improved design processes and more robust in-service structural assessment capabilities.
- Robert Keane – Ship Design USA, Inc. brings the long career of Bob Keane to the team with extensive knowledge of Navy design practices and current initiatives to improve the design, construction and in-service performance of current and future U.S. Navy ships.

- P. Jaquith & Associates brings the career experience and knowledge in ship design, production engineering, planning, and production including lean design of Pete Jaquith to the team.
- SPAR Associates, Inc. brings fifty years' experience in ship new construction and ship repair operations including costing models, resource and budget planning, construction performance analysis, and methods for evaluating work content of ship designs.

Collectively, this NSRP team offers a full spectrum of shipbuilder, U.S. Navy, U.S. Coast Guard, Ship Classification, and industry leading ship design and construction personnel and expertise to support the successful accomplishment of the NSRP RA project objectives.

The technical team is comprised of experienced and diverse personnel, with collaborative involvement on many high profile NSRP projects in the past. MAESTRO Marine leads the development of the MAESTRO software with a core staff that has been working together for more than twenty-five years. Longstanding working relationships have been developed between MAESTRO Marine and the key team members of the project.

Austal USA, as the major shipbuilder team member, occupies an important role in representing the U.S. shipbuilding community on the team. The ships that Austal designs and builds are especially challenging from a structural design, construction and in-service performance perspective. Austal will bring unique experience and expertise to the project in the design, production and fielding of complex warships.

The NSWC and SFLC both bring valuable organizational experience, responsibilities and personnel to the team. Both organizations serve major fleets of vessels with diverse and demanding service-life requirements. The team member representatives are closely aligned with their organization's structural design methods and evolution.

ABS, as a major ship classification society, brings a broad and deep scope of experience and technical knowledge to the team in both ship design requirements and methods and in-service lifecycle maintenance and safety processes.

Bob Keane, Pete Jaquith and SPAR Associates bring knowledge of design processes, lean design and production, cost estimating, and shipbuilder implementation capabilities to the team. Collectively, the Project Team represents major stakeholders and directly related expertise for the accomplishment of project objectives to develop and field ship structural design software tools to facilitate reduction of Total Ownership Costs (TOC) of the U.S. Navy and U.S. Coast Guard fleets.

PROJECT OVERVIEW AND SCHEDULE

This project's plans were to define requirements for improvements in ship structural design and assessment software and develop enhanced software tools based on these requirements as described in the following:

1. Investigate that the root cause of the unsustainable surface ship in-service structural maintenance costs are the inadequate methods of designing ship structures in the early-stage ship design process. The state of practice today is largely unchanged from the early-stage structural design processes developed decades ago and still in use for the ships in today's fleet, which are currently experiencing high levels of in-service structural damage, fatigue cracking, and related repair costs and unavailability of ships.
2. Leverage a mature software system that is already in use within the U.S. Navy's ship design and shipbuilder community, within the U.S. Navy's internal ship design groups at NAVSEA and NSWC Carderock Division, and within the U.S. Coast Guard. This software system is the MAESTRO ship structural design and optimization code.
3. Develop new software within the MAESTRO system to provide enhanced early-stage ship structural design for producibility and life-cycle performance, and improved in-service ship structural integrity assessment tools.
4. Demonstrate the improvements and new developments using worked example structural design, optimization and in-service assessments.
5. Publish this Final Report to document results of the project and facilitate technology transfer of the enhanced tools to industry and government through technical publications, webinars, and the distribution of commercial software products.

Project Schedule and Technical Reviews. The project is organized into four six-month phases as shown below. Each phase includes a software development cycle addressing the four tasks of the project Statement of Work. As finalized at the Project Kickoff Meeting held on-line on December 08, 2021, the following Technical Project Review Meetings have been completed:

Technical/Design Review	Estimated date	Purpose	Location
Project Kickoff	Nov/Dec 2021	Initial team meeting, project kickoff	Virtual
Phase I Q1 Technical Review	February 2022	Technical review to date	Virtual
Development Phase 1 Review, Phase 2 Kickoff	May 2022	Technical review of Phase 1 software developments, planning for Phase 2	Virtual
Phase 2 Q1 Technical Review	August 2022	Technical review to date	Virtual
Development Phase 2 Review, Phase 3 Kickoff	November 2022	Technical review of Phase 2 software developments, planning for Phase 3	Virtual
Phase 3 Q1 Technical Review	February 2023	Technical review to date	Virtual
Development Phase 3 Review, Phase 4 Kickoff	May 2023	Technical review of Phase 3 software developments, planning for final Phase 4	Virtual
Phase 4 Q1 Technical Review	August 2023	Technical review to date	Virtual
Final Project Technical Review	January 2024	Final Program Review	Virtual

PROJECT PROBLEM STATEMENT AND OBJECTIVES

Problem Statement. Studies sponsored by the Chief of Naval Operations Assessment Division (N81) in recent years document the "exponential" rate of growth in U.S. Navy surface ship maintenance and repair costs across multiple Ships Work Breakdown Structure (SWBS) groups. A 2015 study performed by the Acquisition and Technology Policy Center of the RAND National Defense Research Institute states in part:

> **"**Since 1998, however, the expenditures per ship have gone up steadily, with an exponential function being the best fit for describing cost per ship through this period…Even absent sequestration, continued growth in per-ship maintenance cost is likely unsustainable, at least at the rate seen in the last 15 years. At the rate seen, maintenance would either become a larger component of the O&M budget or come at the expense of new construction or modernization or require deferral.**"**
>
> *"This research was sponsored by the Assessment Division (N81) of the Office of the Chief of Naval Operations and conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, 2015"*

This cost growth trend in surface ship maintenance has been studied at a SWBS level and reported in additional studies, see Figure 1 on the following page. Figure 1 and its related report, developed by RAND in 2017, document that ***ship structural maintenance and repair costs lead the major SWBS categories with structural repairs and maintenance exceeding $3 Billion during the period 2003-2015.*** The multiple reports on this subject describe this cost as not being sustainable without major impact to other maintenance and/or new ship construction programs.

In addition, the U.S. Government Accountability Office (GAO) reported in its March 2020 GAO-20-2 Report, "Increasing Focus on Sustainment Early in the Acquisition Process Could Save Billions", that although the Navy has received significant resources, *the Navy has nevertheless struggled to build and maintain ships to its desired standards within estimated cost and schedule. For instance, the GAO previously found that in the seven-year period from 2012-2018, the Navy experienced over 27,000 days of unexpected maintenance delays across all of its ship classes—delays that increase sustainment costs and degrade readiness.*

This NSRP RA Project addresses the problems of inadequate structural performance in-service, and of unsustainable structural maintenance costs at two levels which define the project's general objectives:

Project Objective 1: Enhanced early-stage ship structural design for producibility. A root cause of the unsustainable surface ship in-service structural maintenance costs are the inadequate methods of designing ship structures in the early-stage ship design process. The state of practice today is largely unchanged from the early-stage structural design processes developed decades ago and still in use for the ships in today's fleet, which are currently experiencing high levels of damage, fatigue cracking, and related repair costs. As one shipyard stated "…the differentiator here in using this tool is the very early application of direct analysis into the structural design. Current practice is that nearly all the ship structure is defined before direct analysis is used as a check and then non-optimal solutions are incorporated to fix 'hot-spots'."

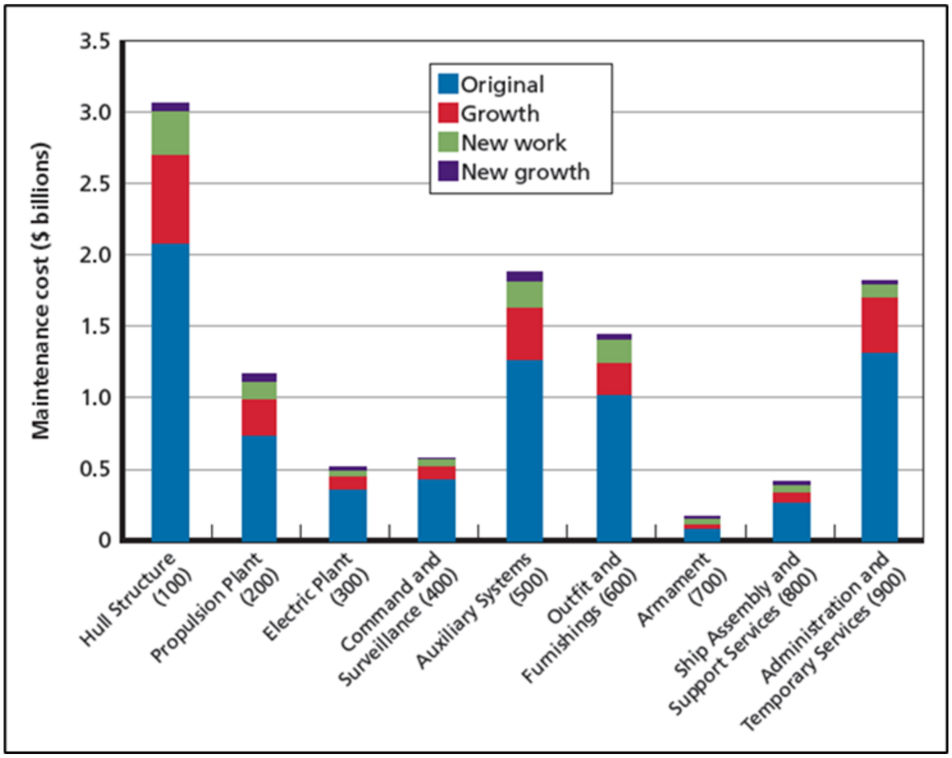


Figure 1: U.S. Navy Surface Ship Depot Maintenance Costs by ESWBS, 2003-2015

[2017 RAND Report 1187]

This NSRP RA Project will bring a significantly higher-fidelity physics-based structural design and optimization method into practical use during early-stage ship design. This objective builds directly on work that has been completed under RA 2017-443. This capability moves beyond traditional early-stage rule-based, one-dimensional structural design tools and methods to utilize 3D finite element methods combined with advanced capabilities to automate structural design space exploration. These new tools will result in more efficient, more producible, and more robust structures that are also compatible with the design constraints of the overall ship design.

The U.S. Navy's NSWC Carderock Division (NSWCCD), Code 65 was a member of the RA 2017-443 team, and NSWCCD has had an opportunity to participate in and comment on the proposed implementation. There has been serious interest expressed in the potential for the proposed tools and structural design optimization (and design space exploration) technology to contribute to the Navy's current early-stage ship design methods that are using tools such as the CREATE (Computational Research & Engineering Acquisition Tools & Environments) Ships, Rapid Ship Design Environment (RSDE) and Integrated Structural Design Environment (ISDE). Project Objective 1 addresses the early-stage design "root cause" of increased shipbuilding work content, inadequate structural performance during service life, and the resulting unnecessary maintenance and repair costs and lost ship availability time.

Project Objective 2. Improved in-service ship structural integrity assessment. U.S. Navy and U.S. Coast Guard ships are required to operate over long and often extended service lives with associated high structural damage and fatigue cracking, which have been documented as causing operational availability and maintenance cost issues. This NSRP RA Project's second key objective is to extend and implement a systematic method and toolset for: 1) tracking the structural condition and damage of Navy and Coast Guard ships; and 2) efficiently and accurately using in-service condition and damage data to assess the structural integrity of the ships, and to develop cost-effective repair and maintenance plans.

During the completed NSRP 2017-443 Project, the U.S. Coast Guard participated in the project and allowed the use of a ship structural corrosion database tool for which the Coast Guard had sponsored the development of a prototype version in recent years. The Coast Guard became an informal member of the NSRP 2017-443 project and is now also a team member of the current NSRP RA Project.

The corrosion or structural condition database tool utilizes an efficient means to build databases of ship structural corrosion, damage, and fatigue conditions based on in-service surveys and reports. These condition databases are also seamlessly interfaced with the MAESTRO structural toolset and its finite element models of ship structures, which enables efficient and high-fidelity structural integrity assessment. This structural condition database toolset includes capabilities that enable reliability-based forward projections of ship structural adequacy based on in-service corrosion and damage data experienced to date. These tools would also streamline the structural repair and maintenance work processes performed by shipbuilders in support of Navy and Coast Guard ships.

PROJECT WORK SCOPE AND TASKING

The technical approach for the Project takes the baseline, existing MAESTRO system including enhancements for reducing work content, improving structural producibility, saving structural fabrication cost, and improving the structural performance of the ship, and builds improvements to address the two key Project Objectives: 1) Enhanced early-stage ship structural design for producibility; and, 2) Improved in-service ship structural integrity assessment. The project uses four tasks to extend the early-stage ship structural design, engineering, and optimization (design space exploration) tools. Each of these tasks will be addressed and worked on throughout the two-year project using an Agile development approach.

Task 1. MAESTRO Integration with Rhino. Develop a MAESTRO modeling plugin to the Rhino CAD environment to aid in rapid structural design definition and rapid design iteration. Develop a universal Rhino-based modeling and finite element meshing interface to MAESTRO to reduce early-stage design start time and to facilitate generating design alternatives for analysis during early-stage ship design. Task 1 will reduce the time required to initialize and modify a full ship structural finite element model in early-stage design.

Task 2. Improve the Handling of Cost Metrics. Structural optimization with least work content as an objective function requires extending the existing producibility, work content, and cost metrics and tools. Task 2 implements enhanced software for use by shipyard production engineers to input data that provides higher fidelity work content metrics for structural fabrication. This data will be used within the structural optimization analyses to achieve more complete and effective optimization of alternative structural designs reflecting reduced work content and cost to manufacture. At the start of the project during the initial quarter of Phase 1, a report will be generated under Task 2 on the equivalence of MAESTRO to NASTRAN and ANSYS as an analysis tool for ABS and NAVSEA.

Task 3. Optimize Structure for Reliability and Producibility as Early in Design as Possible. Develop a "Least Work Content" structural design algorithm for implementation in the Navy's ship synthesis model ASSET (Advanced Ship and Submarine Evaluation Tool), and implement an interface of the RA project tools with U.S. Navy early-stage design tools such as RSDE and ISDE via the Navy's LEAPS (Leading Edge Architecture for Prototyping Systems) early-stage design product model. The Task 3 results will provide early-stage structural optimization based on reduced work content while ensuring that structural design criteria are met. These developments provide an alternative to the current least weight methodologies.

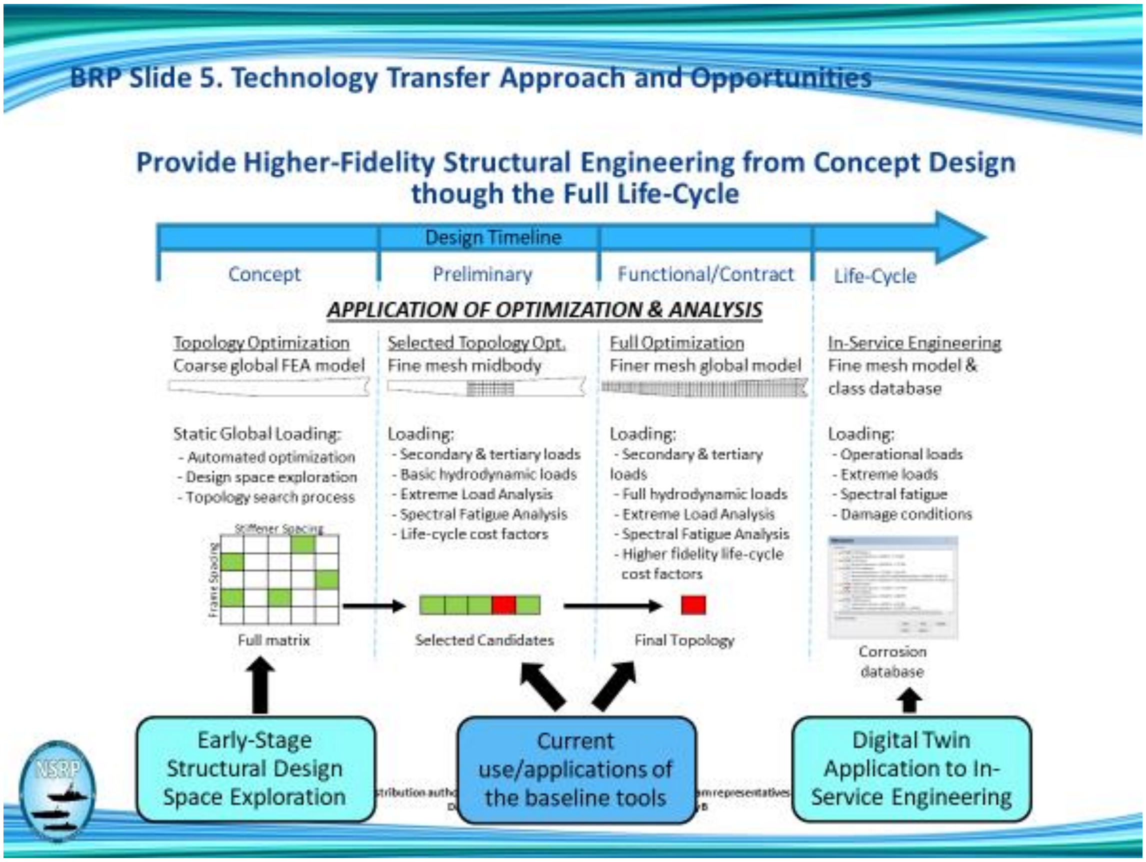
Task 4. Implement a Structural Digital Twin Application. Task 4 continues the development of the structural corrosion/condition database and structural integrity and fatigue life assessment tools from RA 2017-443. These tools use a Rhino plugin-based component that is interfaced with MAESTRO. Enhanced methods for importing in-service structural survey data into the database will be developed, as will additional analysis methods for assessing the condition of the structure. Sample data will be used to demonstrate implementation for U.S. Navy and U.S. Coast Guard ships.

Project Metrics. A set of metrics were developed under the project Statement of Work (SOW), see Table 1 below. These metrics are associated with each of the four tasks of the SOW and will be monitored and assessed in each of the four Phase Completion Technical Reports.

Table 1: Project Metrics

Metric	"As-Is" Baseline	Project Goal	Delta	% Change (+/-)	Tracking & Reporting Plan
Task 1 Metrics - Improve early-stage finite element modeling time for full ship models	60 Days	30 Days	30 Days	-50%	Use a representative ship design with actual modeling times assessed using "before" versus "after" modeling tools. Monitor and report with each Phase completion.
Task 2 Metrics - Provide more accurate and faster input for structural work content metrics	Limited input interfaces exist	Develop an effective set of interfaces	Significant improvement	-50% in time required; +50% in accuracy	Report for each Phase as process improvements are implemented using example inputs.
Task 3 Metrics – Complete and test the least work content algorithm; assess interface plans for RA tools with US Navy tools	No least work content algorithm exists; no interface plans for RA tools exist	Successful development and test of least work content algorithm; effective interface plans developed	New tools available for US Navy use within Navy ship design environment	+100%	Evaluate at completion of each Phase, including: • Global structural weight • Hull girder properties • Structural VCG • Structural performance metrics, e.g. stresses and limit states • Number of unique plate/stiffener combinations • Number of unique design cluster configurations • MAESTRO-based structural work content metrics
Task 4 Metrics – Digital Twin provides in-service databasing, and interface for structural integrity assessments.	A limited functionality prototype tool exists at the start of the project	Improve and demonstrate enhanced digital twin functionality	Significant improvements in databasing capabilities, data analysis and structural assessment tools	+50%	Evaluate at completion of each Phase, including: • Structural survey databasing tools • Statistical analysis of survey data • Structural integrity assessment of in-service conditions
Technology Readiness Level	TRL 7-8; Prototype demonstrated and system qualified	TRL 8-9; System qualified; proven through mission operations			The metrics cited above and feedback from the shipbuilder users/participants will be used to assess TRL progress.

Overview of Project Technology Transfer Approach. In the graphic below the development focus of this NSRP RA project is indicated by the two light-blue boxes at the bottom of the graphic. These two boxes indicate a focus on: 1) Early-stage Structural Design Space Exploration during the concept design process; and 2) a structural digital twin application to enhance in-service structural engineering during the in-service years of a ship's life-cycle. The project's SOW supports this expanded use of 3D finite element analysis tools, work content or lean design-based optimization, and higher fidelity analysis and design methods during early-stage design, and during the through-life engineering support for the ships in the fleet. As indicated below, to date the use of 3D finite element-based tools for ship design has been largely restricted to supporting the preliminary and contract design phases of ship design. The objectives and tasking of this RA project are intended to deliver enhanced tools that can result in the design of more robust ship structures that can better withstand the demands of the operational life-cycle and mitigate the high structural maintenance and repair costs being experienced by today's ships.



BRP Slide 5. Technology Transfer Approach and Opportunities

Provide Higher-Fidelity Structural Engineering from Concept Design though the Full Life-Cycle

Design Timeline

Concept | Preliminary | Functional/Contract | Life-Cycle

APPLICATION OF OPTIMIZATION & ANALYSIS

Concept:
Topology Optimization
Coarse global FEA model

Static Global Loading:
- Automated optimization
- Design space exploration
- Topology search process

Full matrix

Preliminary:
Selected Topology Opt.
Fine mesh midbody

Loading:
- Secondary & tertiary loads
- Basic hydrodynamic loads
- Extreme Load Analysis
- Spectral Fatigue Analysis
- Life-cycle cost factors

Selected Candidates

Functional/Contract:
Full Optimization
Finer mesh global model

Loading:
- Secondary & tertiary loads
- Full hydrodynamic loads
- Extreme Load Analysis
- Spectral Fatigue Analysis
- Higher fidelity life-cycle cost factors

Final Topology

Life-Cycle:
In-Service Engineering
Fine mesh model & class database

Loading:
- Operational loads
- Extreme loads
- Spectral fatigue
- Damage conditions

Corrosion database

Early-Stage Structural Design Space Exploration

Current use/applications of the baseline tools

Digital Twin Application to In-Service Engineering

Status of Milestone Deliverables.

The status of Milestones completed through Quarter 8 is shown in the following Table. All Q8 Milestones have been completed and submitted. The project has had positive progress through its completion.

Phase	Milestone	Deliverable Title	Due Date (DACA)	Due Date (Actual)	Percent Completed Through Q8	Cumulative Percent Completed
1	01	Project Management Plan	10	12/10/2021	100%	100%
1	02a[3]	Kick-off Meeting Presentation	10	12/10/2021	100%	100%
1	02b[3]	Kick-off Meeting Minutes	10	12/10/2021	100%	100%
1	03	Software Development Plan	30	12/30/2021	100%	100%
1	04	Quarterly Technical Review Minutes 1	90	2/28/2022	100%	100%
1	05	Quarterly Report 1[4]		2/19/2022	100%	100%
1	06	Phase 1 Technical Report	180	5/29/2022	100%	100%
1	07	Phase 1 Presentation	180	5/29/2022	100%	100%
1	08	Quarterly Report 2		5/19/2022	100%	100%
1	09	Quarterly Technical Review Minutes 2	180	5/29/2022	100%	100%
2	10	Quarterly Report 3		8/19/2022	100%	100%
2	11	Quarterly Technical Review Minutes 3	270	8/27/2022	100%	100%
2	12	Phase 2 Techncial Report	365	11/30/2022	100%	100%
2	13	Phase 2 Presentation	365	11/30/2022	100%	100%
2	14	Tech Transfer & Implementation Plan Updat	365	11/30/2022	100%	100%
2	15	Quarterly Report 4		12/20/2022	100%	100%
2	16	Quarterly Technical Review Minutes 4	365	11/30/2022	100%	100%
3	17	Quarterly Report 5		3/20/2023	100%	100%
3	18	Quarterly Technical Review Minutes 5	455	2/28/2023	100%	100%
3	19	Phase 3 Techncial Report	545	5/29/2023	100%	100%
3	20	Phase 3 Presentation	545	5/29/2023	100%	100%
3	21	Quarterly Report 6		6/20/2022	100%	100%
3	22	Quarterly Technical Review Minutes 6	545	5/29/2023	100%	100%
4	23	Quarterly Report 7		9/20/2023	100%	100%
4	24	Quarterly Technical Review Minutes 7	635	8/27/2023	100%	100%
4	25	Phase 4/Final Presentation	730	1/29/2024	100%	100%
4	26	Quarterly Report 8		1/29/2024	100%	100%
4	27	Final Report and Project Results Summary	730	1/29/2024	100%	100%

PROJECT TASK 1 REVIEW

Statement of Work: Task 1. MAESTRO Integration with Rhino. Develop a MAESTRO modeling plugin to the Rhino CAD environment to aid in rapid structural design definition and rapid design iteration. Develop a universal Rhino-based modeling and finite element meshing interface to MAESTRO to reduce early-stage design start time and to facilitate generating design alternatives for analysis during early-stage ship design. Task 1 will reduce the time required to initialize and modify a full ship structural finite element model in early-stage design.

Work Completed for Task 1. The following major developments were completed on the Rhino plugin for MAESTRO in support of Task 1:

- The MAESTRO finite element model can be imported into Rhino3D, and the Rhino mesh model can be brought into MAESTRO. These capabilities support the MAESTRO finite element model's Topology, MAESTRO Groups, MAESTRO Loads and querying element and nodes in Rhino. Capabilities were developed that support:
    - Model persistence in Rhino 3dm and MAESTRO XML formats
    - Creating Frame Systems
    - Creating Stiffener Layout Systems
    - Creating Strake Properties which allow regions to be assigned different structural scantlings. Structure is created by associating a strake property with one or more model surfaces.
    - Creating Parametric Mesh Generation so updates in frame system (frame spacing, stiffener spacing, bulkhead locations, etc.) will automatically update the mesh in early-stage design.
- MAESTRO FE model materials and properties can be created in Rhino.
- Properties can be assigned to elements in the Rhino mesh for import into MAESTRO.
- Corrosion groups and corrosion details can be assigned in Rhino for import into MAESTRO.
- These developments represent significant progress toward completion of a working and distributable MAESTRO/Rhino3D Two-way Interface software product as a "Rhino Plugin", which is the primary objective of Task 1 of the RA project.
- It is also noted that members of the NSRP Project Team (MAESTRO Marine, Bob Keane, Pete Jaquith and Spar Associates) are now engaged with the Navy's DDGX Design Team performing MAESTRO based structural finite element modeling, analysis and optimization of the early-stage design with the application of the tools developed under the NSRP RA 21-11 Project to the Concept Design Phase of DDGX. The DDGX Design Team is developing ship geometry in or compatible with the Rhino environment, which facilitates application of capabilities being developed under the NSRP RA Project directly to the DDGX early-stage design. This enables rapid and efficient use of 3D finite element analysis to support the ship's concept design.
- Additional demonstrations of MAESTRO capabilities were conducted for the team to provide familiarization with the functionality of the software.

Task 1 Metrics Assessment. The metrics for Task 1 are to assess the time or manhours to develop a certain finite element model of a structure based on typical input data such as a surface model of the hull, drawings of the general arrangement, and drawings of typical structural sections. Phase 4 of the project included implementation of a working version of the MAESTRO/Rhino3D Two-way Interface software. These implemented capabilities enabled development of a MAESTRO model in the Rhino3D environment, as planned. The finite element mesh development, structural property assignments, and export/transfer to MAESTRO for analysis have been successfully tested and have shown savings in finite element modeling time on the order of the 50% reduction set in the Task 1 metrics.

PROJECT TASK 2 REVIEW

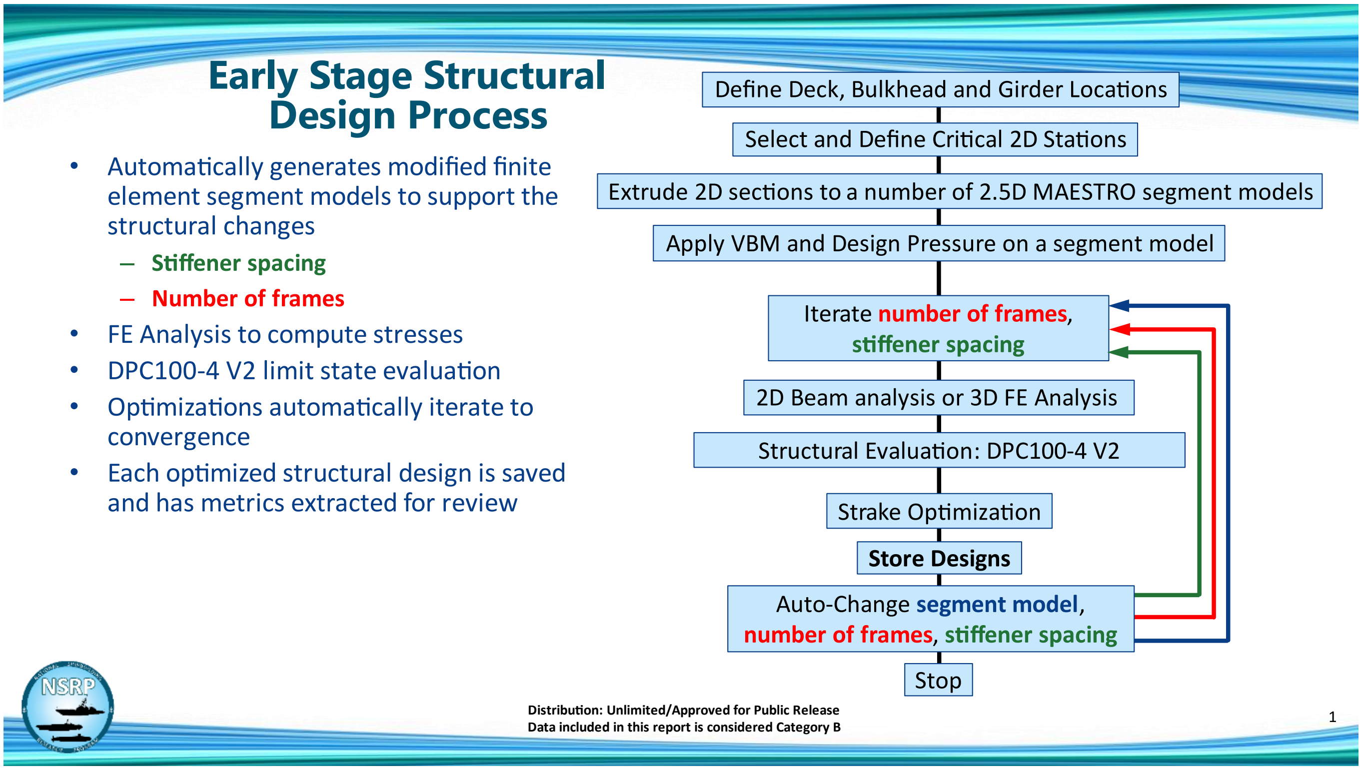
Statement of Work: Task 2. Improve the Handling of Cost Metrics. Structural optimization with least work content as an objective function requires extending the existing producibility, work content, and cost metrics and tools. Task 2 implements enhanced software for use by shipyard production engineers to input data that provides higher fidelity work content metrics for structural fabrication. This data will be used within the structural optimization analyses to achieve more complete and effective optimization of alternative structural designs reflecting reduced work content and cost to manufacture. At the start of the project during the initial quarter of Phase 1, a report will be generated under Task 2 on the equivalence of MAESTRO to NASTRAN and ANSYS as an analysis tool for ABS and NAVSEA.

Work Completed for Task 2. The following were completed in support of Task 2:

- A MAESTRO Interface with SPAR’s Work Content/Cost Models was further developed and tested during Phase 4. This interface groups the ship’s structural model defined in MAESTRO into data output from MAESTRO that transfers structural and ship design parameters to the SPAR work content/cost model. This interface has been developed and tested successfully.
- The structural input from MAESTRO enables the SPAR work content/cost model to generate an updated ship concept model that flows from the structural definition to other major SWBS groups for the ship concept being developed (e.g., frigate).
    - The SPAR work content/cost model processes the updated concept design through a set of mature cost and work content cost estimating relationships to generate a substantial work content estimate for the concept design, e.g., labor hours and materials content and costs. SPAR’s cost models provide a relational database of ship characteristics and work content. The models are organized by ship type and size (e.g., frigate versus tanker). The models include SWBS level cost-estimating relationships (CERs).
- These models accept input from a structural model such as MAESTRO’s along with key ship characteristics to populate and exercise the embedded CER’s which generate cost parameters for the ship or ship class.
- This MAESTRO-SPAR Interface provides the early-stage design team with a more comprehensive assessment of the work content and cost for the concept being studied and yields important metrics to assess and evaluate alternate designs during the early-stage or concept design process.

- Structural Affordability Opportunities, such as tracking weld length, coating areas, reducing numbers of different plate types and structural profiles, and designing for combined loads, developed by team-member Pete Jaquith, provided a list of Ship Structural Affordability Opportunities that identify aspects of structural design that can impact the construction work content and the through-life maintenance and repair costs and ship availability. These opportunities were prioritized as metrics to leverage under Task 2 of the project.
- Based on Mr. Jaquith's recommendations: Weld length for the structural design is the most effective single metric for assessing Group 100 work content. For early-stage design, when Production Engineering is likely not participating with the design team, weld length can be used as a key metric to achieve lean design and design for production.
- More complex metrics that differentiate process lanes and associated metrics for structural construction units could be effective when Production Engineering is participating with the design team, which is likely to occur during later stages of design.
- MAESTRO calculates weld length and coating areas (by assigned groups) for the structure, for both early-stage design coarse mesh models and for more refined mesh models used in later stages of design. These capabilities directly support the basic work content metric of weld length for the structure and generate metrics for paint/coating areas. The weld length and paint areas are key metrics that can be used for structural optimization.
- Pete Jaquith updated and expanded his list of Ship Structural Affordability Opportunities for Early-Stage Design which can be enabled through structural design optimization:
    - **Design for Combined Loads**: Design for combined loads including fatigue is critical for thru-life performance
    - **Reduce Work Content**: Minimizing work content (i.e., weld length and coating surface) is a key affordability driver
    - **Avoid Difficult Steel Grades**: Avoid steel grades requiring special weld treatment
    - **Reduce Profile Variation**: Reduce profile variation, 180 profiles/ship is wasteful and many of these profiles are no longer available
    - **Reduce Plate Variation**: Reduce plate variation to improve procurement, material storage, inventory and logistics, and production
    - **Standard Series of Steel Profiles**: Develop a standard series of profiles for warship design; consider small bulbs and built-up tees
    - **Fatigue Resistant Structural Details**: Develop USN fatigue resistant structural details following Ship Structure Committee (SSC) work in late 1980's and early 1990's
    - **Design for Paint**: Commercial design, profiles, construction details, and construction are optimized for paint; consider USN application of similar practices
    - **Ensure Proper Access**: Ensure safe access for construction, blast/paint, inspection, and maintenance.

Case Study: Design Alternatives for USCG National Security Cutter (NSC) Forward Module. An example of the implementation of early-stage design structural optimization software was performed. This example uses a single module of the NSC forward structure to develop alternate designs by varying the stiffener spacing supporting decks and shell plating. Figure 2(a through g) summarize these alternatives, which conclude with providing the design team with choices that all meet structural design criteria while potentially reducing structural weight at the expense of additional weld length.



Early Stage Structural Design Process

- Automatically generates modified finite element segment models to support the structural changes
  - Stiffener spacing
  - Number of frames
- FE Analysis to compute stresses
- DPC100-4 V2 limit state evaluation
- Optimizations automatically iterate to convergence
- Each optimized structural design is saved and has metrics extracted for review

Define Deck, Bulkhead and Girder Locations

Select and Define Critical 2D Stations

Extrude 2D sections to a number of 2.5D MAESTRO segment models

Apply VBM and Design Pressure on a segment model

Iterate number of frames, stiffener spacing

2D Beam analysis or 3D FE Analysis

Structural Evaluation: DPC100-4 V2

Strake Optimization

Store Designs

Auto-Change segment model, number of frames, stiffener spacing

Stop

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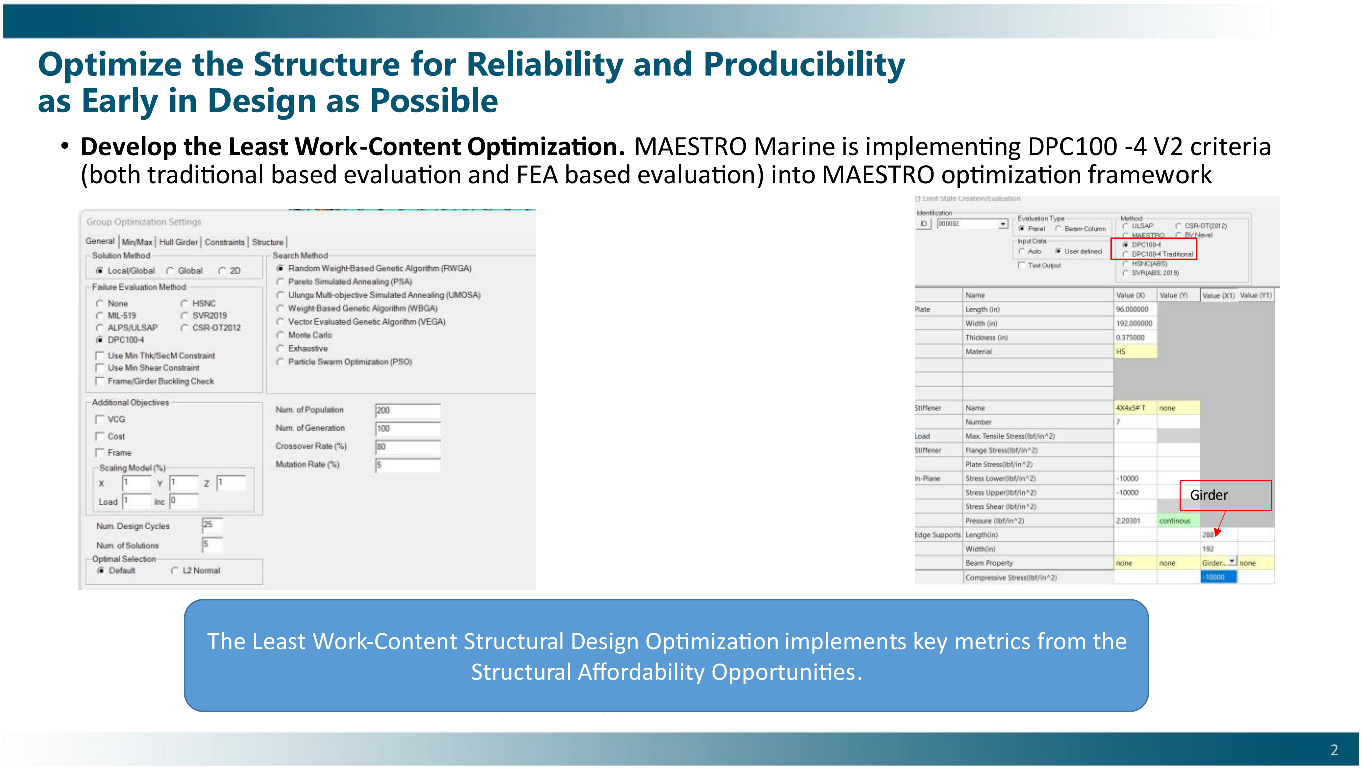
Figure 2a: Early-stage Design Structural Optimization



Optimize the Structure for Reliability and Producibility as Early in Design as Possible

- **Develop the Least Work-Content Optimization.** MAESTRO Marine is implementing DPC100 -4 V2 criteria (both traditional based evaluation and FEA based evaluation) into MAESTRO optimization framework

Group Optimization Settings

General | Min/Max | Hull Girder | Constraints | Structure

Solution Method: ● Local/Global ○ Global ○ 2D

Failure Evaluation Method: ○ None ○ HSNC ○ MIL-519 ○ SVR2019 ○ ALPS/ULSAP ○ CSR-OT2012 ● DPC100-4

☐ Use Min Thk/SecM Constraint
☐ Use Min Shear Constraint
☐ Frame/Girder Buckling Check

Search Method:
● Random Weight-Based Genetic Algorithm (RWGA)
○ Pareto Simulated Annealing (PSA)
○ Ulungu Multi-objective Simulated Annealing (UMOSA)
○ Weight-Based Genetic Algorithm (WBGA)
○ Vector Evaluated Genetic Algorithm (VEGA)
○ Monte Carlo
○ Exhaustive
○ Particle Swarm Optimization (PSO)

Additional Objectives: ☐ VCG ☐ Cost ☐ Frame

Scaling Model (%): X 1 Y 1 Z 1 Load 1 Inc 0

Num. of Population: 200
Num. of Generation: 100
Crossover Rate (%): 80
Mutation Rate (%): 5
Num. Design Cycles: 25
Num. of Solutions: 5

Optimal Selection: ● Default ○ L2 Normal

Limit State Creation/Evaluation

Identification: ID 000002

Evaluation Type: ● Panel ○ Beam-Column

Input Data: ○ Auto ● User defined

☐ Text Output

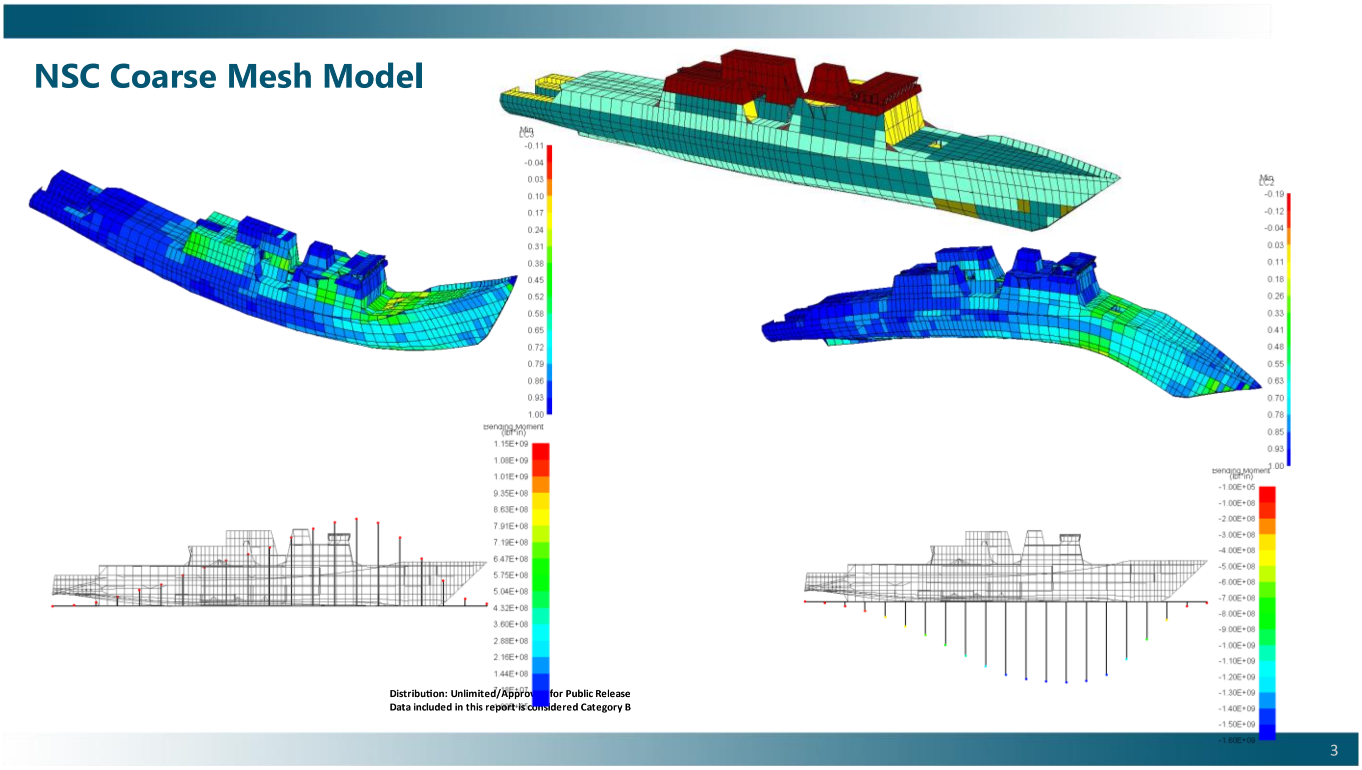
Method: ○ ULSAP ○ CSR-OT(2012) ○ MAESTRO ○ BV Naval ● DPC100-4 ○ DPC100-4 Traditional ○ HSNC(ABS) ○ SVR(ABS, 2019)

	Name	Value (X)	Value (Y)	Value (X1)	Value (Y1)
Plate	Length (in)	96.000000			
	Width (in)	192.000000			
	Thickness (in)	0.375000			
	Material	HS			
Stiffener	Name	4X4x5# T	none		
	Number	7			
Load	Max. Tensile Stress(lbf/in^2)				
Stiffener	Flange Stress(lbf/in^2)				
	Plate Stress(lbf/in^2)				
In-Plane	Stress Lower(lbf/in^2)	-10000			
	Stress Upper(lbf/in^2)	-10000			
	Stress Shear (lbf/in^2)				
	Pressure (lbf/in^2)	2.20301	continous		
Edge Supports	Length(in)			288	
	Width(in)			192	
	Beam Property	none	none	Girder...	none
	Compressive Stress(lbf/in^2)			-10000	

The Least Work-Content Structural Design Optimization implements key metrics from the Structural Affordability Opportunities.

2

Figure 2b: Early-stage Design Structural Optimization



NSC Coarse Mesh Model

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Figure 2c: Early-stage Design Structural Optimization

NSC Coarse Mesh Model Forward Module

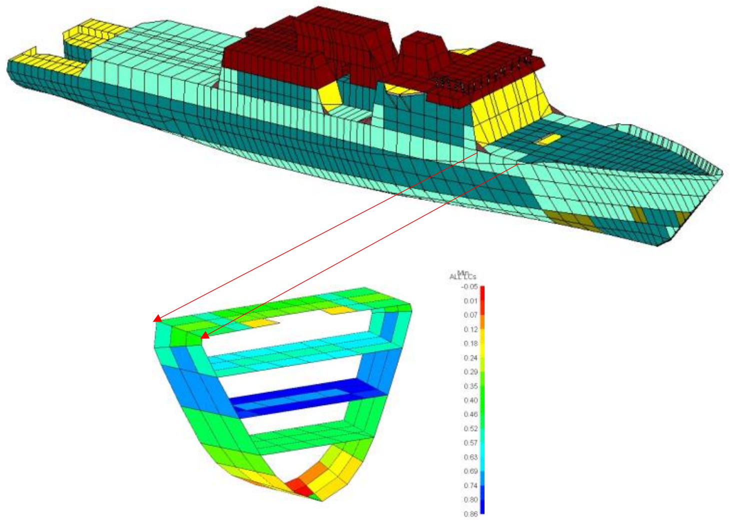

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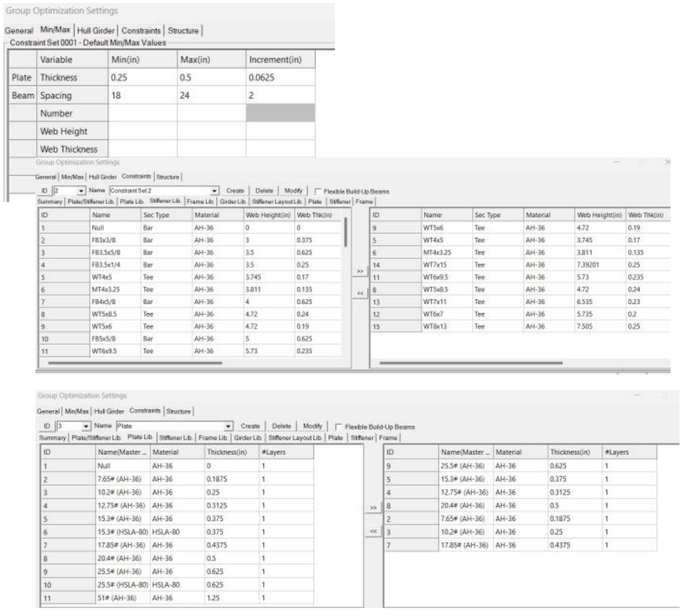
Figure 2d: Early-stage Design Structural Optimization

NSC Coarse Mesh Model Forward Module Optimization Setup

- Plate and stiffener layout are optimized against full load under still water and wave loads defined by SPECTRA
- DPC100-4 criteria is used
- Frames and girders are not optimized because local design pressure data were not available



Constraint Set 0001 - Default Min/Max Values

	Variable	Min(in)	Max(in)	Increment(in)
Plate	Thickness	0.25	0.5	0.0625
Beam	Spacing	18	24	2
	Number			
	Web Height			
	Web Thickness			

ID: 2
Name: Constraint Set 2
☐ Flexible Build-Up Beams

ID	Name	Sec Type	Material	Web Height(in)	Web Thk(in)
1	Null	Bar	AH-36	0	0
2	FB3x3/8	Bar	AH-36	3	0.375
3	FB3.5x5/8	Bar	AH-36	3.5	0.625
4	FB3.5x1/4	Bar	AH-36	3.5	0.25
5	WT4x5	Tee	AH-36	3.745	0.17
6	MT4x3.25	Tee	AH-36	3.811	0.135
7	FB4x5/8	Bar	AH-36	4	0.625
8	WT5x8.5	Tee	AH-36	4.72	0.24
9	WT5x6	Tee	AH-36	4.72	0.19
10	FB5x5/8	Bar	AH-36	5	0.625
11	WT6x9.5	Tee	AH-36	5.73	0.235

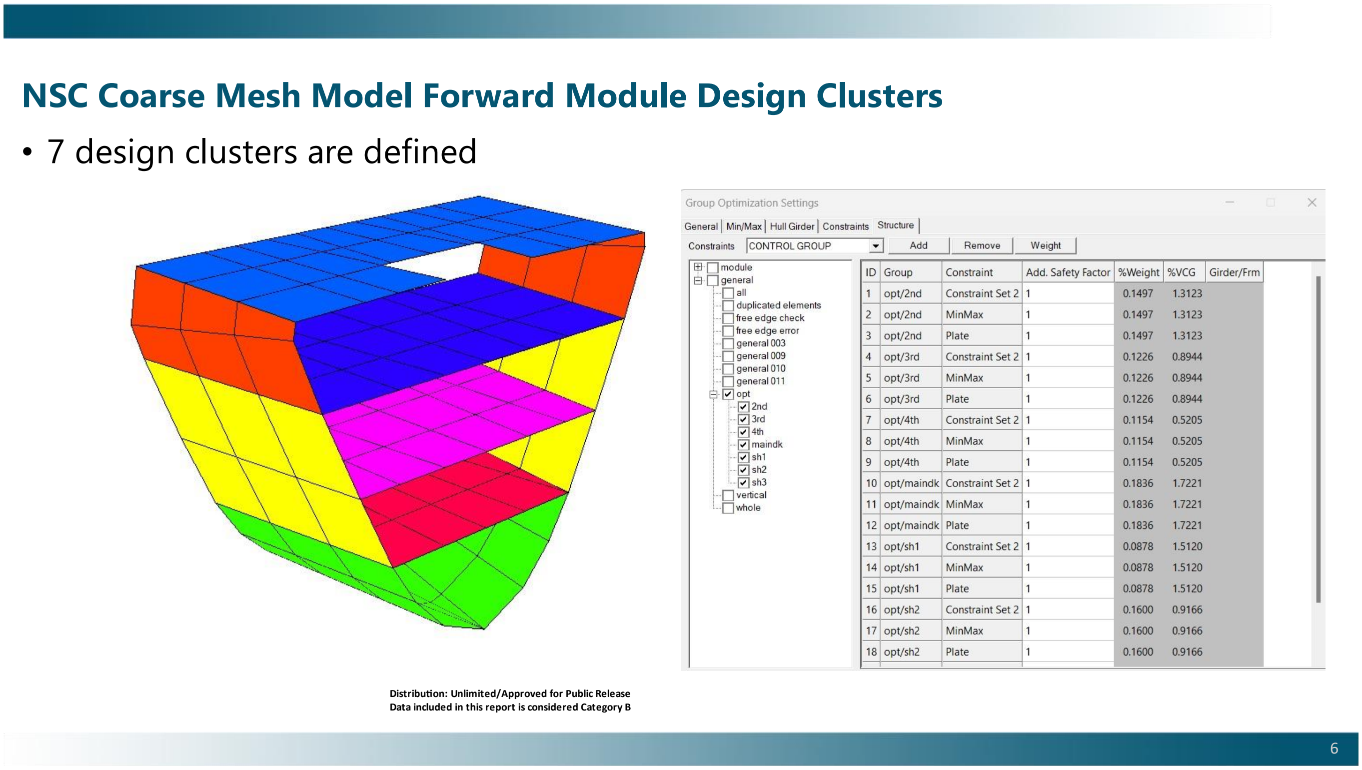
ID	Name	Sec Type	Material	Web Height(in)	Web Thk(in)
9	WT5x6	Tee	AH-36	4.72	0.19
5	WT4x5	Tee	AH-36	3.745	0.17
6	MT4x3.25	Tee	AH-36	3.811	0.135
14	WT7x15	Tee	AH-36	7.39201	0.25
11	WT6x9.5	Tee	AH-36	5.73	0.235
8	WT5x8.5	Tee	AH-36	4.72	0.24
13	WT7x11	Tee	AH-36	6.535	0.23
12	WT6x7	Tee	AH-36	5.735	0.2
15	WT8x13	Tee	AH-36	7.505	0.25

ID: 3
Name: Plate
☐ Flexible Build-Up Beams

ID	Name(Master ...	Material	Thickness(in)	#Layers
1	Null	AH-36	0	1
2	7.65# (AH-36)	AH-36	0.1875	1
3	10.2# (AH-36)	AH-36	0.25	1
4	12.75# (AH-36)	AH-36	0.3125	1
5	15.3# (AH-36)	AH-36	0.375	1
6	15.3# (HSLA-80)	HSLA-80	0.375	1
7	17.85# (AH-36)	AH-36	0.4375	1
8	20.4# (AH-36)	AH-36	0.5	1
9	25.5# (AH-36)	AH-36	0.625	1
10	25.5# (HSLA-80)	HSLA-80	0.625	1
11	51# (AH-36)	AH-36	1.25	1

ID	Name(Master ...	Material	Thickness(in)	#Layers
9	25.5# (AH-36)	AH-36	0.625	1
5	15.3# (AH-36)	AH-36	0.375	1
4	12.75# (AH-36)	AH-36	0.3125	1
8	20.4# (AH-36)	AH-36	0.5	1
2	7.65# (AH-36)	AH-36	0.1875	1
3	10.2# (AH-36)	AH-36	0.25	1
7	17.85# (AH-36)	AH-36	0.4375	1

Figure 2e: Early-stage Design Structural Optimization



NSC Coarse Mesh Model Forward Module Design Clusters

- 7 design clusters are defined

Group Optimization Settings

Constraints: CONTROL GROUP

☐ module
☐ general
  ☐ all
  ☐ duplicated elements
  ☐ free edge check
  ☐ free edge error
  ☐ general 003
  ☐ general 009
  ☐ general 010
  ☐ general 011
  ☑ opt
    ☑ 2nd
    ☑ 3rd
    ☑ 4th
    ☑ maindk
    ☑ sh1
    ☑ sh2
    ☑ sh3
  ☐ vertical
  ☐ whole

ID	Group	Constraint	Add. Safety Factor	%Weight	%VCG	Girder/Frm
1	opt/2nd	Constraint Set 2	1	0.1497	1.3123	
2	opt/2nd	MinMax	1	0.1497	1.3123	
3	opt/2nd	Plate	1	0.1497	1.3123	
4	opt/3rd	Constraint Set 2	1	0.1226	0.8944	
5	opt/3rd	MinMax	1	0.1226	0.8944	
6	opt/3rd	Plate	1	0.1226	0.8944	
7	opt/4th	Constraint Set 2	1	0.1154	0.5205	
8	opt/4th	MinMax	1	0.1154	0.5205	
9	opt/4th	Plate	1	0.1154	0.5205	
10	opt/maindk	Constraint Set 2	1	0.1836	1.7221	
11	opt/maindk	MinMax	1	0.1836	1.7221	
12	opt/maindk	Plate	1	0.1836	1.7221	
13	opt/sh1	Constraint Set 2	1	0.0878	1.5120	
14	opt/sh1	MinMax	1	0.0878	1.5120	
15	opt/sh1	Plate	1	0.0878	1.5120	
16	opt/sh2	Constraint Set 2	1	0.1600	0.9166	
17	opt/sh2	MinMax	1	0.1600	0.9166	
18	opt/sh2	Plate	1	0.1600	0.9166	

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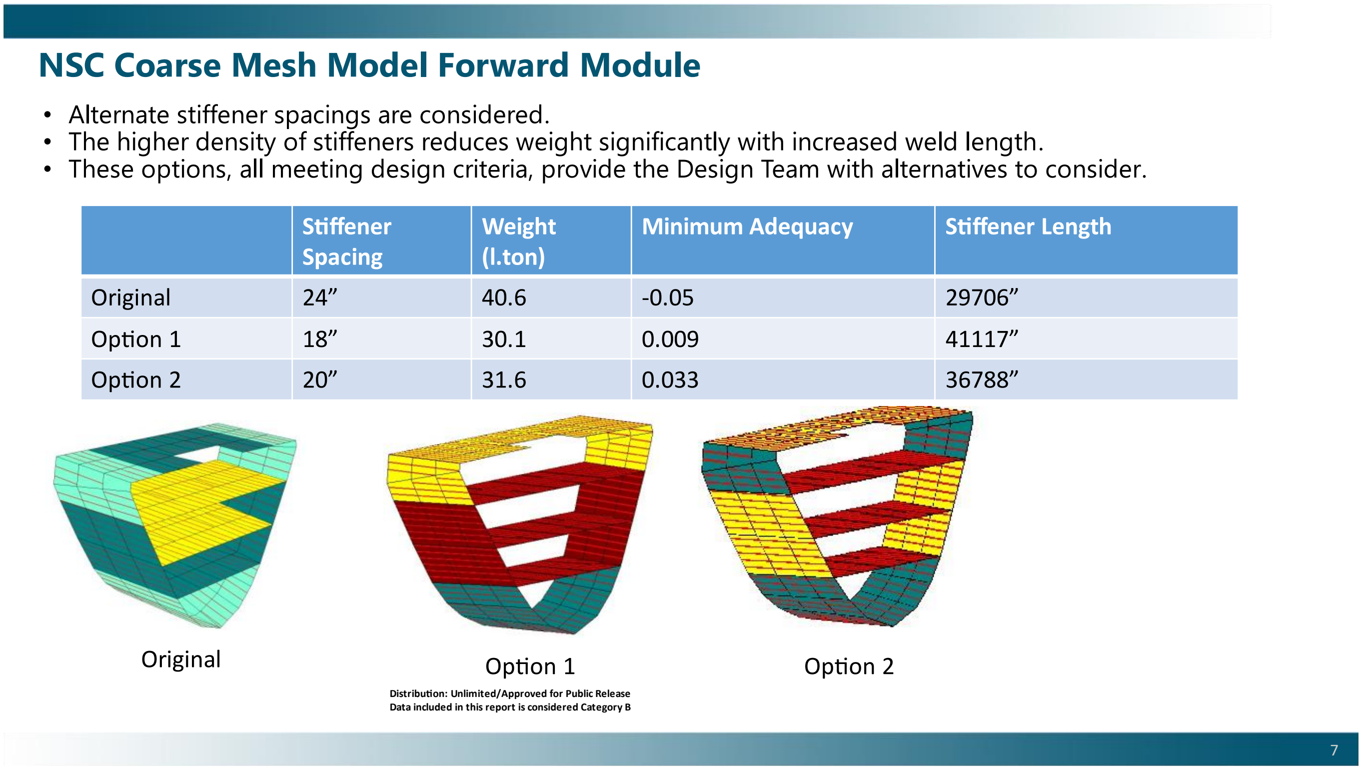
Figure 2f: Early-stage Design Structural Optimization



NSC Coarse Mesh Model Forward Module

- Alternate stiffener spacings are considered.
- The higher density of stiffeners reduces weight significantly with increased weld length.
- These options, all meeting design criteria, provide the Design Team with alternatives to consider.

	Stiffener Spacing	Weight (l.ton)	Minimum Adequacy	Stiffener Length
Original	24”	40.6	-0.05	29706”
Option 1	18”	30.1	0.009	41117”
Option 2	20”	31.6	0.033	36788”

Original

Option 1

Option 2

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Figure 2g: Early-stage Design Structural Optimization

Task 2 Metrics Assessment. The Task 2 metrics focused on identifying and then developing methods within the software to utilize key parameters of the ship design that drive or control the work content or cost of construction, and also the parameters that drive the structural maintenance and repair costs during the ship's life cycle. Mr. Pete Jaquith's Ship Structure Affordability Opportunities provided clear guidance regarding priorities for ship design parameters that influence both construction costs and in-service structural maintenance and repair costs. Task 2, in combination with the Case Study reported under Task 4, demonstrated that MAESTRO can compute and track many of the key parameters identified, including weld length of the full ship structure and coating areas by coating type. A software interface was developed and successfully tested from the MAESTRO structural model to SPAR's concept design cost models providing a potentially important capability to leverage existing work content cost estimating relationships, which can also be utilized in early-stage design to drive improved designs. Task 2 metrics are assessed as meeting the objectives.

PROJECT TASK 3 REVIEW

Statement of Work: Task 3. Optimize Structure for Reliability and Producibility as Early in Design as Possible. Develop a "Least Work Content" structural design algorithm for implementation in the Navy's ship synthesis model ASSET (Advanced Ship and Submarine Evaluation Tool) and implement an interface of the RA project tools with U.S. Navy early-stage design tools such as RSDE and ISDE via the Navy's LEAPS (Leading Edge Architecture for Prototyping Systems) early-stage design product model. The Task 3 results will provide early-stage structural optimization based on reduced work content while ensuring that structural design criteria are met. These developments provide an alternative to the current least weight methodologies which overly constrain the ship structural design engineer and lead to excessive in-service structural repair and maintenance costs and lost ship availability.

Work Completed for Task 3. The following have been completed in support of Task 3:

- Skylar Stevens, NSWC Carderock Code 65, hosted a meeting on 10 May 2022 at Carderock with Bob Keane, Ming Ma, Tobin McNatt, Pete Jaquith, Randy Greenwell (SPAR), Tristen Wright (NSWC) and Alex Gray (NSWC) to review the technical approach alternatives for Task 3.
- The Task 3 objective was to develop a code module that implements a minimum work content structural design algorithm to serve as an alternative to the minimum weight optimization algorithm derived from the Structural Synthesis Design Program (SSDP), which is currently used to define structural scantlings in ASSET.
- SSDP, developed in the 1980's, provides a 2D structural design and optimization tool for the U.S. Navy's Advanced Surface Ship and Submarine Evaluation Tool (ASSET) concept design ship synthesis computer program, which for surface ships has been integrated into the Rapid Ship Design Environment (RSDE). SSDP optimizes for a least structural weight design that meets U.S. Navy structural design criteria but does not address minimum work content in a multi-objective design optimization.

- The Task 3 developed code offers an alternative multi-objective structural design tool that optimizes the design to ensure that U.S. Navy structural design criteria are met while addressing design objectives that reduce fabrication work content and enhance in-service structural performance such as fatigue mitigation, and then search for minimum weight solutions. The technical approach for the developed software is provided under Appendix D of this report.
- A list of work content metrics was developed to serve as the new tool's design objectives. A follow-up meeting was held on 07 December 2022 for a discussion of structural producibility objectives that could be implemented in the new algorithm. NSWC Carderock Division has been conducting research in this area under its internal independent research program, and the objective of the meeting was to agree on the structural design parameters that will be used to minimize work content.
- An interface of the RA project tools with U.S. Navy early-stage design tools such as the Rapid Ship Design Environment (RSDE) and Integrated Structural Design Environment (ISDE) via the Navy's LEAPS (Leading Edge Architecture for Prototyping Systems) early-stage design product model was also considered under Task 3. In a January 2024 project meeting with Carderock, Robert Keane, and MAESTRO Marine, the Navy acknowledged that funding has been planned and requested in 2024 to conduct this evaluation of the project developed least work content and least weight structural design tool.

Task 3 Metrics Assessment. Task 3 had the unique challenge of being coupled with U.S. Navy personnel and software systems. This adds a level of complexity that requires additional attention and coordination. The metrics of Task 3 were the successful development and testing of the new least work content structural design algorithm. At project completion Task 3 is assessed as having successfully completed the new work content design algorithm.

PROJECT TASK 4 REVIEW

Statement of Work: Task 4. Implement a Structural Digital Twin Application. Task 4 continues the development of the structural corrosion/condition database and structural integrity and fatigue life assessment tools from RA 2017-443. These tools use a Rhino plugin-based component that is interfaced with MAESTRO. Enhanced methods for importing in-service structural survey data into the database will be developed, as will additional analysis methods for assessing the condition of the structure. Sample data will be used to demonstrate implementation for U.S. Navy and U.S. Coast Guard ships.

Work Completed for Task 4. The following were completed in support of Task 4:

- A Case Study was developed and performed to demonstrate design and in-service structural engineering tools addressing structural fatigue life, ultimate strength or buckling service life, and corrosion/wastage service life.

- The Case Study uses the U.S. Coast Guard National Security Cutter (NSC)
    - NSC: Length: 418 ft.
    - Displacement: 4,600 LT
    - Speed: 28+ kts
- The NSC Case Study Outline was developed around four focus areas. The Case Study used two full-ship finite element models of the NSC; one of which was a full-ship coarse mesh FE model. This model used orthotropic plate elements to represent stiffened panels in the structure. The orthotropic plate element is a long-standing feature of MAESTRO that speeds modeling, analysis and optimization in early-stage design. The other NSC model incorporated a more refined mesh model used through the midbody of the hull girder. The two models, developed and used extensively by the U.S. Coast Guard's SFLC, enable rapid analysis and documentation of results for the RA 21-11 project Case Study. The four aspects of the Case Study outline were:
    - Evaluating structural design options that are typical of an early-stage structural design space exploration effort.
    - Evaluating multiple levels of corrosion on targeted corrosion-prone locations.
    - Validating the correlation between the coarse mesh model with orthotropic plate and a more conventional FE model with explicitly modeled beams.
    - Evaluating the use of Spectral Fatigue Analysis (SFA) in early-stage design.
- The NSC Case Study was performed during the second year of the project. USCG/SFLC, ABS and MAESTRO Marine performed the Case Study analyses. This work also supports demonstrations of Task 2 objectives of how early-stage design can address more trade studies and design space exploration and continued in year-2 to demonstrate the use of structural digital twin capabilities and the development of extensions to these capabilities.
- ABS is an important team member for Task 4 as the subject of in-service structural condition monitoring and maintenance of certifications is a major area of work for ABS.
- During the project ABS installed, tested and reviewed the Task 4 prototype Structural Digital Twin toolset using the USCG 87 WPB and 210 WMEC vessels. Brian Corbett of ABS reported in a project White Paper that there were industry unique features of the software that were not available from other finite element analysis software and that these features could leverage structural condition survey data from operating ships within the industry. He also discussed potential applications of the tools for assessing corrosion margins during early-stage design which could be beneficial.
- Karl Stambaugh, Project Team Lead for USCG/SFLC, provided a set of remarks describing the use of the prototype tools by SFLC to date including descriptions of both enterprise-level use of the tools and use for specific ship condition assessment.

ABS also developed the following section of the Final Report, Task 4, with a discussion and case study of how digital twin systems can be designed, developed, and implemented.

Definition of a Digital Twin

A digital twin is a virtual representation of a physical asset, along with its environment and processes, comprised of integrated models that are updated through data exchange to provide decision-making support over its lifecycle. The digital twin can extend across the digital thread and exist in all lifecycle phases – design, build and sustain. The digital twin's scope and model fidelity are driven by desired insights and decision-making support.

Digital twins are comprised of three main elements: a physical asset, a virtual representation of that asset and the data connections between them.

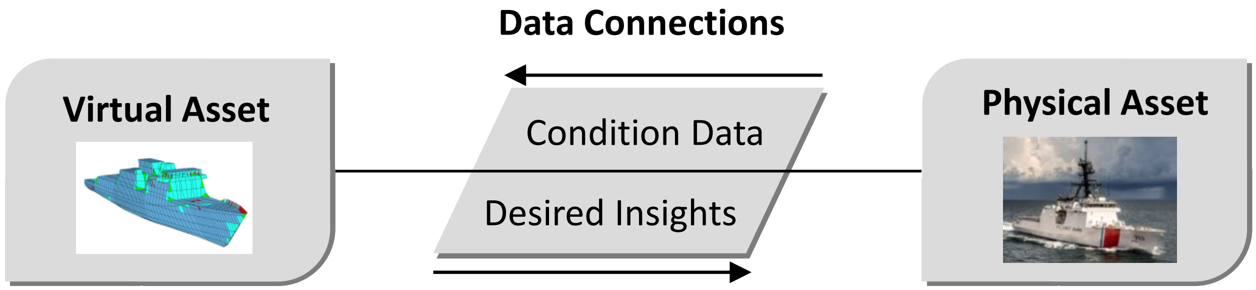

Figure 3: Three components of a digital twin

- Physical Asset - For complex systems such as a ship, the scope of the digital twin will be limited such that the physical asset being represented by the digital twin is often a subset of the full system. In the context of this project the physical asset is the hull structure of the vessel. A separate digital twin for the same vessel may only consider the propulsion system.
- Virtual Representation - The virtual representation of the asset is composed of integrated models to represent relevant aspects of the physical asset. The scope of the virtual representation for the digital twin must also be well defined. While a 3D representation of the hull structure and knowledge of its material strength properties are common for structural digital twins, other attributes may be only relevant to certain vessels or use cases. For example, the effects of temperature are important for LNG carriers with their cryogenic cargo but may not need to be considered for a conventional vessel.
- Data Connections - The data connections between the physical and virtual are defined to support the intended use case for the digital twins. Data from the physical asset serves as inputs to the virtual asset while outputs from the virtual asset provide information that can be used to drive how the vessel is operated or maintained. In order to be considered as a digital twin the data connection must be two-way. If data is only passed from the physical output to the virtual asset to archive how vessel condition has changed no outputs are generated and the system would be considered as a digital shadow. If the virtual asset is used to generate outputs but never updated to reflect changes in the condition of the physical asset, then the system is equivalent to a typical engineering model used for vessel design.

Digital twins are dynamic in the sense that their state changes with that of the physical asset due to the data connection. It is necessary to periodically store representations of the digital twin so that they are retained. While the stored representations are vessel specific, often the computational representations used by digital twins can be reused. For a series of sister vessels, the as-designed computational representations are equivalent. They may be replicated to create a digital twin instance for each vessel with each instance having its own periodically stored representations.

Digital Twin application for early-stage design

The focus of this project on reducing TOC using early-stage design optimization is not a traditional digital twin application because no physical asset has been produced in early-stage design. When no physical asset is available the digital twin must rely on a prototype of the physical asset. The prototype contains the same type of condition information that will be available from the physical asset[1]. Once the vessel is commissioned, a transition from the prototype to the physical asset can be made. A digital twin prototype can provide value in early-stage design if it is prepopulated with sufficient data to enable the vessel's life cycle to be simulated. Because the simulated condition data in the digital twin prototype is specified by the designer, multiple scenarios can be created to support design decisions. By generating a range of lifecycle conditions, it is possible to understand the long-term sensitivity of a design to various operational conditions and therefore enable the TOC to be predicted for various design alternatives.

Framework for Developing a Digital Twin

Use Case - The development of a digital twin typically begins with the definition of a use case. The use case defines the key attributes of the digital twin including its purpose, the desired outputs, its behavior, and user interactions. A well-defined use case is important for establishing the list of requirements for the digital twin that will guide its development. It is recommended that the use case be defined without considering any constraints or restrictions. This will help ensure that the digital twin will provide the desired value. This is particularly relevant for developing digital twins that involve existing vessels. If the use case is developed considering only historical data sets and currently available models, then the capability and value of the digital twin may be compromised. A critical review of the use case can guide decision making before additional resources are committed and help ascertain whether a digital twin is even the correct approach or not.

Implementation Strategy - Once a use case and requirements list for the digital twin have been established an implementation strategy needs to be developed. The implementation strategy needs to consider available resources, development time and costs. In general, a digital twin could be developed as a stand-alone tool or be compiled from a set of existing models. The approach of integrating existing models is expected to be the most common for the early adoption of digital twins because it leverages existing resources. In the maritime industry engineering models have been widely adapted and many are considered reliable and trustworthy. One drawback of a model integration approach is that much more user interaction is likely necessary as the user will need to sequentially execute each model versus a stand-alone approach where the user only needs to focus on preparing the initial inputs with the internal subtasks

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[1] Grieves, Michael. (2016). Origins of the Digital Twin Concept. 10.13140/RG.2.2.26367.61609.

automated. Task 4 focuses on demonstrating how a structural digital twin that supports early-stage design can be implemented using the model integration approach.

Functional Decomposition – A functional decomposition of the digital twin is necessary to determine the subfunctions needed to accomplish the overall function of the digital twin. During the design of a marine vessel, numerous engineering models are created and used to evaluate the design. Ship designers have an existing library of models that can be used to support the development of digital twins. Using the digital twin use case as a starting point, a functional decomposition of the digital twin can be conducted until a point at which the individual functions identified as being required by the digital twin can be mapped to the available engineering models. The process of mapping models in the available model library to the functional decomposition is illustrated below. New models will need to be created for any subfunctions that cannot be performed using available resources. The results of the functional decomposition can serve as a second point for performing a review of the digital twin project to affirm it is still technically feasible with available resources if significant capability gaps exist.

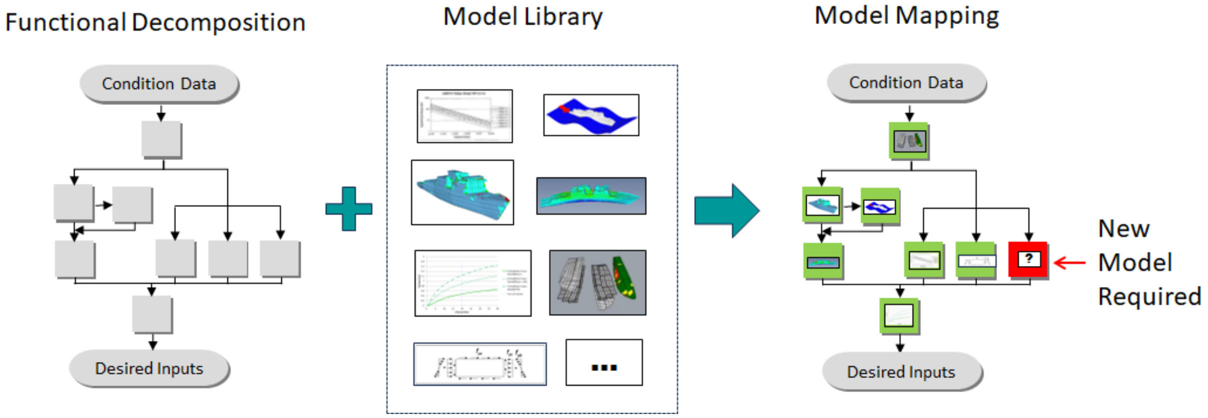


Figure 4: Model Mapping

The functional decomposition will also help identify the hierarchy and ordering of the models that need to be integrated to form the digital twin. Once the hierarchical arrangement of the models is established the flow of data from function to function can be mapped. Because the digital twin will likely only use a subset of the input and output data provided by existing models, it is important to identify the inputs and outputs that are critical at each step for the digital twin. Inputs and outputs on the external boundary of the digital twin system should be distinguished from internal input and output interfaces. Because many models use the same information multiple data flow diagrams are possible. The adopted data flow diagram will likely be influenced by ease of implementation considerations.

Data Interfaces - The final aspect influencing the adopted digital twin implementation strategy is a detailed evaluation of each data interface between the subfunctions required for the digital twin. While the data mapping phase affirms that the correct data types are exchanged, additional details need to be considered. Data quality issues such as unit consistency need to be documented. Technical details such as file formats need to be considered. Any differences in data resolution need to be identified. For example, encountered wave conditions may be recorded hourly while vessel loading is only updated every voyage. Similarly, a buckling evaluation may consider one stress value per panel while a finite element model may subdivide the panel into multiple elements. Each of these factors present challenges that must be addressed.

The primary task in implementing a digital twin through the integration of existing models is the development tools to exchange data across each functional interface. No additional work may be needed for specific interfaces in some instances. For example, the same software vendor or application may be used to support multiple models and functions therefore ensuring data and format consistency. Many models may also be commonly used in the same workflows for other purposes and therefore import and export utilities may already exist and enable the necessary data exchange. Engineering applications may also have programming interfaces that allow users to create custom tools that enable the import or export of unique datasets and provide opportunities for automation. In other situations, the data exchange at interfaces needs to be performed manually or through the development of standalone programs. Although manual data exchange is inelegant, for a structural digital twin the approach may be practical for infrequent activities. For example, gauging data is typically only collected at intervals that are annual or greater. If insufficient time or budget is available to automate a task initially, initial deployment of the digital twin may utilize manual data exchange with automated tools implemented over the time before the next gauging survey.

<u>Additional Considerations</u> - Prior to the implementation of a digital twin several other aspects need to be considered. The required user interaction with the digital twin should be considered to ensure that the intended workflow is supported. This is an important consideration for early-stage design when model configurations may change frequently as the use of multiple corrosion instances is often counter to the standard structural analysis process. For example, many finite element analysis applications enable multiple load cases to be associated with a single model and solved at the same time. Multiple corrosion levels cannot be supported therefore multiple models must be created and solved separately with the results consolidated in a separate process. Figure 5 demonstrates how the generation of three output sets can vary greatly depending on how well the desired workflow is supported by the models selected for the digital twin. For the digital twin use case on the right half of Figure 5, the development of automation tools may be necessary to ensure the digital twin has sufficient usability.

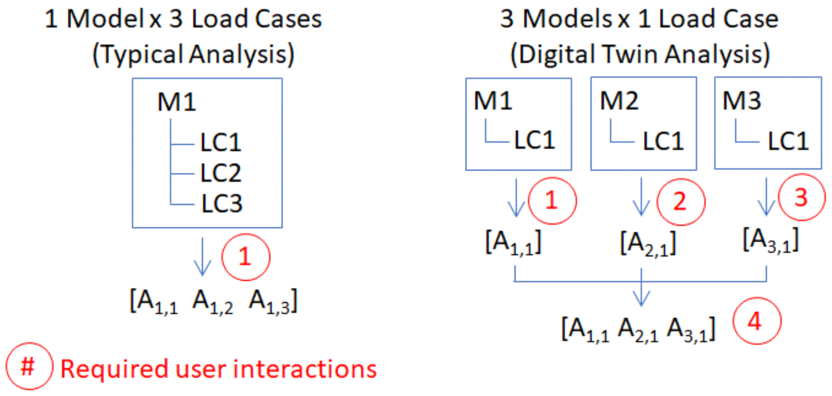


Figure 5: Workflow challenges presented by digital twin implementation

Data storage policies should be established to detail what data is to be retained, how frequently digital twin representations are stored, and responsibilities for maintaining and granting access to the data detailed. Finally, planning for how changes to the digital twin will be managed should be considered. Verification and validation of the digital twin is important to ensure the desired outputs are being generated correctly. This topic is the subject of project NSRP 2023-329-003 and will be detailed in depth there. Due to the long service life of vessels, technology or use case changes may require the digital twin to be revised during the life of the vessel.

Simulated corrosion for an early-stage design digital twin prototype

In early-stage design it is common to consider both gross and net scantlings when evaluating the design. The gross scantlings reflect the original thicknesses for the design condition, and the net scantlings account for anticipated wastage due to corrosion at the design service life. Traditionally, considering only these two scantling conditions has been considered sufficient. The application of a digital twin prototype during early-stage design provides opportunity for evaluating an even larger set of wastage conditions. Use of the digital twin prototype to simulate corrosion enables the traditional design approach to be conducted at a higher level of fidelity. Rather than considering just two data points, the beginning and end of service life, intermediate time steps can be considered in addition to points beyond the original design life as illustrated in Figure 6 below. These additional data points may provide enhanced insights during early-stage design by enabling trends to be more readily visualized.

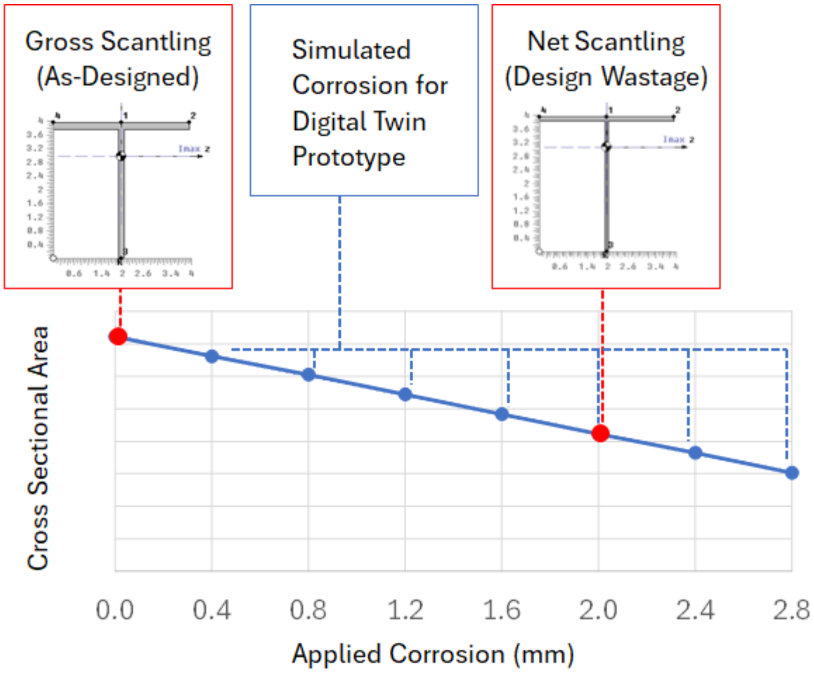


Figure 6: Use of simulated corrosion to evaluate additional conditions in early-stage design

To support a digital twin prototype during early-stage design a process for simulating future corrosion levels is necessary. This process may differ from the normal process used for mapping gauging data to the virtual asset because it may not require some of the complexity associated with spatially mapping measured data on the physical asset to the virtual asset. Instead, the simulated corrosion process prioritizes the efficient iterative application of corrosion. While the gauging data may vary from survey to survey, particularly as new suspect areas are found, the inputs for simulated corrosion can be highly structured which supports automation. In the prior figure, all simulated corrosion data could be generated by simply specifying the incremental amount of corrosion applied in each step (0.4 mm) and iterating until the upper wastage limit is reached (2.8 mm). This section outlines the implementation of a simulated corrosion application tool.

Defining the corrosion distribution

To implement a corrosion simulation tool, it is necessary to specify how corrosion will be distributed throughout the vessel. This step is unique to simulated corrosion and not necessary when corrosion application is governed by survey data. While highly elaborate corrosion distributions could be developed, for early-stage design, simpler approaches were considered to enable more time for exploration of design alternatives.

The most basic approach to simulating corrosion is to apply uniform wastage amounts to all elements in the finite element model used for the digital twin's virtual representation. Such an approach requires the least amount of logic and input data to apply. To account for the fact that the nature and extent of surface exposure will influence the amount of corrosion expected to occur, the case study considered a slightly more advanced approach that considered the number of plating surfaces exposed to more corrosive conditions: either zero, one or two faces. The least amount of corrosion is expected when a plate has no surfaces directly exposed to the marine environment or corrosive cargo. An interior bulkhead is an example of structure that is expected to have zero surfaces directly exposed. A tank top or weather deck typically has only one surface exposed to a more corrosive environment. Bottom shell plating common to an internal tank is an example of structure with two exposed surfaces. This approach was seen as sufficient for general early-stage design use, although when extensive data and experience is available vessel type and structure specific categories could be employed. The Nominal Design Corrosion Values (NDCV) defined in the ABS Marine Vessel Rules are an example of an experience-based prescriptive corrosion distribution.

To capture the exposure level information for structure in the digital twin virtual asset, the vessel is subdivided into specific corrosion groups. Each corrosion group contains a set of elements from the finite element model used to represent the vessel with the same number of exposed surfaces: zero, one or two. This approach was taken because this type of functionality is common among finite element analysis applications and the practice of creating groups to organize finite element models has been widely adopted by users. By associating each element in the finite model with a corrosion group the entire model can be readily corroded once the end of service wastage values associated with each group are defined. For the case study a design wastage value of 1mm was assumed for structure with zero exposed surfaces, 1.5mm for structure with one exposed surface, and 2mm for structure with two exposed surfaces. Figure 7 illustrates how a vessel is decomposed into these three corrosion groups.

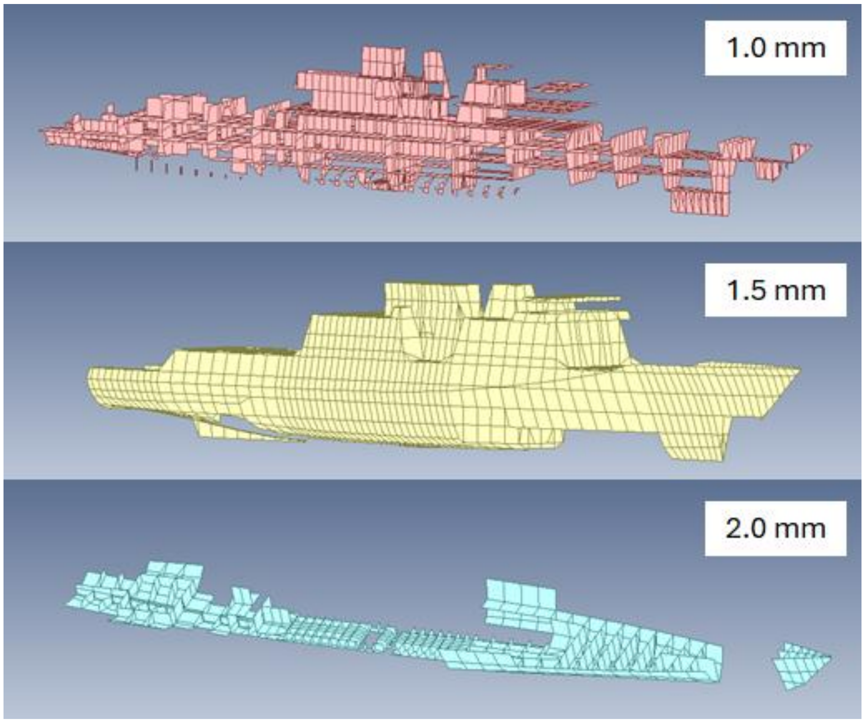


Figure 7: Division of a vessel into corrosion groups with different wastage levels

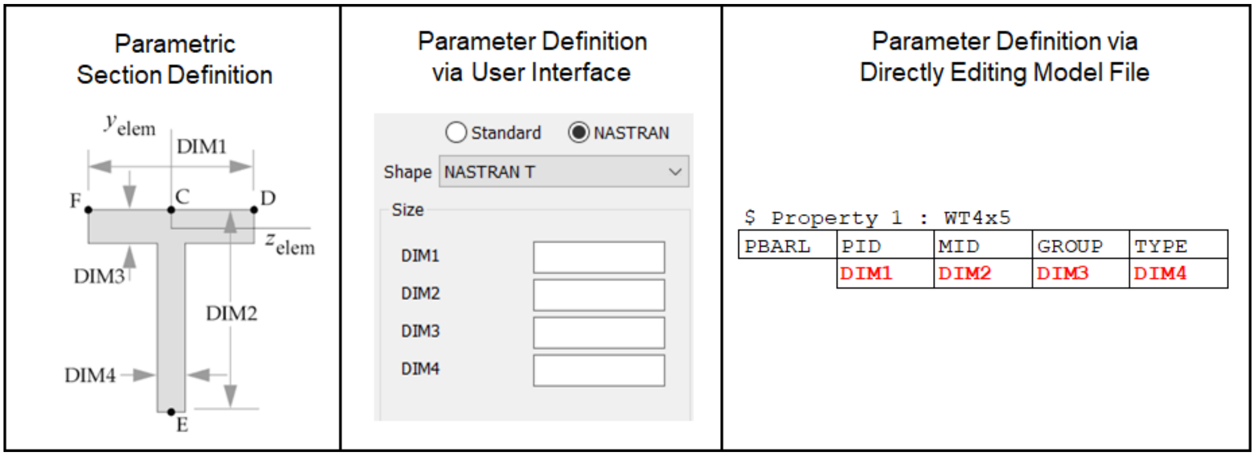
The level of effort to subdivide the model into corrosion groups will be greatly reduced if existing groups are available for common hull structure such as decks and tanks. For example, a freeboard deck group may be subdivided into two corrosion groups: one for exposed plating (one exposed surface) and one for internal plating and the stiffeners (zero exposed surfaces). The Boolean intersection of two tank groups or between a tank and shell group can quickly identify surfaces with two surfaces exposed to corrosive environments.

The MAESTRO software incorporates the functionality to implement corrosion via groups. Users can create corrosion groups and input individually the amount of corrosion applied to plates, webs, and flanges. The corrosion groups are associated to loading conditions and therefore do not directly change the as-designed scantling definitions. Because this capability is not commonly available, a more general approach to applying corrosion to finite element models is discussed.

Corrosion application with finite element models

For a structural digital twin a finite element model is typically used to store all the relevant information relative to the 3-dimensional representation of the vessel. To apply corrosion to the finite element model an understanding of how thickness information is entered and stored is necessary. While specific methods will be software specific, structural finite element models typically store thickness information within the properties used to define the physical characteristics of the elements. For properties associated with two-dimensional plate elements thickness is an explicitly defined parameter. Stiffeners, flat bars, bulb flats and other sections can often be defined in a variety of ways. Some bar and beam property formats enable thicknesses to be directly entered when defining the cross-section geometry. Other 1-D property formulations may not explicitly define the cross-sectional geometry but require the relevant cross-sectional attributes such as cross-sectional area, inertias, and the torsional constant to be directly entered.

When finite element software enables stiffener sections to be defined in a parametric manner, the user can directly edit thicknesses to apply corrosion. The Nastran PBEAML and PBARL properties are examples of this type of parametric property definition. The MAESTRO software also defines beam sections parametrically. Figure 8 illustrates how a T-section is parametrically defined, how finite element software enables the parameters to be input via a user interface, and how the values are stored in text format within the model file where they may be directly edited.

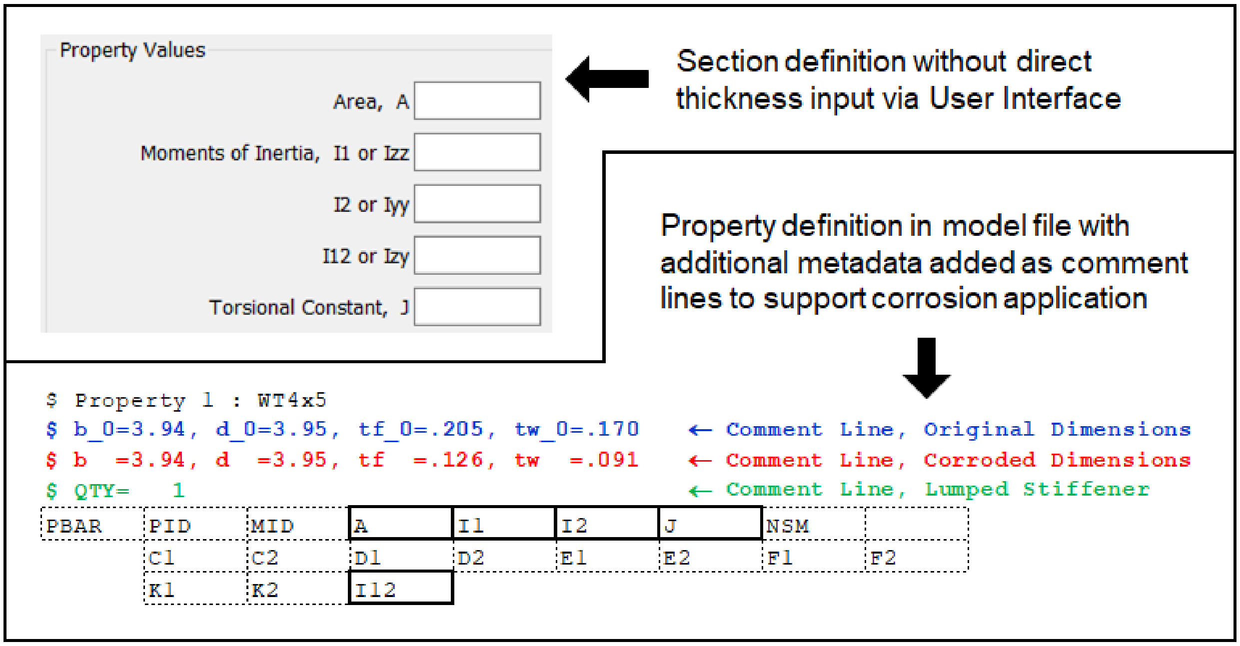


○ Standard ● NASTRAN
Shape: NASTRAN T
Size
DIM1
DIM2
DIM3
DIM4

```
$ Property 1 : WT4x5
PBARL   PID     MID     GROUP   TYPE
        DIM1    DIM2    DIM3    DIM4
```

Figure 8: Parametric definition of a T-section

Some types of property definitions do not define sections by directly dimensional inputs but require derived attributes such as area (A), moments of inertia (I1, I2 & I12), and torsional constant (J) to be specified. Figure 9 illustrates how these types of properties such as the Nastran PBAR and PBEAM are entered via a user interface or stored in text format within the model file. To simulate corrosion when the finite element property definitions that do not enable thickness to be modified directly, methods for incorporating the relevant thickness information must be derived. Text fields such as the property title or comment lines were considered in the case study for adding the relevant thickness and other geometric dimensions needed to compute the new cross section properties for the corroded condition. In addition to information reflecting the current corrosion wastage, the same text fields may also be used to include the parameters for the original design condition. Maintaining a record of the original scantling dimensions helps provide provenance to the corroded property data. The colored lines in Figure 9 are an example of how the relevant dimensional information can be stored. The lines begining with the “$” character to indicate that they are comments and therefore ignored when the files are used in a normal way.



Section definition without direct thickness input via User Interface

Property definition in model file with additional metadata added as comment lines to support corrosion application

```
$ Property 1 : WT4x5
$ b_0=3.94, d_0=3.95, tf_0=.205, tw_0=.170     ← Comment Line, Original Dimensions
$ b  =3.94, d  =3.95, tf  =.126, tw  =.091     ← Comment Line, Corroded Dimensions
$ QTY=   1                                     ← Comment Line, Lumped Stiffener
PBAR    PID     MID     A       I1      I2      J       NSM
        C1      C2      D1      D2      E1      E2      F1      F2
        K1      K2      I12
```

Figure 9: Specification of a T-section without direct thickness inputs

The need to support finite element property definitions that do not explicitly indicate material thickness is important for early-stage design when coarser mesh finite element models are often used. Often the coarse mesh models use mesh densities in some regions that result in plate elements spanning multiple panels on the vessel. When the mesh density is less than the stiffener spacing the elements between the plates that represent will represent multiple stiffeners. These lumped stiffener elements require properties that contain additional provenance regarding the quantity of stiffeners being represented. Combined with the thickness and geometric data associated with the property, the relevant lumped section properties can be computed. In Figure 9, the green comment line is used to illustrate how the number of stiffeners associated with a property can be captured. In the MAESTRO software the stiffener layout functionality allows multiple stiffeners to be associated with plate elements.

Generating multiple corrosion instances

Having established a corrosion distribution and identifying methods for updating finite element models, a process for generating multiple corrosion instances is required. Each corrosion instance simulates a different corrosion level anticipated to occur at some time during the vessel's service life. The intent of this section is to outline a general process for generating multiple corrosion instances so that a broad range of implementation challenges can be addressed. The general approach assumes that a user developed application is necessary due the absence of the required functionality within available software.

The application development process can begin after the functional decomposition and required interfaces for the digital twin have been identified. When information exchange among multiple models is necessary, the use of a highly accessible file format for storing the finite element model data reduces the number of required data transformations. Finite element analysis applications often store data in proprietary binary formats to minimize file size. These binary formats frequently restrict their usage to native software applications only. In addition, the binary formats are often version specific which can complicate sharing and access among users with different software versions or when software updates occur. To avoid the drawbacks of working with binary files text-based file formats are preferred. Text files can be read and written in any programming language. For structural finite element models the Nastran bulk data file format (BDF) is prevalent, often being both an import and export option in software applications. The use of Nastran BDF is recommended because interface data exchange utilities developed for that format will likely be reusable for other digital twins.

The Nastran bulk data format is well structured and documented. Each bulk data entry is identified by a unique keyword that allows that entry to be distinguished in the file. An application that generates multiple corrosion instances will need to read the input file and identify property cards impacted by corrosion. When relevant property cards are identified the data can be parsed to collect variables impacted by the corrosion application process. Using the collected data, the necessary calculations can be performed to compute the values for the variables needed to express the desired level of corrosion. The updated data can then be written to the output file. Bulk data entries in the input file not associated with the corrosion application process do not require processing and can be directly rewritten to the output file. This input/output process can be iterated to generate the desired set of simulated corrosion instances.

The application for generating corrosion instances must contain the capability to update corrosion data for any type of scantling section present on the vessel such as an I-beam, tee, bulb flat, flat bar or angle. Each section type has a different set of equations governing sectional properties such as area, inertias, and the torsional constant. The Nastran bulk data cards are general therefore a scheme for identifying the section type associated with each property is required. The use of descriptive property titles is one method of archiving the necessary information as the use of comment lines preceding a property bulk data entry is common. For example, in Figure 9 the initial comment line “$ Property 1 : WT4x5” indicates that the section is a tee with the subsequent comment lines providing additional details. The descriptive property titles are not part of the bulk data entry therefore many software applications rely on the numerical property ID value to distinguish one property from another. An alternative approach to retaining property information in comment lines is to maintain a separate database to store the descriptive property information and use the property ID for cross referencing.

The application of corrosion to a finite element model has the potential to significantly alter the data structure of the model. For example, a property representing a specific plate thickness may be used throughout the vessel however the corrosion distribution may specify that some elements with that thickness require one level of corrosion and other plate elements a different amount. Consequently, multiple instances of the original property must be generated to sufficiently represent corrosion in the as-corroded file. This will result in the corroded model having more properties than the original model. The model will be further complicated as each element directly references a property. Elements associated with the new corrosion properties must be updated to reflect the new property references. Managing these changes requires careful planning to ensure all the relevant changes are coordinated.

The development of a standalone application for implementing the generation of multiple corrosion instances is possible in any standard programming language. Use of the Nastran BDF requires the ability to read and write text files which is universally available, and the file format is structured and well documented enabling data to be easily accessed. The calculation of the necessary section properties for the corroded conditions can also be performed with basic arithmetic operators. The greatest challenge in implementation is the identification of a schema for ensuring that necessary data is available for the application to ingest, and the output file contains sufficient provenance to inform the end user of the all the relevant details regarding the applied corrosion.

When the majority of the functionality required by a digital twin can be performed within the same software or suite of software external interfaces may not be required and internal tools or functions can be used to generate multiple corrosion instances. When using corrosion groups in MAESTRO, multiple corrosion instances can be generated by altering the scale factor used when the corrosion group is applied to a loading condition. For example, if the MAESTRO corrosion group specifies 1mm of wastage, then a scale factor of 0.5 can be used to generate a corrosion instance with 0.5mm wastage. Some finite element applications offer advanced programing interfaces (API) that enable users to develop programs to perform custom functions. Use of the API is another alternative to generating simulated corrosion instances for an early-stage design digital twin.

Corrosion prediction for an early-stage design digital twin prototype

The ability of a digital twin to simulate multiple corrosion instances allows the designer to know the exact amount of corrosion required for each element in the finite element model to fail. The addition of a corrosion prediction model to the digital twin allows the designer to take a further step and predict when failure will occur at each element. This provides an additional level of detail and insight over a traditional approach that verifies whether each element has sufficient capacity at the expected end of service wastage condition simply on a go or no-go basis. By enabling structural analysis results to be converted into the time domain, the incorporation of a corrosion prediction model into a digital twin for early-stage design enables TOC calculations to be supported. While all design alternatives are expected to reach the design service life without concern, they may diverge in terms of anticipated maintenance cost 5 or 10 years beyond the design life. This section details a corrosion prediction model that can be applied to a structural digital twin.

The corrosion prediction model considered for use in early-stage design digital twin was one of the three models considered as part of a joint industry project Lifecycle Management of Hull Structures[2]. The models considered both the initial coating degradation and subsequent corrosion progression. While the models were based on data from tankers and in-service FPSOs they are considered to account for the relevant factors that influence coatings and corrosion and should have broader applicability. Although considered for early-stage design use here, using simulated corrosion data the models can be updated using actual thickness measurement data.

The selected corrosion prediction model from the joint industry project was developed by ClassNK[3] and is a probabilistic power model. The model probabilistically considers corrosion initiation and progression in a sequential process. Corrosion initiation correlates to the breakdown of the coating. The model reports predictions for different probabilistic levels so various scenarios can be considered from an early-stage design perspective. The corrosion propagation portion of the model is considered conservative because

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[2] Life Cycle Management of Hull Structures JIP, Long-Term Corrosion Prediction Model Rev 1, Prepared by ABS & ClassNK (2014)

[3] Yamamoto, N., Ikegami, K. A study on the degradation of coating and corrosion of ship's hull based on the probabilistic approach, Journal of Offshore Mechanics and Arctic Engineering (1998)

it does not account for a cessation of corrosion due to the formation of rust scale. Figure 10 below contains a sample output from the ClassNK corrosion prediction model.

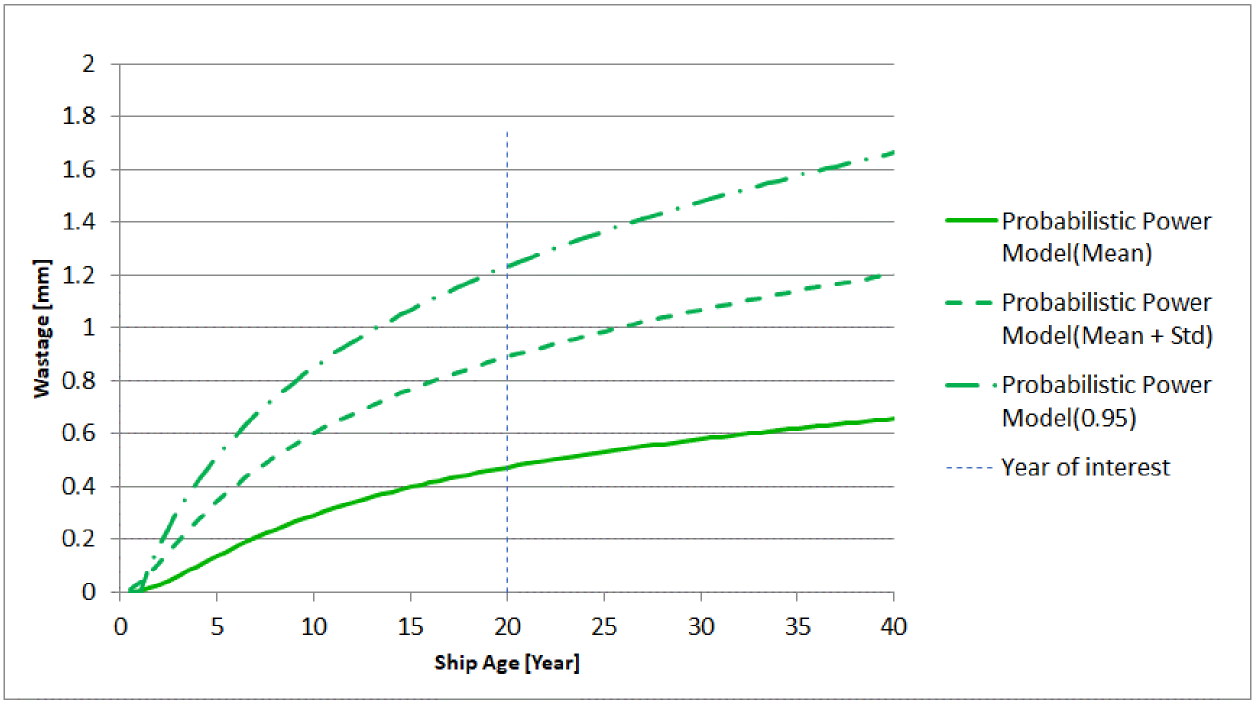


Figure 10: Sample output from ClassNK corrosion prediction model

The ClassNK probabilistic power model uses five parameters to characterize the model. The two parameters influencing corrosion initiation are the mean and standard deviation for the time to corrosion initiation. Corrosion propagation is based on the mean corrosion wastage, standard deviation for corrosion wastage and a propagation coefficient.

The corrosion prediction values obtained by the ClassNK model can be further adapted to different operational scenarios by applying environmental adjustment factors[2]. The two categories considered to influence corrosion are marine immersion and marine atmospheric conditions. Those categories are influenced by the environmental variables listed in Table 2. The environmental adjustment factors are used to directly scale the corrosion prediction values. From an early-stage design perspective the environmental adjustment factors provide insight into how different operational profiles may influence corrosion.

Table 2: Individual environmental attribute variables

Variable	Environmental Category	Nominal Value	Equation
Water Temperature	Marine Immersion	15.5°C	$f(T_r) = 0.5844 \cdot T_r + 0.4156*$
Dissolved Oxygen	Marine Immersion	5.88 ml/L	$f\left(O_{2,r}\right) = 0.9483 \cdot O_{2,r} + 0.0517*$
Flow Velocity	Marine Immersion	5.144 m/s	$f(V_r) = 1.0978 \cdot [1 - \exp(-2.2927(V_r + 0.0548)]$
Air Temperature	Marine Atmospheric	16.2°C	$f\left(T_{r,air}\right) = 0.415 \cdot T_{r,air} + 0.585*$
Chloride Concentration	Marine Atmospheric	180.7 $\text{mg/m}^2\text{/day}$	$f(Cl_r) = 0.523 \cdot Cl_r + 0.477*$
Relative Humidity	Marine Atmospheric	81.9%	$f(Rh_r) = 3.467 \cdot Rh_r - 2.467$

The variable equations marked with * are truncated between 0.1 and 2.0, where if the variable exceeds either boundary, it adopts the exceeded value. Additionally, the relative humidity (Rh_r) is restricted to values in the range [0.733,1.221]. Rh_r is not allowed to exceed 1.221 as this corresponds to $Rh = 100\%$, and it is not possible to exceed this value. If Rh_r goes below 0.733 (corresponding to $Rh = 60\%$) the air is dry enough that atmospheric corrosion is negligible^2.

The equations in Table 2 all use ratio values as inputs. The ratio values are calculated by dividing the actual value for the parameter by the nominal value. An example for water temperature, T, for marine immersion is shown below.

$$T_r = \frac{T}{T_n} = \frac{T}{15.5°C}$$

Digital Twin case study for early-stage design

To demonstrate how the methods for implementing a digital twin for early-stage design presented in the previous section can be applied, a case study was performed. One objective of the case study was to demonstrate that existing libraries of models can be used to help create digital twins. The purpose of this first objective is to encourage the adoption of digital twins in the present. A second objective of the case study is to illustrate how the use of a digital twin prototype during early-stage design can help generate additional information that can support design decisions. The goal of the second objective is to inspire the development of new digital twin use cases for the marine industry.

The use case for digital twin case study is focused on reducing TOC associated with corrosion. To calculate TOC, information about the state of the vessel throughout its lifecycle must be known. To account for TOC during early-stage design it is necessary to predict the number and extent of corrosion related repairs anticipated during the service life for each design alternative. The use case for the digital twin case study is to simulate corrosion at numerous points during and beyond the vessel's design service life and evaluate the vessel's structure for yielding and buckling. A requirement for the digital twin is the ability to support MAESTRO models used for early-stage design.

The subject vessel for the case study was the Legend Class USCG National Security Cutter (NSC). The vessel has a length of 418 ft, displaces 4500 LT, and has operational speed of 28+ knots. The case study was centered around a MAESTRO coarse mesh model containing approximately 17,800 elements which corresponds to a mesh size of roughly one element between frames and one element between decks. Due to the coarse mesh size, multiple stiffeners are associated with each plate element.

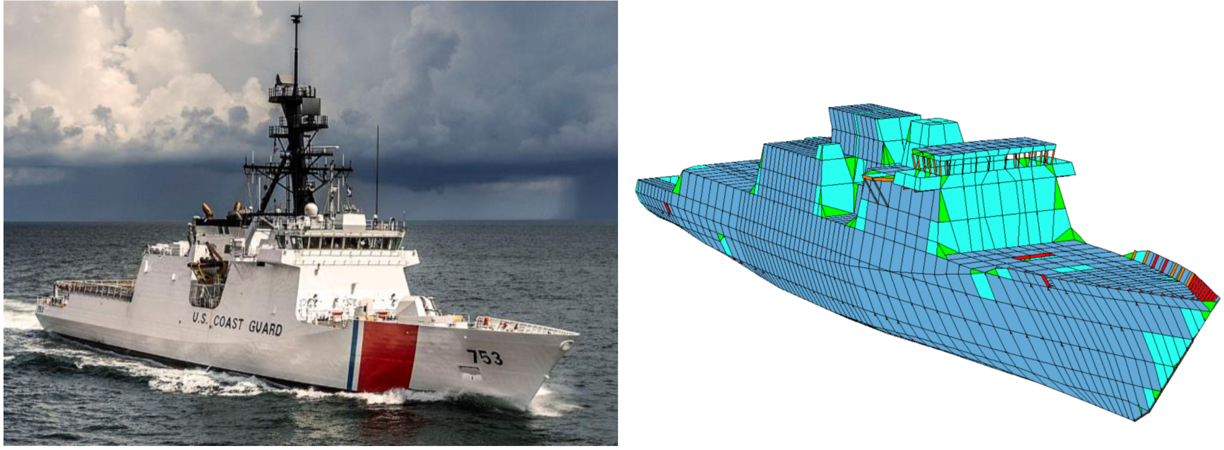


Image source: wikipedia.org

Figure 11: USCG NSC and MAESTRO model

The NSC case study began by identifying the functions commonly performed for a finite element-based structural evaluation of a vessel design. Next the functions required to simulate and evaluate numerous corrosion levels were considered. Both sets of functions were merged to identify the functional decomposition for the digital twin illustrated in Figure 12. The two new models required to implement the digital twin case study are a corrosion application model and a corrosion prediction model. The corrosion application model modifies the thicknesses of the as-designed finite element model to reflect the desired corrosion condition. The corrosion prediction model is used to predict when in the vessel's service life each corrosion level will occur. Each finite element model can only represent a single corrosion instance therefore several functions must be performed in an iterative manner. The digital twin requires new inputs to define the desired corrosion levels that will be simulated. It should also be noted that digital twin functionality does not impact all functions necessary to perform the structural evaluation of the vessel. For example, the seakeeping model will remain unchanged for all corrosion instances.

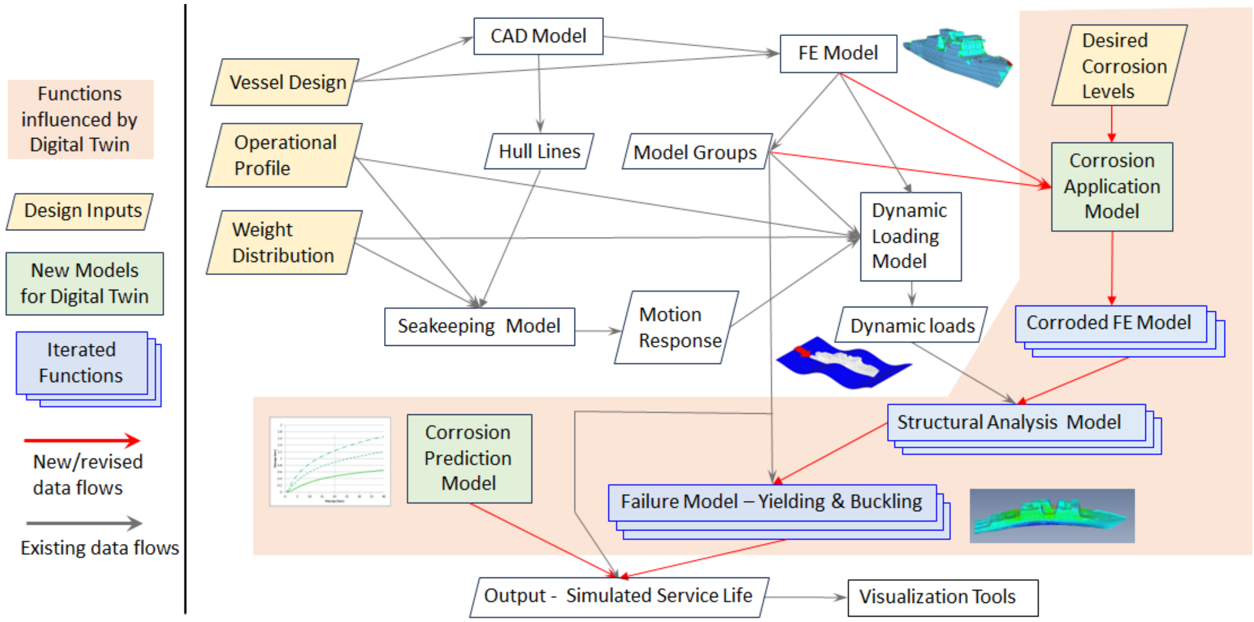


Figure 12: Functional decomposition for NSC Digital Twin

After establishing the functional decomposition, the models and functions were mapped to software tools. For the NSC case study a range of software applications was selected. The mapping shown in Table 3 is illustrative of just one of many software combinations that could be selected to achieve the desired digital twin function. Table 3 maps each model to one software tool, however this is not a strict requirement. For example, the ABS DLA software incorporates the seakeeping model, dynamic loading model, and structural analysis model into the same user interface effectively behaving like a software suite. Likewise other applications such as MAESTRO are capable of performing multiple functions.

Table 3: Model mapping to software tools

Corrosion Application Model	→	Python
FE Model	→	Maestro
Corroded Model	→	Nastran
Seakeeping Model	→	Precal
Dynamic Loading Model	→	ABS DLA
Structural Analysis Model	→	NX Nastran
Failure Model	→	DPC 100-4
Corrosion Prediction Model	→	ClassNK

The data flows highlighted in red in Figure 12 represent new or revised data flows to support the implementation of the digital twin for the NSC case study. The formatting and content of the data transferred is defined by the capabilities of the software applications at either end of the data flow. When the requirements at each end of the data flow are not equivalent, solutions must be formed to enable the necessary interface. For the NSC case study available software import and export utilities were used to prevent the need to develop custom tools to convert data from one file format to another. As an example of this approach, the data exchange between the structural analysis model (NX Nastran) and the failure model (DPC 100-4) was conducted in multiple steps to enable the exchange to be performed using software tools. The structural analysis model was solved with NX Nastran which outputs elemental stresses in a binary format (.op2). For the NSC case study the DPC 100-4 failure models were calculated using Excel which has its own native binary file format (.xlsx). Because neither software supports the other's file format the data flow could not be completed. To resolve the issue, an additional software application, Femap, was used to perform the format conversion. The Femap software is capable of reading Nastran models (.bdf) and analysis outputs (.op2), organizing the desired outputs into a tabular format, and export the table to Excel (.xlsx).

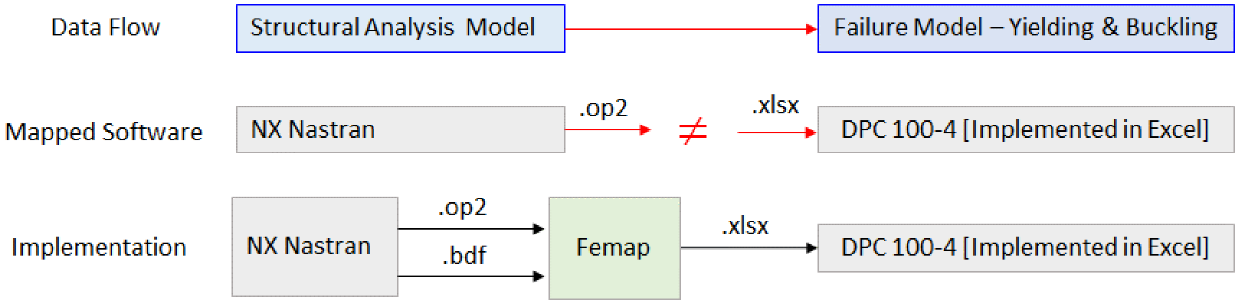


Figure 13: Example resolution of data exchange challenges at functional interfaces

When available software tools cannot perform the necessary data conversions at functional interfaces in the digital twin the use of text files instead of binary files is recommended. Revisiting the prior example, if the Femap software was not available it is possible to request text based output from NX Nastran (.f06) and load text based inputs (.csv) into Excel. A custom tool could be developed to read the stresses from the .f06 file and save them in the desired tabular format with commas as the delimiter.

For the NSC case study a limited number of load cases were assessed for simplicity. Because the ABS DLA software was used to apply the dynamic loads to the finite element model, the standard dominant loading parameters considered for classification were applied which include vertical bending, vertical shear, horizontal bending, bow acceleration and roll. The analysis considered extreme load conditions therefore the IACS North Atlantic wave scatter diagram was applied. Only a single weight distribution was evaluated. The results from all wave load conditions were enveloped such that the reported elemental stress values reflect the highest observed stress level among all the cases. Use of the enveloped stress values allowed more focus to be placed on understanding the role that generating results from multiple corrosion instances will have in interpreting the relative performance of one design alternative to another.

The ability of a digital twin prototype to generate multiple data points for a simulated vessel lifecycle supports outputs for visualizing how data varies with time. For the NSC case study trends in strength capacity were plotted alongside predicted stress levels. As the applied corrosion levels increase, strength capacity decreases while stresses increase due to a reduction in cross section. Failure occurs at the intersection of the two curves when stresses first exceed capacity. The relative slopes of the two curves provide insight into design sensitivity. The left half of Figure 14 is an example of a stress versus capacity plot. The right half of Figure 14 demonstrates how the data can be displayed three dimensionally on the finite element model. In the figure three hull sections are evaluated on a pass/fail basis for each corrosion increment. As the amount of applied corrosion increases, the progression of failures can be tracked. The model-based visualizations help identify which areas remain local failures and those that were just early indicators of broader failures. This type of information provides insight into the type of design alternatives that should be investigated.

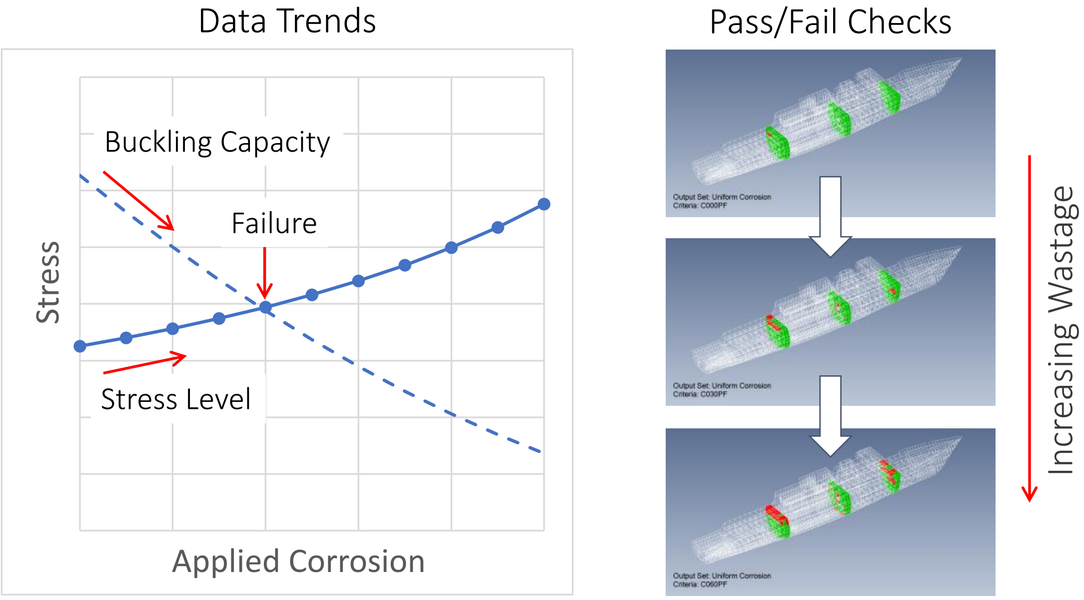


Figure 14: Visualization of predicted failures from Digital Twin

The NSC digital twin prototype was used to evaluate two different design alternatives for a superstructure deck. One design utilized 3/16″ plating and another 1/4″ plating. The results are illustrated in Figure 15. Point 1 represents the wastage limit for the design with the thinner plating. Increasing the plate thickness results in an increase in buckling capacity which extends the wastage limit to point 2. The wastage limit is further increased to point 3 due to the thicker plating reducing the stress level in the deck.

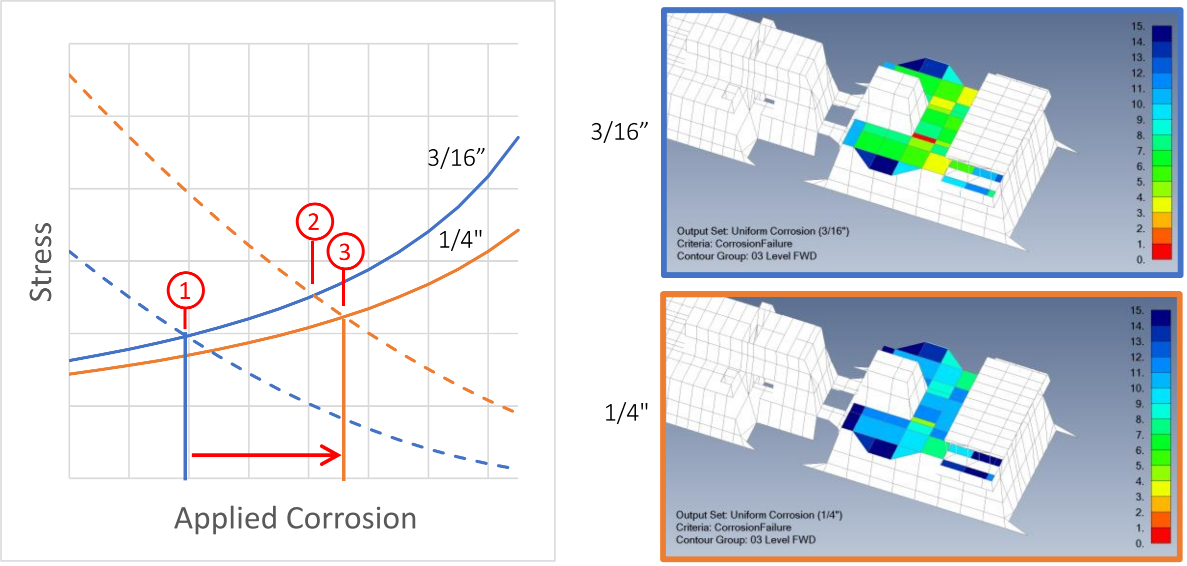


Figure 15: Use of Digital Twin to evaluate design alternatives

The incorporation of operational details into the digital twin enables the effects of different operational profiles to be evaluated. Figure 16 demonstrates the relative impact of four environmental scenarios. Operations on the US Atlantic east coast and Pacific west coast were evaluated under both summer and winter conditions. The results indicate that operational time in the winter on the Atlantic east coast are expected to be most severe while the Pacific west coast during the winter is not expected to cause failure until long past the vessel service life. While no vessel is expected to strictly operate under just one of the four profiles, by plotting all scenarios it is possible to understand the boundaries of the design space.

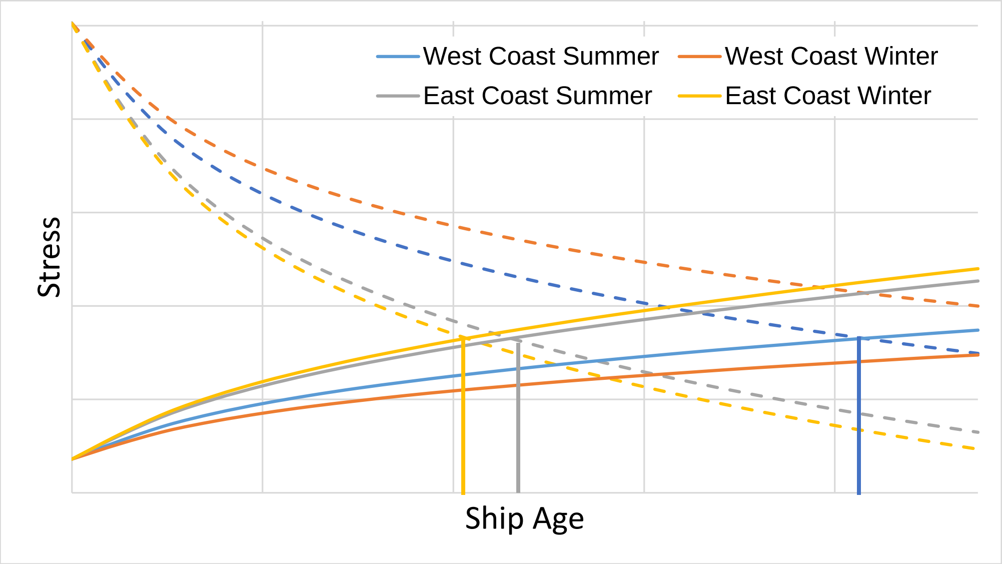


Figure 16: Use of Digital Twin to evaluate different operational profiles

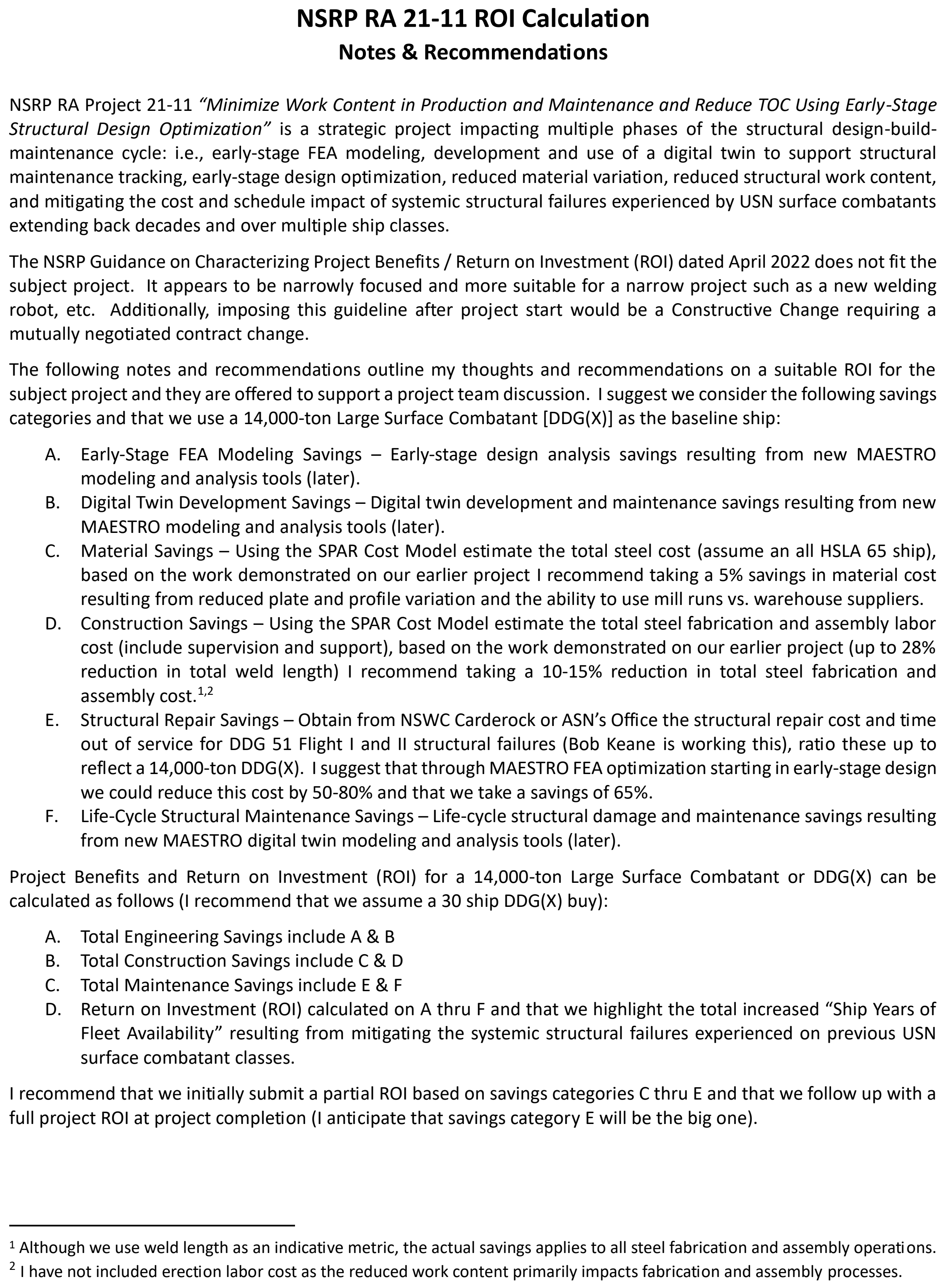
The NSC case study demonstrated that the data generated by a digital twin prototype during early-stage design can be useful for obtaining new insights regarding the expected timing of structural failures during a vessel's simulated service life due to corrosion. While initial simulations simply continue to track the progression of failures, additional logic could be applied to virtually repair the vessel by resetting scantling thickness or coating life before continuing the simulated service life. Adding capability to the digital twin to simulate virtual repairs and maintenance would further support TOC calculations.

Understanding that the development of digital twins is feasible with current technologies, efforts to explore the impact of different parameters is needed to help identify and refine the most impactful use cases for supporting TOC decisions. The collection of actual in-service data will help calibrate and refine models. Finally, more practical experience with structural digital twins will identify how their use integrates into the early-stage design workflow which will support the development of user-friendly implementations.

Task 4 Metrics Assessment. Task 4 assessment metrics include evaluating capabilities improvements for storing survey data, conducting statistical analysis of survey conditions, and performing structural integrity assessments using the interface with MAESTRO. During the project the team developed a Case Study plan and initial analyses to use the USCG NSC to demonstrate the value of having the structural digital twin toolset as a means to show the impact of structural design changes on the in-service performance of the ship's structure. The overview of designing, developing and implementing a digital twin was also prepared under Task 4. For Task 4 the metrics assessment is positive, supporting the definition of specific improvements, demonstrating the capabilities of the tools, and providing a roadmap for digital twin development and implementation.

PROJECT RETURN ON INVESTMENT (ROI)

Return On Investment (ROI) Assessment. An initiative was developed to assess the RA 21-11 Project ROI Assessment. An approach was developed by Pete Jaquith for the ROI assessment that used project related aspects of the ship design, construction and in-service life cycle to decompose the ROI assessment process into manageable components or categories. This document is provided on the following page. Items A through F identify specific categories of cost savings and cost avoidance associated with the application of the software tools being developed under the project. The ROI Assessment focused on the set of cost savings categories: (C) Material Savings, (D) Construction Savings, and (E) Structural Repair Savings.



NSRP RA 21-11 ROI Calculation

Notes & Recommendations

NSRP RA Project 21-11 *"Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-Stage Structural Design Optimization"* is a strategic project impacting multiple phases of the structural design-build-maintenance cycle: i.e., early-stage FEA modeling, development and use of a digital twin to support structural maintenance tracking, early-stage design optimization, reduced material variation, reduced structural work content, and mitigating the cost and schedule impact of systemic structural failures experienced by USN surface combatants extending back decades and over multiple ship classes.

The NSRP Guidance on Characterizing Project Benefits / Return on Investment (ROI) dated April 2022 does not fit the subject project. It appears to be narrowly focused and more suitable for a narrow project such as a new welding robot, etc. Additionally, imposing this guideline after project start would be a Constructive Change requiring a mutually negotiated contract change.

The following notes and recommendations outline my thoughts and recommendations on a suitable ROI for the subject project and they are offered to support a project team discussion. I suggest we consider the following savings categories and that we use a 14,000-ton Large Surface Combatant [DDG(X)] as the baseline ship:

A. Early-Stage FEA Modeling Savings – Early-stage design analysis savings resulting from new MAESTRO modeling and analysis tools (later).
B. Digital Twin Development Savings – Digital twin development and maintenance savings resulting from new MAESTRO modeling and analysis tools (later).
C. Material Savings – Using the SPAR Cost Model estimate the total steel cost (assume an all HSLA 65 ship), based on the work demonstrated on our earlier project I recommend taking a 5% savings in material cost resulting from reduced plate and profile variation and the ability to use mill runs vs. warehouse suppliers.
D. Construction Savings – Using the SPAR Cost Model estimate the total steel fabrication and assembly labor cost (include supervision and support), based on the work demonstrated on our earlier project (up to 28% reduction in total weld length) I recommend taking a 10-15% reduction in total steel fabrication and assembly cost.[1,2]
E. Structural Repair Savings – Obtain from NSWC Carderock or ASN's Office the structural repair cost and time out of service for DDG 51 Flight I and II structural failures (Bob Keane is working this), ratio these up to reflect a 14,000-ton DDG(X). I suggest that through MAESTRO FEA optimization starting in early-stage design we could reduce this cost by 50-80% and that we take a savings of 65%.
F. Life-Cycle Structural Maintenance Savings – Life-cycle structural damage and maintenance savings resulting from new MAESTRO digital twin modeling and analysis tools (later).

Project Benefits and Return on Investment (ROI) for a 14,000-ton Large Surface Combatant or DDG(X) can be calculated as follows (I recommend that we assume a 30 ship DDG(X) buy):

A. Total Engineering Savings include A & B
B. Total Construction Savings include C & D
C. Total Maintenance Savings include E & F
D. Return on Investment (ROI) calculated on A thru F and that we highlight the total increased "Ship Years of Fleet Availability" resulting from mitigating the systemic structural failures experienced on previous USN surface combatant classes.

I recommend that we initially submit a partial ROI based on savings categories C thru E and that we follow up with a full project ROI at project completion (I anticipate that savings category E will be the big one).

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[1] Although we use weld length as an indicative metric, the actual savings applies to all steel fabrication and assembly operations.
[2] I have not included erection labor cost as the reduced work content primarily impacts fabrication and assembly processes.

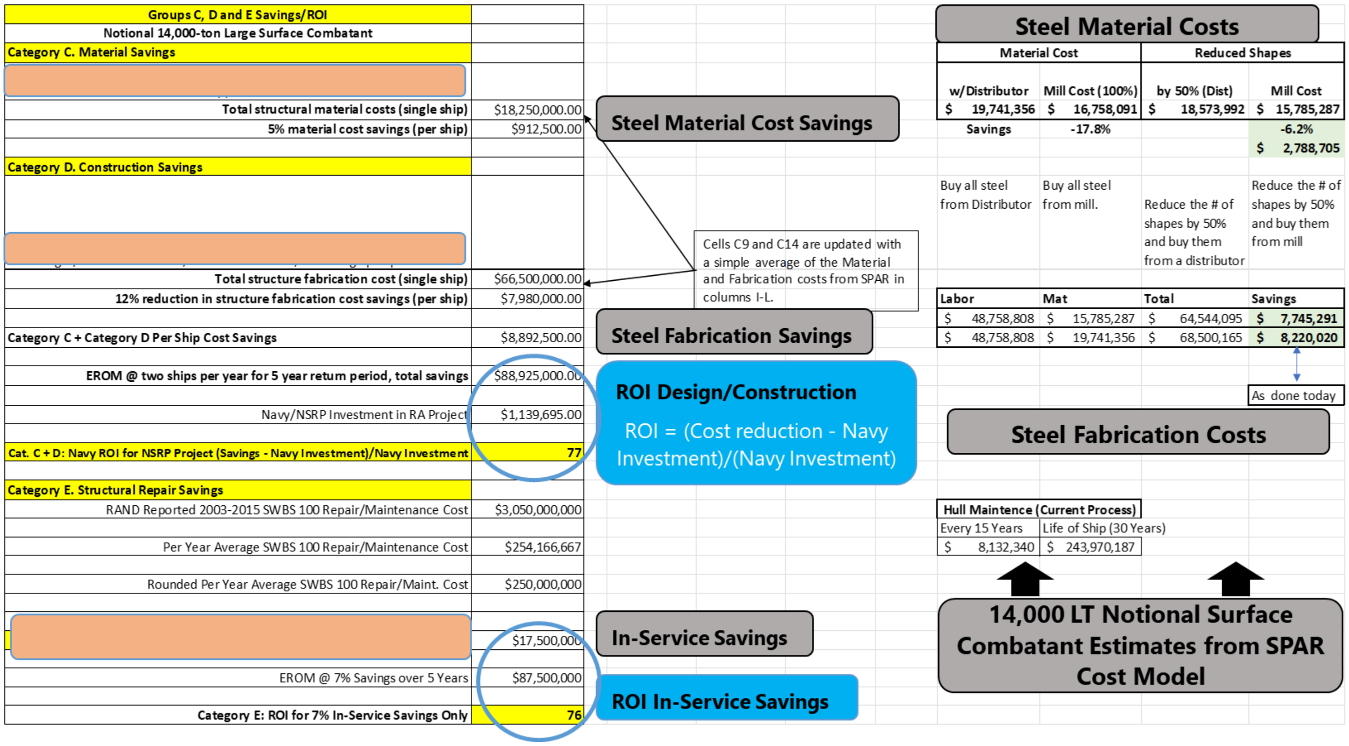
The ROI Assessment used the SPAR work content/cost model for large surface combatants to develop a cost model for a 14,000 LT notional surface combatant. This model uses proven cost estimating relationships (CERs) and the U.S. Navy's ASSET ship concept development software to develop a concept design of the notional ship and uses a full set of SWBS CERs to develop bills of materials and labor quantities and estimated costs for ship construction across all SWBS groups. Based on this notional 14,000 LT combatant, the SWBS Group 100 structural bill of materials was generated, as was the Group 100 steel fabrication cost. Savings categories C, D and E are described below with ROI engineering rough order of magnitude (EROM) calculations shown in the following Figure.

- **Category C. Material Savings.** The SPAR model was used to estimate the total steel cost based on an all HSLA 65 structure. A 5% cost savings on the steel procurement was used based on material cost savings resulting from reduced plate and profile variation and the ability to use mill runs versus warehouse suppliers.
- **Category D. Construction Savings.** The SPAR cost model was used to estimate the total steel fabrication and assembly labor cost. Based on structural optimization examples performed using the project tools showing weld length reductions as high as 28%, a 12% reduction in total steel fabrication and assembly cost was used for the ROI calculation.
- **Category E. Structural Repair Savings.** Numerous reference studies, including the RAND study documented earlier in this report, document surface ship Group 100 structural repair and maintenance costs on the order of $250,000,000 per year. These costs are the result of structural damage from heavy weather, structural fatigue damage/cracking, and corrosion damage. Based on the use of project tools to design more robust structures and improved design for coatings a 7% savings in these costs is used for the ROI Assessment.

ROI Results. As shown in the ROI figure below, Categories C. Material Savings and D. Construction Savings combine for savings based on two ships per year and the NSRP standard five-year ROI EROM Return Period to generate an ROI for the RA 21-11 project of 77. The Category E. Structural Repair Savings generates an ROI EROM of 76. The target NSRP ROI is a value of 2, which is far exceeded by the calculated EROM ROI values. Additional material supporting the ROI assessment can be found in Appendix E.

Phase 3 – Return On Investment (ROI) Assessment - NSRP RA 21-11 ROI Calculations and Results

ROI Design/Construction=77:1 ROI In-Service=76:1 NSRP ROI Goal/Target=2:1



Groups C, D and E Savings/ROI	
Notional 14,000-ton Large Surface Combatant	
Category C. Material Savings	
[redacted]	
Total structural material costs (single ship)	$18,250,000.00
5% material cost savings (per ship)	$912,500.00
Category D. Construction Savings	
[redacted]	
Total structure fabrication cost (single ship)	$66,500,000.00
12% reduction in structure fabrication cost savings (per ship)	$7,980,000.00
Category C + Category D Per Ship Cost Savings	$8,892,500.00
EROM @ two ships per year for 5 year return period, total savings	$88,925,000.00
Navy/NSRP Investment in RA Project	$1,139,695.00
Cat. C + D: Navy ROI for NSRP Project (Savings - Navy Investment)/Navy Investment	**77**
Category E. Structural Repair Savings	
RAND Reported 2003-2015 SWBS 100 Repair/Maintenance Cost	$3,050,000,000
Per Year Average SWBS 100 Repair/Maintenance Cost	$254,166,667
Rounded Per Year Average SWBS 100 Repair/Maint. Cost	$250,000,000
[redacted]	$17,500,000
EROM @ 7% Savings over 5 Years	$87,500,000
Category E: ROI for 7% In-Service Savings Only	**76**

Cells C9 and C14 are updated with a simple average of the Material and Fabrication costs from SPAR in columns I-L.

ROI Design/Construction

ROI = (Cost reduction - Navy Investment)/(Navy Investment)

Material Cost		Reduced Shapes	
w/Distributor	Mill Cost (100%)	by 50% (Dist)	Mill Cost
$ 19,741,356	$ 16,758,091	$ 18,573,992	$ 15,785,287
Savings	-17.8%		-6.2%
			$ 2,788,705
Buy all steel from Distributor	Buy all steel from mill.	Reduce the # of shapes by 50% and buy them from a distributor	Reduce the # of shapes by 50% and buy them from mill

Labor	Mat	Total	Savings
$ 48,758,808	$ 15,785,287	$ 64,544,095	**$ 7,745,291**
$ 48,758,808	$ 19,741,356	$ 68,500,165	**$ 8,220,020**

As done today

Hull Maintence (Current Process)	
Every 15 Years	Life of Ship (30 Years)
$ 8,132,340	$ 243,970,187

PROJECT FINAL REPORT SUMMARY

Major Developments

Through the project the MAESTRO Marine team has advanced early-stage design tools to Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization for each task as follows:

Task 1. MAESTRO Integration with Rhino. Significant developments were completed on the Rhino plugin for MAESTRO in support of Task 1: The MAESTRO finite element model can be imported into Rhino3D, and the Rhino mesh model can be brought into MAESTRO. These capabilities support the MAESTRO finite element model's Topology, MAESTRO Groups, MAESTRO Loads and querying elements and nodes in Rhino. Capabilities were developed that support model persistence in Rhino 3dm and MAESTRO XML formats, creating Frame Systems, creating Stiffener Layout Systems, creating Strake Properties which allow regions to be assigned different structural scantlings, and creating Parametric Mesh Generation so updates in frame system (frame spacing, stiffener spacing, bulkhead locations, etc.) will automatically update the mesh in early-stage design. Corrosion groups and corrosion details can be assigned in Rhino for import into MAESTRO.

These developments represent significant progress toward completion of a working and distributable MAESTRO/Rhino3D Two-way Interface software product as a "Rhino Plugin", which is the primary objective of Task 1 of the RA project.

It is also noted that members of the NSRP Project Team have been engaged with the Navy's DDGX Design Team regarding the application of the tools being developed under the NSRP RA 21-11 Project to the Concept Design Phase of DDGX. The DDGX Design Team is developing ship geometry in or compatible with the Rhino environment, which facilitates application of capabilities being developed under the NSRP RA Project directly to the DDGX early-stage design. This enables rapid and efficient use of 3D finite element analysis to support the ship's concept design. This work is now being performed by MAESTRO Marine for the DDGX Navy-led Design Team.

Task 2. Improve the Handling of Cost Metrics. A MAESTRO Interface with SPAR's Work Content/Cost Models was further developed and tested during the project. This interface groups the ship's structural model defined in MAESTRO into data output from MAESTRO that transfers structural and ship design parameters to the SPAR work content/cost model. This interface has been developed and tested successfully. This MAESTRO-SPAR Interface provides the early-stage design team with a more comprehensive assessment of the work content and cost for the concept being studied and yields important metrics to assess and evaluate alternate structural designs during the early-stage or concept design process.

Structural Affordability Opportunities, such as tracking weld length, coating areas, and reducing numbers of different plate types and structural profiles identify aspects of structural design that can impact the construction work content and the through-life maintenance and repair costs and ship availability. Weld length for the structural design was determined to be the most effective single metric for assessing Group 100 work content. For early-stage design, when Production Engineering is likely not participating with the design team, weld length can be used as a key metric to achieve lean design and design for production. MAESTRO currently calculates weld length and coating areas (by assigned groups) for the structure, for both early-stage design coarse mesh models and for more refined mesh models used in later stages of design. These capabilities directly support the basic work content metric of weld length for the structure and generate metrics of paint/coating areas. The weld length and paint areas are key metrics that can be used for structural optimization.

Task 3. Optimize Structure for Reliability and Producibility as Early in Design as Possible. The Task 3 objective was to develop a software module that implements a minimum work content structural design and optimization algorithm to potentially serve as an alternative to the minimum weight optimization algorithm derived from the Structural Synthesis Design Program (SSDP), which is currently used to define structural scantlings in ASSET. Task 3 did successfully develop software that offers an alternative multi-objective structural design tool that optimizes the design to ensure that U.S. Navy structural design criteria are met while addressing design objectives that reduce fabrication work content and enhance in-service structural performance such as fatigue mitigation, and then search for minimum weight solutions. The technical approach for the developed software is provided under Appendix D of this report. An interface of the RA project tools with U.S. Navy early-stage design tools such as the Rapid Ship Design Environment (RSDE) and Integrated Structural Design Environment (ISDE) via the Navy's LEAPS (Leading Edge Architecture for Prototyping Systems) early-stage design product model was also considered under Task 3. In a January 2024 project meeting with Carderock, Robert Keane, and MAESTRO Marine, the Navy acknowledged that funding has been planned and requested in 2024 to conduct this evaluation of the project developed least work content and least weight structural design tool.

Task 4. Implement a Structural Digital Twin. Task 4 focused on assessing the prototype structural digital twin provided to the project by U.S. Coast Guard SFLC for its functionality and potential to serve as a fielded structural digital twin. This digital twin was reviewed, improved and provided back to the USCG SFLC for their continued use in providing in-service structural assessments and engineering for the USCG fleet. This was a successful aspect of Task 4. Additionally, ABS also reviewed and assessed the prototype digital twin and developed an important contribution to Task 4 and the project by developing a technical approach and Case Study examples of how digital twins should be designed, developed and implemented. This work, provided in the project Final Report, offers a technical roadmap for organizations to use in developing digital twins to support their requirements. This Task 4 work also demonstrates using the USCG National Security Cutter as a test case, how structural digital twins can be used effectively during early-stage design to assess service life performance under corrosion or other structural degradation. This in turn provides design alternatives to mitigate the TOC of a new ship class during its long service life.

Realized Benefits to Industry and Navy

At the project completion actual benefits to industry and Navy are maturing and being realized. The work completed confirms the potential to realize gains in early-stage structural design space exploration and cost reduction for ship construction and in TOC. This project is motivated in part by high lifecycle repair and maintenance costs associated with structural cracking and corrosion on Navy and USCG vessels. The project work, tools and capabilities related to early-stage design and for work content/cost modeling is under active discussion with respect to implementation near-term under ongoing U.S. Navy programs such as CREATE Ships and new ship design programs such as DDGX. The multi-objective structural design software resulting from this project will be a critical ship design tool to enable the Navy-Industry Collaborative Ship Design acquisition strategy recently announced by the CNO and the Acting ASN (RDA) for DDGX. The project lead, MAESTRO Marine, is currently under tasking to support the DDGX Design Team with the tools developed under this NSRP RA project. The software being developed under the project has reached a level of maturity that provides confidence in the ability of the project team to offer project technology transfer through the distribution of commercial grade software tools.

Technology Transfer

The software tools that have been developed under the project are being presented to the industry through forums including the NSRP All Panel Meeting held in March 2023 and a technical symposium paper presented at the SNAME 2023 SMC conference in San Diego in September 2023. The developed tools are being distributed to, trained on, reviewed by and used by team members including Austal USA, ABS and USCG Surface Forces Logistics Center. This usage has provided Quality Assurance (QA) review and feedback for use during the project. The application of the tools of the project are in use now by MAESTRO Marine in support of the DDGX Design Team. These technology transfer actions provide strong evidence that the transfer has already begun and will continue following completion of the project.

APPENDIX A. PROJECT RESULTS SUMMARY

PROJECT RESULTS SUMMARY
Project Title:

Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization
NSRP RA Control No. 21-11
Task Order Agreement #2022-328-001

Executive Overview

This project implemented production planning software with high-fidelity physics-based structural design and optimization software for practical use during early-stage ship design. These tools will result in:

- Assurance that a wide range of structural design criteria are met while improving structural producibility and workflow and reducing work content and cost in both production and maintenance.
- Improved structural design to reduce service-life corrosion, heavy weather damage, and structural fatigue cracking, while mitigating excessive structural repair and maintenance costs and increasing ship availability
- A comprehensive structural design space exploration capability for use in U.S. Navy and shipbuilder early-stage ship design processes resulting in robust structures with reduced Total Ownership Costs (TOC) of ships for the U.S. Navy and U.S. Coast Guard.

The project’s digital twin component also addresses inadequate ship structural performance of in-service vessels which has resulted in unsustainable structural maintenance costs. This new software will implement a systematic method and toolset for tracking the structural condition and damage of Navy and Coast Guard ships, which enables efficient and accurate assessment of the structural integrity of the ships and supports engineering cost-effective repair and maintenance plans.

Contact Information

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Cell: 410-829-4272

Collaborators

PROJECT TEAM MEMBERS AND ROLES

Project Participant	Role and Key Contribution
MAESTRO Marine LLC	Project Lead – MAESTRO Marine will direct/coordinate the efforts of the entire project team. MAESTRO Marine will lead the software development effort as the creators and developers of the MAESTRO ship structural analysis and optimization software.
Austal USA	A major U.S. shipbuilder; will provide the ship structural design and production/work content planning requirements and collaboration for the team.
Naval Surface Warfare Center (NSWC) Carderock Division, Code 65 – Ship Structures	US Navy lead technology group for ship structural design and for development of the CREATE Ships Integrated Structural Design Environment (ISDE) software; will provide U.S. Navy use cases for project team software design, development and integration with Navy ship design tools.
U.S. Coast Guard - Surface Forces Logistics Center (SFLC)	Lead USCG organization for in-service engineering for USCG fleet; will provide key use cases and demonstrations for structural condition database development and applications under the project.
American Bureau of Shipping (ABS)	Major Ship Classification Society and responsible for structural design rules and criteria for US Naval Auxiliaries, U.S. Navy Unmanned Vessels, Military Sealift Command (MSC) ships and commercial ships; will provide technical guidance and oversight for implementation of design criteria and direct analysis.
Robert Keane – Ship Design USA, Inc.	Former U.S. Navy Chief Naval Architect; will advise on Navy ship design and construction processes and ship design tool development.
P. Jaquith & Associates	Peter Jaquith is an expert in Lean Design and Design for Production; former Shipbuilder Executive; will provide direction and guidance for use cases and applications related to least work content objectives.
SPAR Associates, Inc.	Experts in ship cost estimating and production planning and development of related software models and tools; will provide direction and guidance in these areas

Description of Methodology

This project focused on developments made to the ship structural design and optimization software MAESTRO (www.maestromarine.com) and in related topic areas that included defining technical approaches for implementation of structural digital twins to support early-stage design and ship engineering though the in-service life of the vessel.

- Shipbuilders frequently perform U.S. Navy and U.S. Coast Guard contracts to develop conceptual and/or preliminary designs for new shipbuilding programs. The structural design and optimization tools developed under this project are focused on providing shipbuilder (and Government) design teams with software tools to meet a wide range of structural design specifications and criteria while at the same time reducing the work content and cost for fabricating the structure.

- The tools developed will be applicable to all sizes and classes of ships from U.S. Coast Guard surf-rescue craft and cutters, to surface combatants, amphibious ships, transport vessels, and aircraft carriers.
- The structural design toolset, see Figure 1, supports the structural design development from concept through preliminary and functional/contract design. A number of U.S. shipbuilders and design agents (e.g., Fincantieri Marinette Marine, HII-Ingalls Shipbuilding, GD/Bath Iron Works and GD/NASSCO) already use and apply the core, existing MAESTRO software tools to their designs. These shipbuilders can immediately implement the project results in their ship design and production workflow.

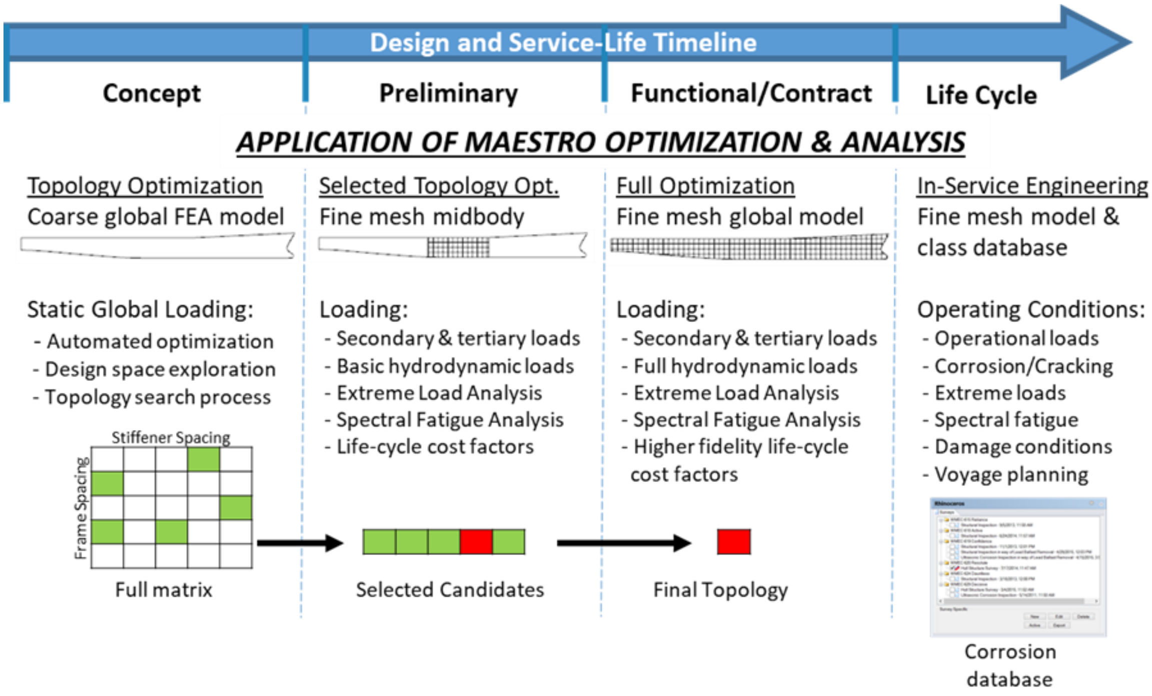


Figure 1. MAESTRO Structural Design Tools Apply Across the Life Cycle

- The U.S. Navy and U.S. Coast Guard and a number of their design support contractors are also already long-term MAESTRO users. The project results can immediately be implemented by these organizations in designing more producible structures for the large bow-wave of new ship designs.
- The digital twin results from the project can be applied to all in-service Navy ships and USCG cutters by both industry and Government.
- The software developed under the project is being incorporated into updates to the commercial software. Users of the software, including U.S. Navy, U.S. Coast Guard, shipbuilders and design firms will receive these new updates with their normal/routine updates to the software that are downloaded by the users under Maintenance & Support contracts.

Resources Needed

The resources needed to implement this project are a small team of staff within the engineering department of a shipbuilder, government design team or design firm. These staff include the Chief Naval Architect and a group of 2-4 structural engineers who are directly involved in designing ship structure for new designs and for in-service repairs and modifications. Some of these staff should have experience using structural finite element modeling and analysis software tools.

This small team of engineers can acquire the commercial software, MAESTRO, or its updates and with a nominal level of training, typically 1-2 weeks for new users, be able to begin developing designs with the tools developed under this project.

In the case of the digital twin, implementation technical approaches have been developed and documented by the project team in the Final Report. These methods can be used by a shipbuilder, design firm or U.S. Navy/USCG office to develop a specific plan for a digital twin that will meet their requirements and be compatible with existing methods and tools in use at those locations. Development and implementation times will vary depending on the extent of numbers of vessels and relative complexity of the intended applications.

Evaluation and Analysis Methods

A set of metrics were developed under the project Statement of Work (SOW), see Table 1 below. These metrics are associated with each of the four tasks of the SOW and were monitored and assessed in each of the four Phase Completion Technical Reports, including the project Final Report.

The tools to support rapid development of ship structural finite element models for early-stage design, under SOW Task 1, are being used at the project completion and going forward in conjunction with the DDGX Design Team. This environment will provide an excellent testing phase for the new software tools. Additional improvements will be made as needed to ensure the tools are productive and efficient.

Table 1: Project Metrics

Metric	"As-Is" Baseline	Project Goal	Delta	% Change (+/-)	Tracking & Reporting Plan
Task 1 Metrics - Improve early-stage finite element modeling time for full ship models	60 Days	30 Days	30 Days	-50%	Use a representative ship design with actual modeling times assessed using "before" versus "after" modeling tools. Monitor and report with each Phase completion.
Task 2 Metrics - Provide more accurate and faster input for structural work content metrics	Limited input interfaces exist	Develop an effective set of interfaces	Significant improvement	-50% in time required; +50% in accuracy	Report for each Phase as process improvements are implemented using example inputs.
Task 3 Metrics – Complete and test the least work content algorithm; assess interface plans for RA tools with US Navy tools	No least work content algorithm exists; no interface plans for RA tools exist	Successful development and test of least work content algorithm; effective interface plans developed	New tools available for US Navy use within Navy ship design environment	+100%	Evaluate at completion of each Phase, including: • Global structural weight • Hull girder properties • Structural VCG • Structural performance metrics, e.g. stresses and limit states • Number of unique plate/stiffener combinations • Number of unique design cluster configurations • MAESTRO-based structural work content metrics
Task 4 Metrics – Digital Twin provides in-service databasing, and interface for structural integrity assessments.	A limited functionality prototype tool exists at the start of the project	Improve and demonstrate enhanced digital twin functionality	Significant improvements in databasing capabilities, data analysis and structural assessment tools	+50%	Evaluate at completion of each Phase, including: • Structural survey databasing tools • Statistical analysis of survey data • Structural integrity assessment of in-service conditions
Technology Readiness Level	TRL 7-8; Prototype demonstrated and system qualified	TRL 8-9; System qualified; proven through mission operations			The metrics cited above and feedback from the shipbuilder users/participants will be used to assess TRL progress.

Time Estimate

As discussed above under the topic of resources needed for implementation, the time required for the software tools to be implemented is modest. If anything, the new tools should flow into use with the normal workflow of applying finite element analysis to a ship design. This is an activity that most shipyards and design firms, and government design teams already have proficiency with. Additional customization should not be required since the software is developed as a generic modeling and analysis suite that can be effectively applied to a broad range of ships and floating structures without customization.

Limitations or Constraints

Factors that can limit the implementation of the results of this project include:

- Types of ships being designed and constructed. The ship specifications associated with a new ship design, either commercial or naval, include requirements and criteria for structural design. Naval surface combatant specifications routinely require full ship finite element analysis as contract deliverables. Ships designed to meet commercial criteria, such as ABS Rules, may have different requirements. The ship specs will influence adoption.
- While larger shipyards have teams of structural engineers with established proficiency in finite element modeling and analysis, not all, and especially smaller shipyards, have these structural teams developed. The same can be said for design firms also. Although, it is becoming relatively common and normal for medium to large shipyards and many design firms to have well-established finite element modeling and analysis capabilities.

Major Impacts on Shipyard

Implementation of the project tools affects engineering and production planning for the ship structure. These activities can be supported by existing staff and proficiencies. Major impacts are not anticipated. The applied project design tools can result in more efficient and robust structural designs that also improve structural fabrication. Organizations such as the UCSG SFLC have used the project's predecessor software to support in-service structural assessment and engineering for many years. These processes will be improved using the project results.

Cost Benefit Analysis/ROI

The project's cost benefits were assessed under the NSRP Return on Investment (ROI) guidance. The ROI is the ratio of cost savings or avoidance less the project cost, divided by the project cost. An ROI was developed for the ship construction phase for a notional 14,000 LT surface combatant vessel class, assuming two ships being built per year. Material (steel) savings and Construction/fabrication savings were combined for savings based on two ships per year and the NSRP standard five-year ROI Engineering Rough Order of Magnitude (EROM) return period to generate an ROI for the RA 21-11 project of 77. Addressing the in-service phase of the ship class lifecycle, Structural Repair Savings generated an ROI EROM of 76. The target NSRP ROI is a value of 2, which is far exceeded by the calculated EROM ROI values for this project.

Lessons Learned

The following lessons learned can be cited for the project:

- Team member staff resources are limited and can be difficult to capture for work on the NSRP RA project. This was evident especially for the shipbuilder team member. It can be difficult for an NSRP research project to compete with actual ship design and construction projects.

- Collaboration from government team members can also be resource constrained or may not be effectively staffed. This project experienced difficulty getting planned participation from U.S. Navy team members, although support from the USCG/SFLC was excellent.
- The support provided by ship classification was excellent with substantial support to project objectives and deliverables being provided. The team's specialist consultant team members also provided excellent and timely contributions to project objectives and deliverables.
- For a shipyard planning to implement the results of the project, the advice would be to have an actual contract-based requirement as the motivation/driver. This will make resource allocation more effective, to ensure the right personnel with adequate hours are assigned to the implementation process. These personnel also need to have proper backgrounds and qualifications to support the work required for implementation. Success will also depend on having top-level management, e.g., within the engineering department, support for the implementation from the VP Engineering and Chief Naval Architect.

Technology Transfer

The following Table summarizes ongoing activities being used to provide follow-up to the project for transfer of the technology to industry.

Stakeholders	Engagement	Continuing Engagement
Shipyard Sponsors	Austal USA: MAESTRO Marine has briefed key Austal engineering staff members for a number of years and developed a working relationship that is committed to implementing the project tools and the overall MAESTRO toolset within the shipyard.	Key Austal staff are involved in many of the project communications and deliverables. Discussions continue to have Austal's objective to apply the tools to an actual design project (separate from the NSRP project) during the execution of the project.
Technical Approval Authorities	NAVSEA 05P, Ship Integrity and Performance Engineering; SEA 05P4 David Qualley, Ship and Submarine Structures; through briefings over recent years by Tobin McNatt and Bob Keane, these key NAVSEA technical authorities have been kept appraised of developments with the MAESTRO software capabilities and applications, as well as progress on this project. Support for the project tools being applied to U.S. Navy ship design is being cultivated at these important technical levels.	Tobin McNatt and Bob Keane continued to lead the interface with senior NAVSEA, Carderock and ONR staff during the project to provide updates, providing copies of project Quarterly presentations and other information about the status and progress of the project. These key Navy staff members, including Jonathan Stergiou, Timothy Mierzwicki and Woei-Min Lin, are providing key insight related to technical warrant aspects of the project that may arise, as well as being an important interface regarding the specific approaches for the project results to be applied within the Navy's CREATE Ships software development project, which Bob Keane continues to support as a consultant.
CREATE Ships Implementation	NSWC Carderock Code 65, Skylar Stephens and Dan Iqbal, participated in the NSRP RA project. They have coordinated closely with Bob Keane and Tobin McNatt to support the development of tasking during and following the RA project that can be utilized within the	NSWC Code 65 was a Project Team Member and was directly engaged in the Project Task 3 development process. Ongoing discussions are focused on the NSRP Project Task 3 implementation within the CREATE

	CREATE Ships ISDE structural design software, which is integrated with the early-stage Rapid Ship Design Environment (RSDE) design software.	Ships Integrated Structural Design Environment (ISDE) and Rapid Ship Design Environment (RSDE).
Guided Missile Destroyer (DDGX) Program Office (PMS 460) and DDGX Shipbuilders Ingalls Shipbuilding and GD Bath Iron Works	The NSRP Project Team has been engaged with the DDGX design team and shipbuilders on an ongoing basis regarding the potential value of utilizing the NSRP Project results associated with designing robust ship structures during early-stage design.	Focused discussions with the DDGX Design Team have resulted in tasking to implement the tools developed under the NSRP Project into the DDGX concept design process. This work started in late 2023 and is ongoing. This work is being performed by MAESTRO Marine, Bob Keane, Pete Jaquith, and SPAR Associates.
U.S. Coast Guard Surfaces Forces Logistics Center (SFLC)	USCG SFLC is an NSRP Project Team Member. Collaboration between the NSRP Project Team and SFLC continues to support the long-standing technical relationship between MAESTRO Marine and SFLC's ship structures group.	NSRP Project results have been provided to SFLC during the project for testing and implementation within their in-service cutter structural maintenance and repair workload.
Commercialization Partners	MAESTRO Marine LLC, the NSRP Project prime contractor and also the worldwide distributor of the MAESTRO ship structural design software products, will be the Commercialization Partner for the project results. MAESTRO Marine's engagement has been in place for decades through the key personnel Tobin McNatt and Ming Ma, Ph.D.	Tobin McNatt as the NSRP Project Manager and Ming Ma as the lead software developer have provided engagement throughout the project. These two individuals have supported the commercialization of MAESTRO for the past three decades and will ensure continuity of the NSRP Project results into the commercially supported MAESTRO software.
Implementation User Group	The Implementation User Group includes structural engineers, naval architects, production engineers and cost engineers at shipbuilders, design firms, and U.S. Navy and U.S. Coast Guard organizations.	There are existing MAESTRO users within the Project Team and also within the broader User Group organizations identified.

Implementation

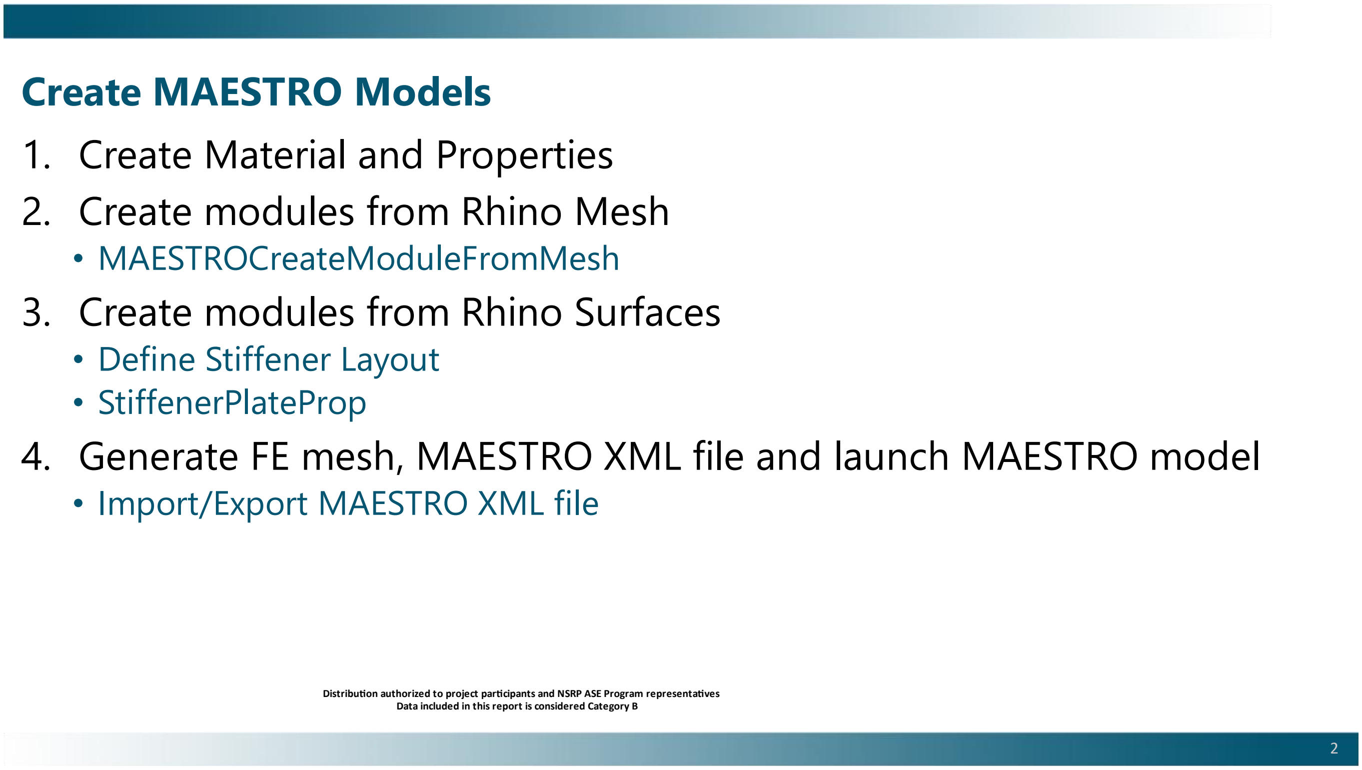
The following summarize current and future implementation of the results for each Project Task.

- Task 1. The Rhino/MAESTRO Plugin will be made available to existing and new users of the MAESTRO software. Implementation will result from seeing usage of this new module as a component of using the overall MAESTRO software system. It is likely that the improved finite element modeling tools being developed under Task 1 will result in adoption by many MAESTRO users in the ship design and shipyard users communities, including Carderock and USCG SFLC. MAESTRO Marine is currently using the Task 1 software on DDGX tasking in support of the Navy Design Team.
- Task 2. The Task 2 enhancements to metrics for design and optimization of ship structures are embedded into the MAESTRO software. This means that existing and new users will have these tools at their disposal when using MAESTRO and can derive the benefits of these new metrics.

- Task 3. Task 3 software will be successfully implemented if the U.S. Navy (Carderock Code 65) completes its evaluation and decides to incorporate the new multi-objective optimization algorithm and method into the CREATE Integrated Structural Design Environment (ISDE) and Rapid Ship Design Environment (RSDE). These are major components of U.S. Navy ship design tools. A meeting was completed with Carderock Code 65 during Quarter 8 of the project, and the government representatives stated that they have funding planned for 2024 that would support their evaluation and potential incorporation of the project software into ISDE/RSDE.
- Task 4. The Task 4 prototype Structural Digital Twin was reviewed and groomed under the RA project and is already experiencing successful implementation by usage of current results from the NSRP RA project within the USCG Surface Forces Logistics Center (SFLC). The digital twin development technical approach prepared and documented under Task 4 provides a set of steps that an organization can take to design and implement an effective structural digital twin system. This provides a roadmap for such future implementations.
- Shipbuilder and Design Agent Implementation Candidates. Key Stakeholders, the following shipbuilders, most of which already license MAESTRO software, are candidates for implementing results of the project: Austal USA, Ingalls Shipbuilding, GD Bath Iron Works, Fincantieri Marinette Marine, GD NASSCO, Newport News Shipbuilding, Vigor Shipyards as well as design agents such as Gibbs & Cox and Glosten. Their respective implementation of project results will occur through annual software license updates and future adoption of the MAESTRO commercial software tools.

APPENDIX B. RHINO-MAESTRO PLUGIN FUNCTIONALITY

Under project Task 1, the Rhino-MAESTRO Plugin was developed to leverage the powerful Rhino CAD/Surface modeling software environment for the purpose of developing MAESTRO structural finite element models. The following slides depict the core functionality that has been developed under the project.



Create MAESTRO Models

1. Create Material and Properties
2. Create modules from Rhino Mesh
    - MAESTROCreateModuleFromMesh
3. Create modules from Rhino Surfaces
    - Define Stiffener Layout
    - StiffenerPlateProp
4. Generate FE mesh, MAESTRO XML file and launch MAESTRO model
    - Import/Export MAESTRO XML file

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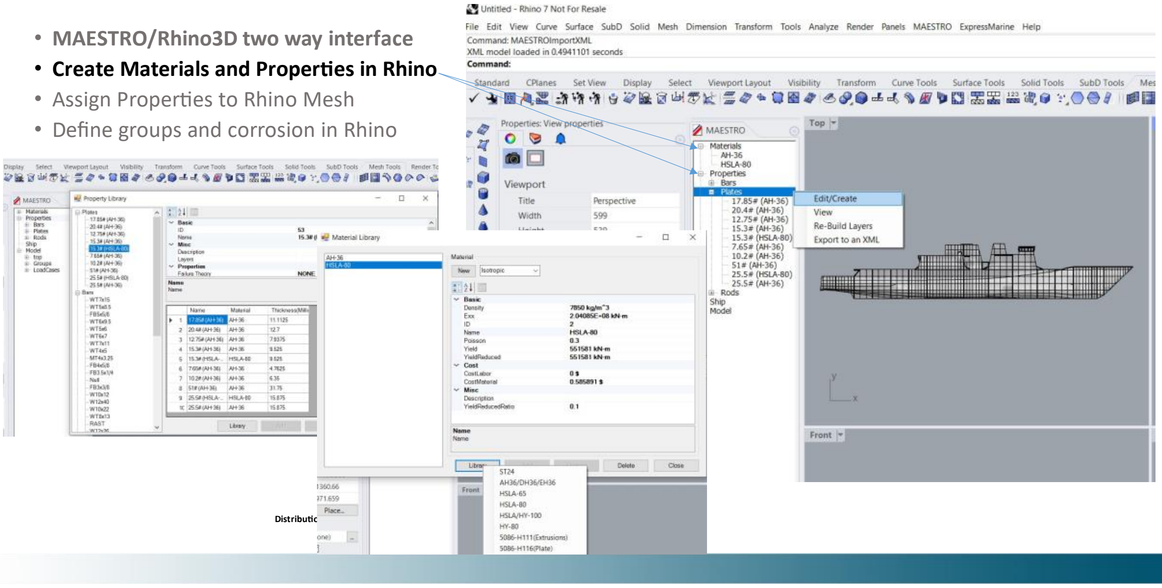
2

1. Create Material and Properties

- **MAESTRO/Rhino3D two way interface**
- **Create Materials and Properties in Rhino**
- Assign Properties to Rhino Mesh
- Define groups and corrosion in Rhino



Command: MAESTROImportXML
XML model loaded in 0.4941101 seconds
Command:

Title	Perspective
Width	599

Basic	
ID	53
Name	15.3# (
Misc	
Description	
Layers	
Properties	
Failure Theory	NONE

Name
Name

	Name	Material	Thickness(Milli
1	17.85# (AH-36)	AH-36	11.1125
2	20.4# (AH-36)	AH-36	12.7
3	12.75# (AH-36)	AH-36	7.9375
4	15.3# (AH-36)	AH-36	9.525
5	15.3# (HSLA-...	HSLA-80	9.525
6	7.65# (AH-36)	AH-36	4.7625
7	10.2# (AH-36)	AH-36	6.35
8	51# (AH-36)	AH-36	31.75
9	25.5# (HSLA-...	HSLA-80	15.875
10	25.5# (AH-36)	AH-36	15.875

Basic	
Density	7850 kg/m^3
Exx	2.04085E+08 kN-m
ID	2
Name	HSLA-80
Poisson	0.3
Yield	551581 kN-m
YieldReduced	551581 kN-m
Cost	
CostLabor	0 $
CostMaterial	0.585891 $
Misc	
Description	
YieldReducedRatio	0.1

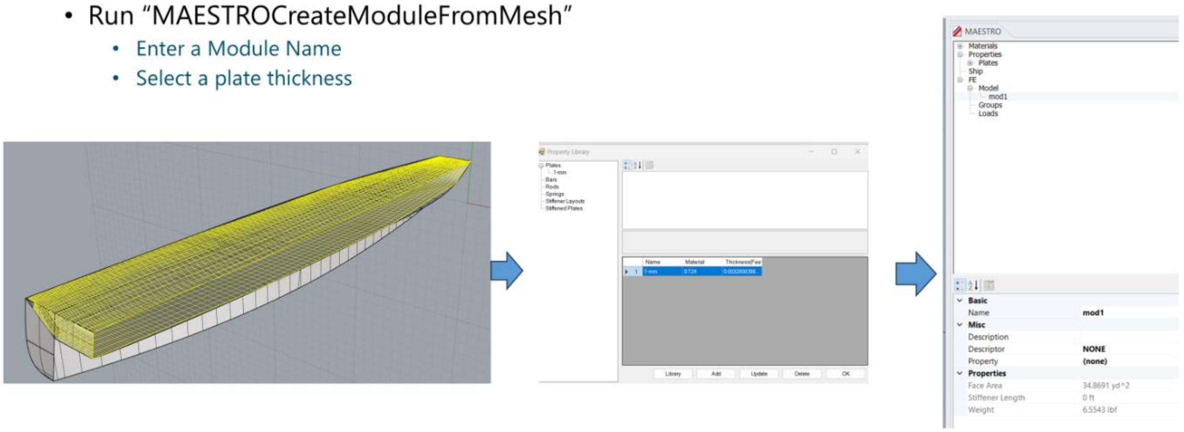
Name
Name

1360.66
971.659

Distributio

2. Create modules from Rhino Mesh

- Generate a Rhino Mesh (QuadReMesh, …)
- Run "MAESTROCreateModuleFromMesh"
  - Enter a Module Name
  - Select a plate thickness



	Name	Material	Thickness(Fee
1	1-mm	ST24	0.0032808398

Basic	
Name	mod1
Misc	
Description	
Descriptor	NONE
Property	(none)
Properties	
Face Area	34.8691 yd^2
Stiffener Length	0 ft
Weight	6.5543 lbf

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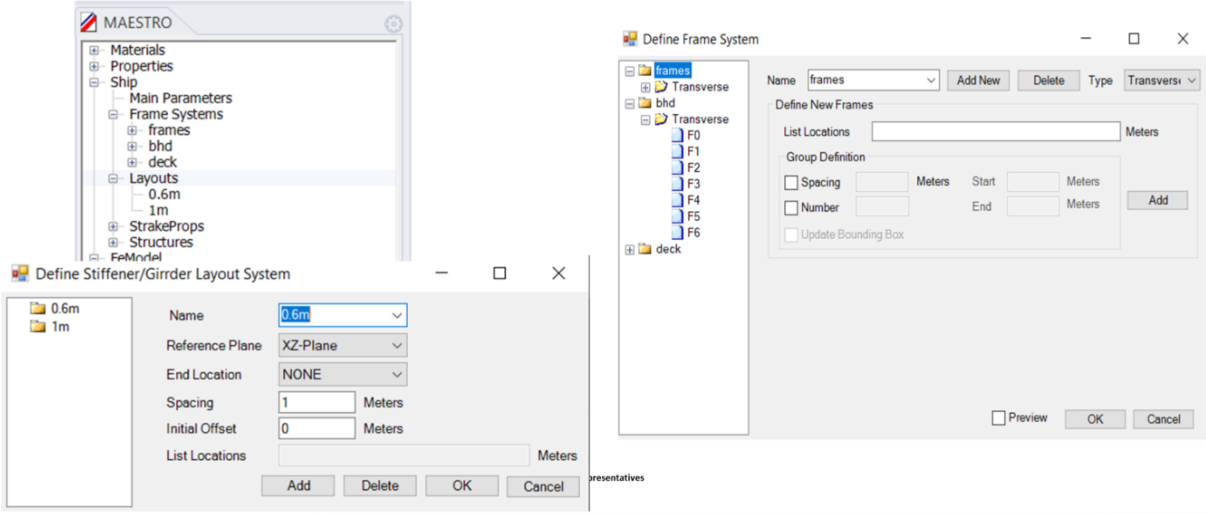
3. Create modules from Rhino Surfaces

Create Named Frame System (transverse and horizontal) and Stiffener Layout System

Create named bulkhead frame locations so frames are not generated at the transverse bulkhead location

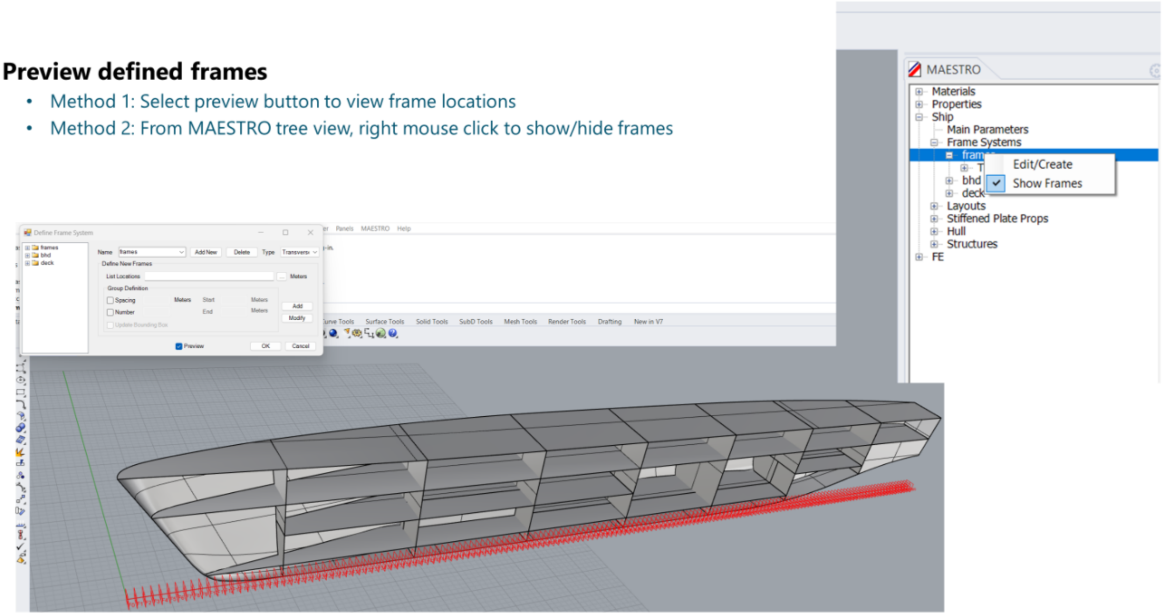


Name: 0.6m
Reference Plane: XZ-Plane
End Location: NONE
Spacing: 1 Meters
Initial Offset: 0 Meters

Name: frames
Type: Transverse

3. Create modules from Rhino Surfaces

- **Preview defined frames**
  - Method 1: Select preview button to view frame locations
  - Method 2: From MAESTRO tree view, right mouse click to show/hide frames



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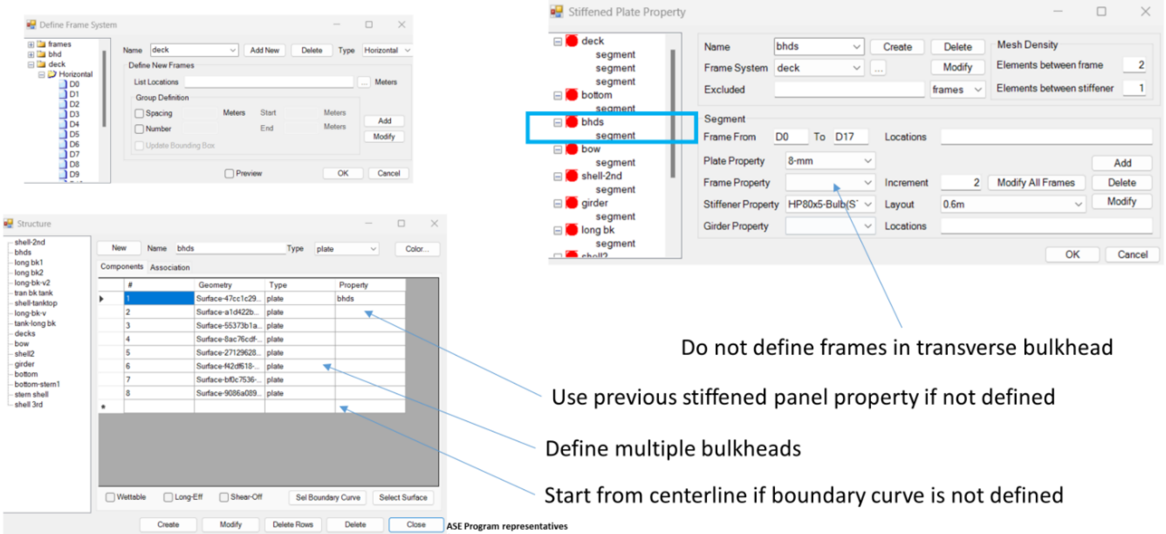
3. Create modules from Rhino Surfaces

Create horizonal frame system and stiffened plate properties for transvers bulkheads



Define Frame System: Name deck; Type Horizontal

Structure: Name bhds; Type plate

#	Geometry	Type	Property
1	Surface-47cc1c29...	plate	bhds
2	Surface-a1d422b...	plate	
3	Surface-55373b1a...	plate	
4	Surface-8ac76cdf-...	plate	
5	Surface-27129628...	plate	
6	Surface-f42df618-...	plate	
7	Surface-bf0c7536-...	plate	
8	Surface-9086a089...	plate	

Stiffened Plate Property:
Name: bhds
Frame System: deck
Excluded: frames
Mesh Density
Elements between frame: 2
Elements between stiffener: 1
Segment
Frame From: D0 To D17
Locations:
Plate Property: 8-mm
Frame Property:
Increment: 2
Stiffener Property: HP80x5-Bulb(S
Layout: 0.6m
Girder Property:
Locations:

Do not define frames in transverse bulkhead

Use previous stiffened panel property if not defined

Define multiple bulkheads

Start from centerline if boundary curve is not defined

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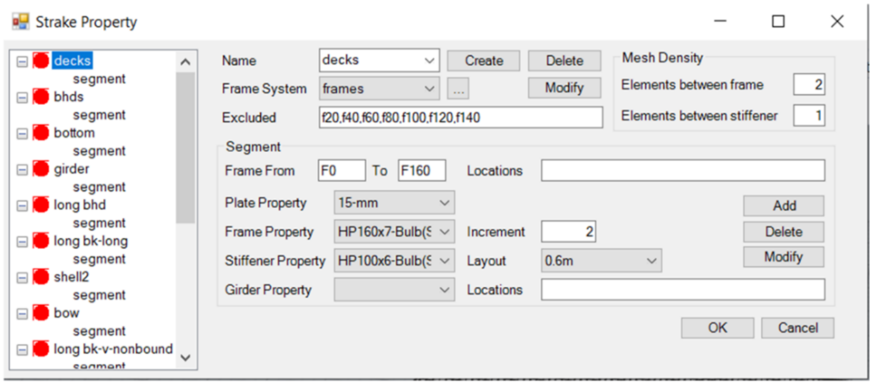
3. Create modules from Rhino Surfaces

- **A stiffened plate property may have multiple segment, each segment can have its own plate property, frame property, girder property and stiffener property**



Name: decks
Frame System: frames
Excluded: f20,f40,f60,f80,f100,f120,f140
Mesh Density
Elements between frame: 2
Elements between stiffener: 1
Segment
Frame From: F0 To F160
Locations:
Plate Property: 15-mm
Frame Property: HP160x7-Bulb(S
Increment: 2
Stiffener Property: HP100x6-Bulb(S
Layout: 0.6m
Girder Property:
Locations:

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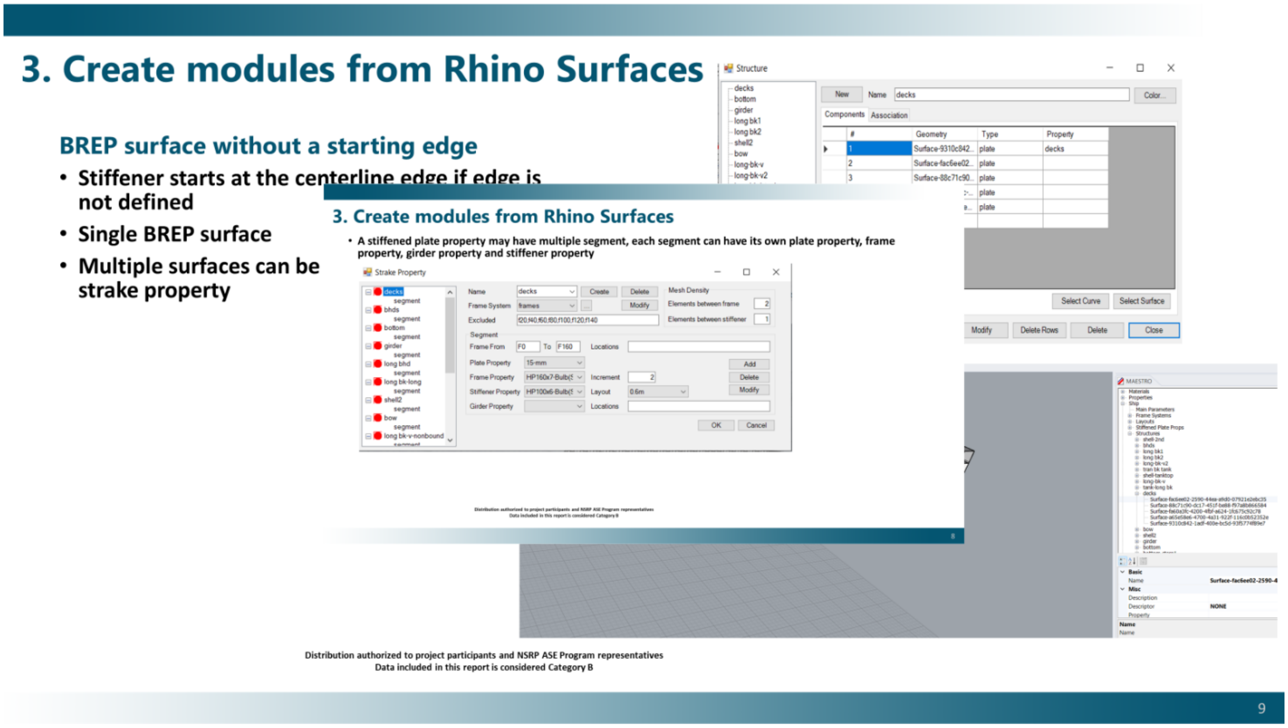

3. Create modules from Rhino Surfaces

BREP surface without a starting edge

- Stiffener starts at the centerline edge if edge is not defined
- Single BREP surface
- Multiple surfaces can be strake property

Structure

Name: decks

#	Geometry	Type	Property
1	Surface-9310c842...	plate	decks
2	Surface-fac6ee02...	plate	
3	Surface-88c71c90...	plate	
		plate	
		plate	

3. Create modules from Rhino Surfaces

- A stiffened plate property may have multiple segment, each segment can have its own plate property, frame property, girder property and stiffener property

Strake Property

Name: decks
Frame System: frames
Excluded: f20,f40,f60,f80,f100,f120,f140
Mesh Density
Elements between frame: 2
Elements between stiffener: 1
Segment
Frame From: F0 To: F160
Plate Property: 15-mm
Frame Property: HP160x7-Bulb(
Increment: 2
Stiffener Property: HP100x6-Bulb(
Layout: 0.6m

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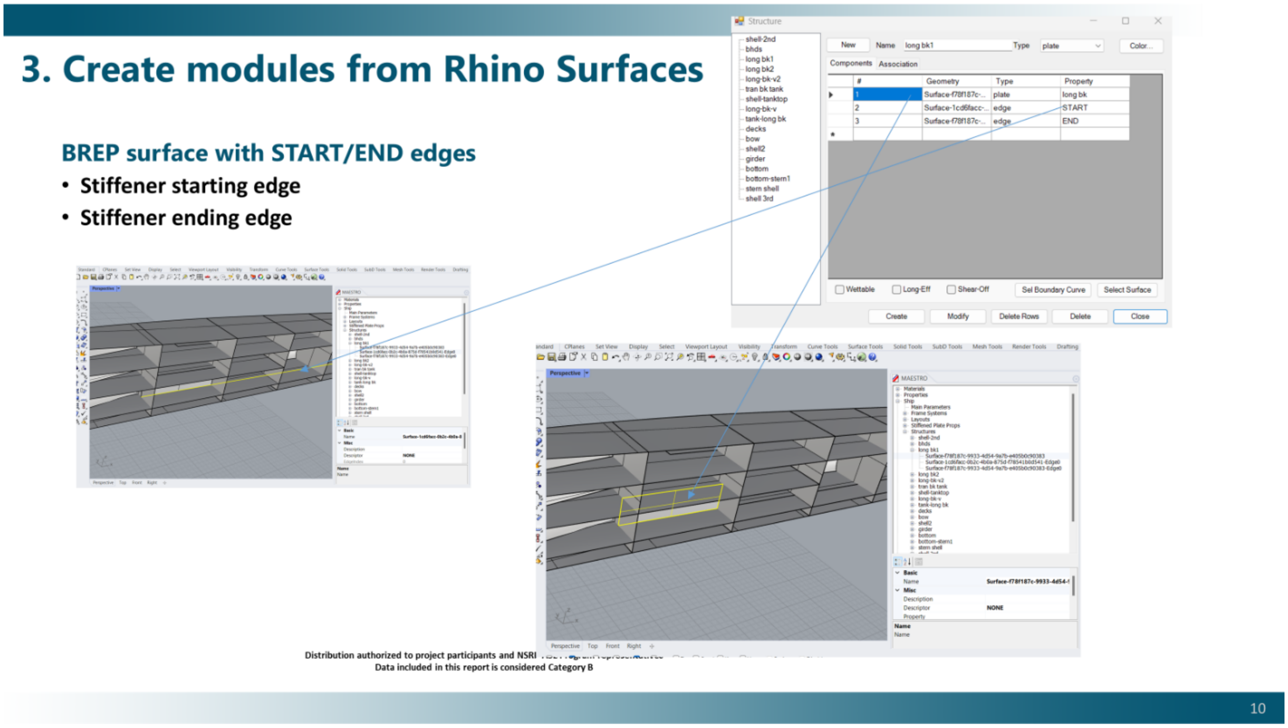

3. Create modules from Rhino Surfaces

BREP surface with START/END edges

- Stiffener starting edge
- Stiffener ending edge

Structure

Name: long bk1
Type: plate

#	Geometry	Type	Property
1	Surface-f78f187c-...	plate	long bk
2	Surface-1cd6facc-...	edge	START
3	Surface-f78f187c-...	edge	END

☐ Wettable ☐ Long-Eff ☐ Shear-Off

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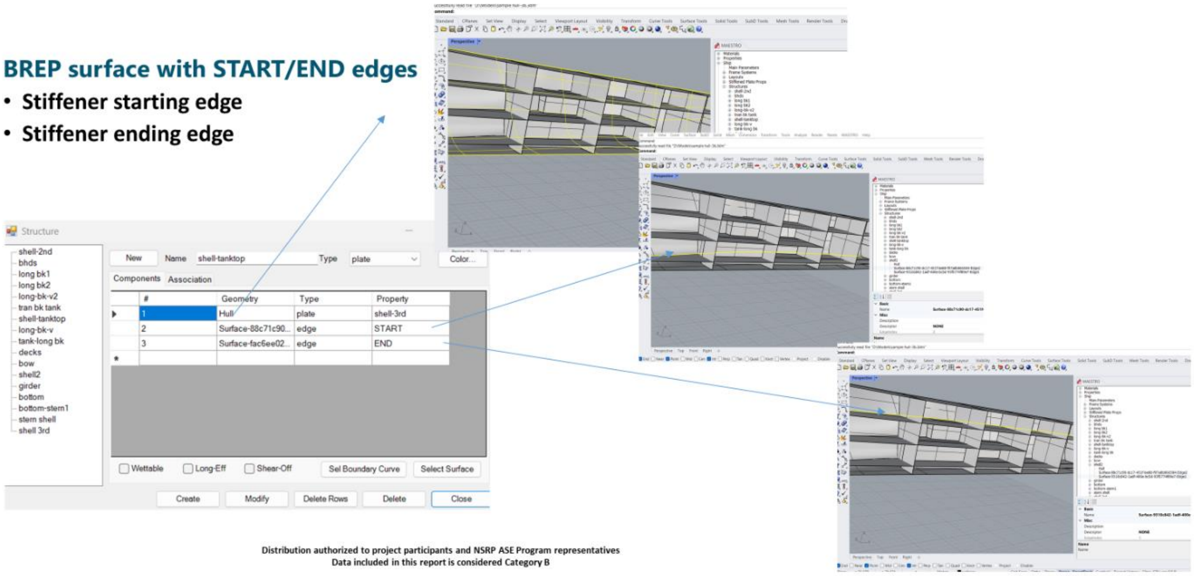
10

3. Create modules from Rhino Surfaces



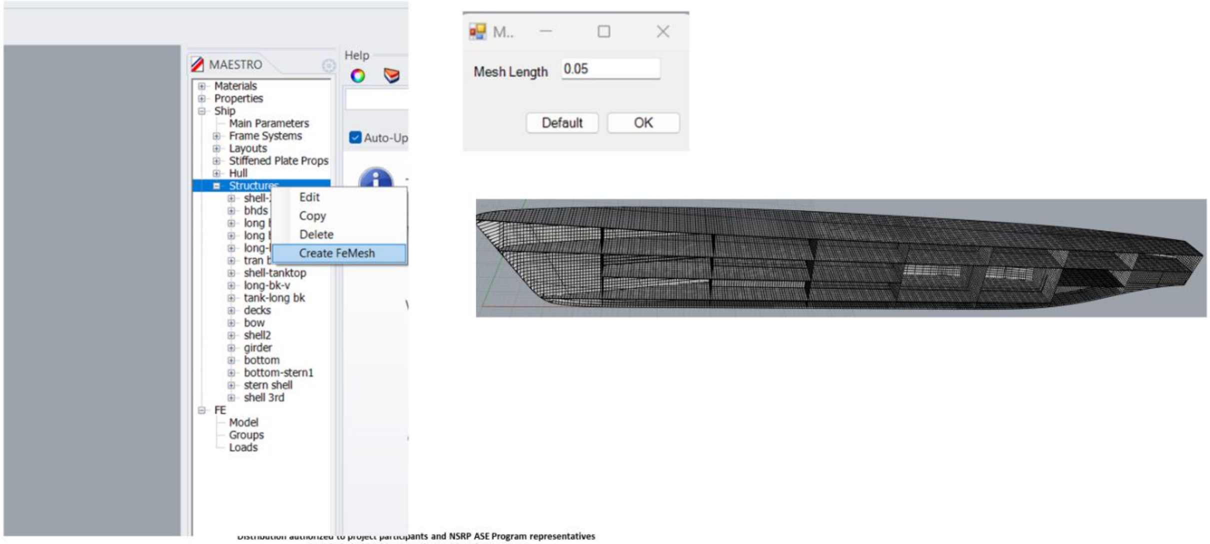
BREP surface with START/END edges

- Stiffener starting edge
- Stiffener ending edge

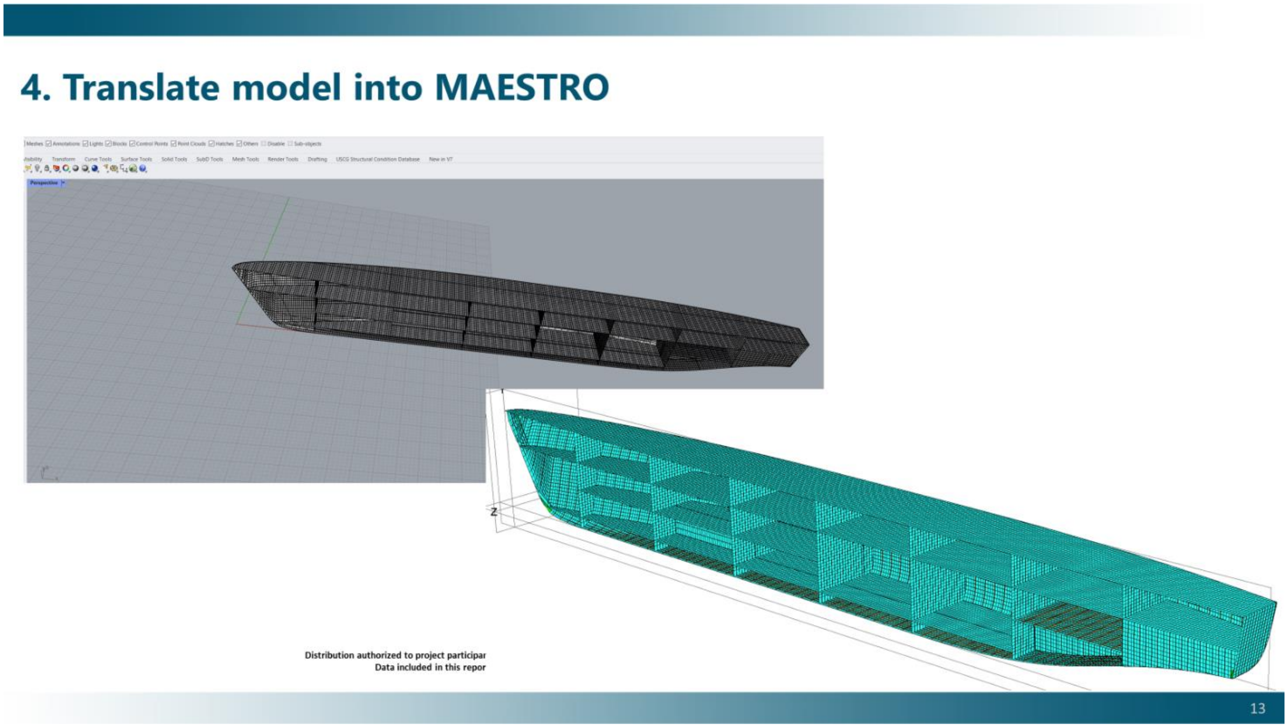
Name: shell-tanktop
Type: plate

#	Geometry	Type	Property
1	Hull	plate	shell-3rd
2	Surface-88c71c90...	edge	START
3	Surface-fac6ee02...	edge	END

4.Generate FE Mesh



Mesh Length 0.05



4. Translate model into MAESTRO

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13

APPENDIX C. WORK CONTENT & COST OPTIMIZATION METRICS

White Paper by Peter Jaquith

January 31, 2022

Work Content & Cost Optimization Metrics

Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-Stage Structural Design Optimization: NSRP Project RA 21-11

Based on development under the previous NSRP Project 2017-443, MAESTRO's current multi-objective structural optimization process addresses three objective functions:

- Ensuring that structural design criteria are met
- Reducing structural weight
- Reducing structural work content/cost

The following notes outline the author's observations and recommendations for application of work content and cost optimization metrics under the new NSRP Project RA 21-11.

Concept and Preliminary Design

During the early-stage concept and preliminary design phases and using set-based design space exploration, multiple ship and structural arrangements are considered. Limited structural definition and a high level of design change are typical in this design phase. Design team members may include NAVSEA engineers, marine design firm engineers, and/or a shipyards Initial Design engineers. While desirable, shipyard production engineering participation may be limited. The following notes apply:

- Recommend that early-stage design structural design optimization utilize "total weld length" as an objective figure of merit.
- While it may be tempting to convert weld length and coating area to labor hours/dollars if appropriate estimating standards are available, I believe that total weld length is straight forward and appropriate for design/production engineering analysis at this design stage.[4]
- Other cost considerations for early-stage design include:
    - Avoid high strength steels (e.g., HY-80 and HY-100) that limit use of automated welding
    - Avoid complex structural arrangements that limit automation
    - Avoid structural design details with poor fatigue resistance
    - Minimize the variation in plate thickness/grade and profile size/grade
    - Coating area and material cost should be calculated for comparison

Functional and Contract Design

---

[4] Discussion with Korean DSME design and production engineering executives showed that they used weld length and coating area as comparative metrics in their structural optimization analysis.

During the functional and contract design phases the process will focus on design convergence and refinement. Increasing levels of design definition will be developed during this phase. In addition to traditional structural design engineers, engagement of shipyard production engineers is recommended. This engagement will support application of more discreet work content and cost metrics as described in Figures 3.17 and 3.18, pages 27-29 of the reference Final Report NSRP Project 2017-443 (FMM 2019). The following notes apply:

- With full shipyard production engineering engagement, recommend that structural design optimization utilize "total fitting and welding labor hours" as an objective figure of merit (labor productivity calculated by structural process per Figures 3.17 and 3.18).
- With only limited production engineering engagement, recommend that structural design optimization continue to utilize "total weld length" as an objective figure of merit.
- While it may be tempting to convert weld length and coating area to dollars if appropriate estimating standards are available, I believe that total fitting and welding hours/weld length are straight forward and appropriate for design/production engineering analysis at this design stage.
- For Naval shipbuilding programs that are tracking TOC Reduction Initiatives in dollars, it is recommended this calculation be performed separately from structural design optimization.
- Other cost considerations for functional and contract design include:
    - Avoid high strength steels (e.g., HY-80 and HY-100) that limit use of automated welding
    - Avoid complex structural arrangements that limit automation
    - Avoid structural design details with poor fatigue resistance
    - Minimize the variation in plate thickness/grade and profile size/grade
    - Coating area and material cost should be calculated for comparison

Other Cost Optimization Considerations

Additional considerations for work content and TOC cost reduction using early-stage MAESTRO structural design optimization include:

- For all shipbuilding programs; recommend early engagement of shipyard production engineers to support structural design optimization as part of the early-stage design team.
- For Naval shipbuilding programs; consider the development of a family of engineered built up tees to avoid the use of stripped I/Ts.
- For Naval shipbuilding programs; consider the development of new fatigue resistant and coating friendly structural details.
- For Naval shipbuilding programs; review structural arrangement alternatives that would result in more coating friendly designs.

Conclusion

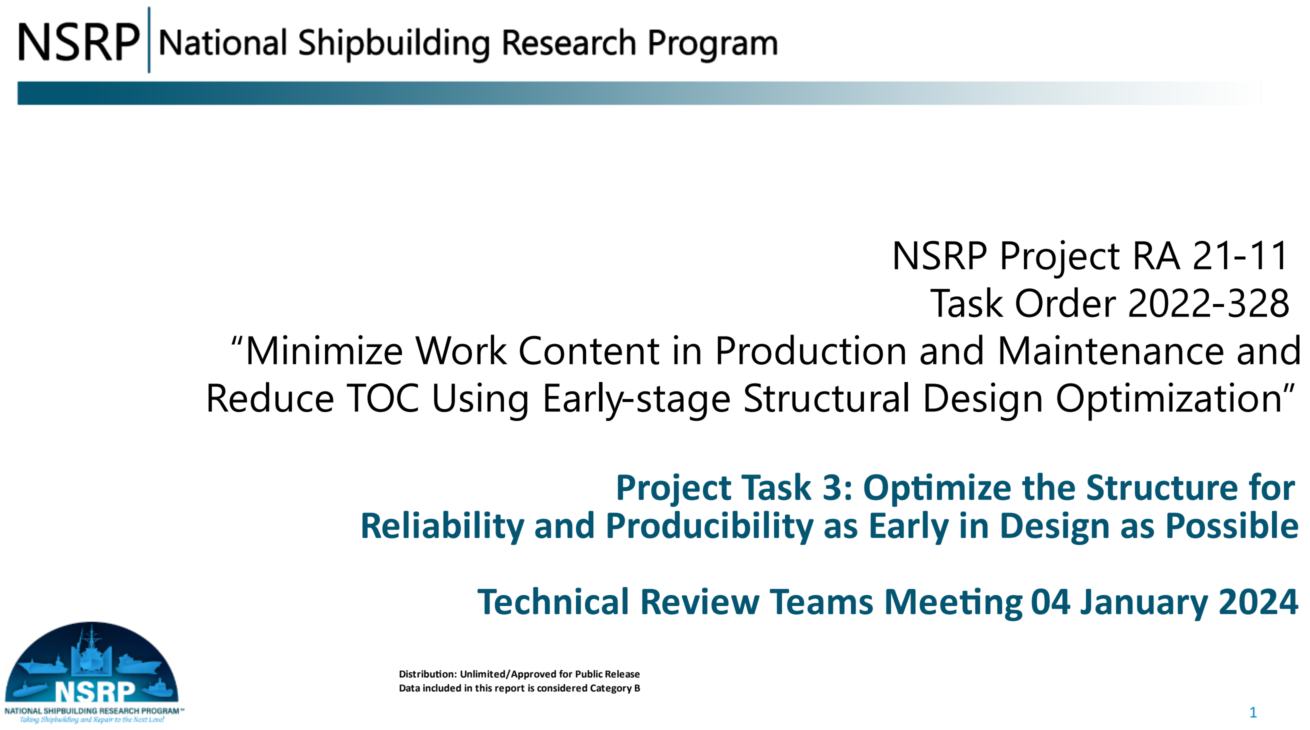
The observations and recommendations noted in this white paper reflect the author's current thoughts for discussion with the RA 21-11 Project Team. In that regard, my principal concern is the metrics selected by straight forward and that the analysis process be transparent to the design engineer and production engineer users.

References

Fincantieri Marinette Marine (FMM), "Ship Structural Design Optimization (SSDO) for Improved Producibility and Enhanced Life-Cycle Performance," Final Report NSRP Project 2017-443, April 2019

APPENDIX D. TASK 3 EARLY-STAGE DESIGN OPTIMIZATION APPROACH

Task 3's objective was to develop a "Least Work Content" structural design algorithm for implementation in the Navy's ship synthesis model ASSET (Advanced Ship and Submarine Evaluation Tool). This would be a multi-objective structural design optimization capability that could be considered by the Navy for use in the ASSET early-stage design tools. The following slides summarize the capabilities of the completed project software.



NSRP | National Shipbuilding Research Program

NSRP Project RA 21-11
Task Order 2022-328
"Minimize Work Content in Production and Maintenance and
Reduce TOC Using Early-stage Structural Design Optimization"

Project Task 3: Optimize the Structure for Reliability and Producibility as Early in Design as Possible

Technical Review Teams Meeting 04 January 2024

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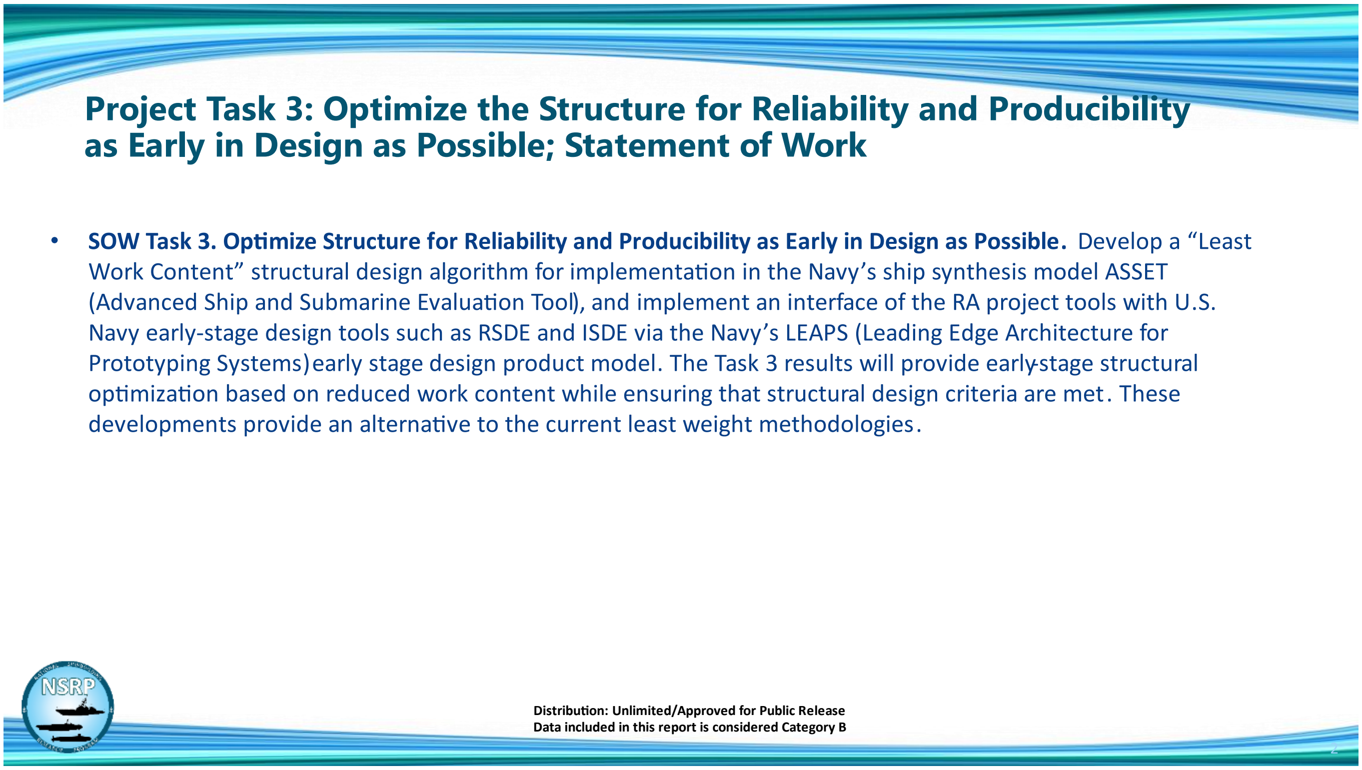
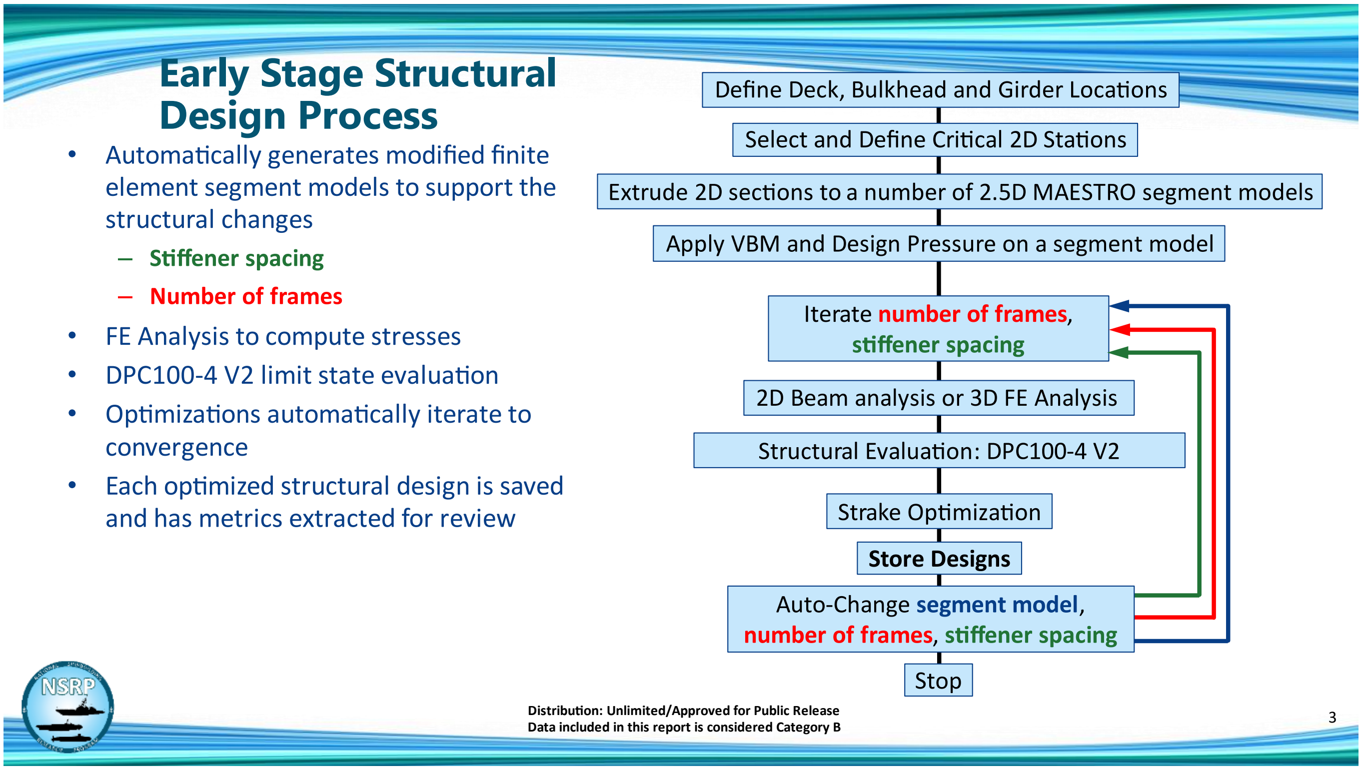


Project Task 3: Optimize the Structure for Reliability and Producibility as Early in Design as Possible; Statement of Work

- **SOW Task 3. Optimize Structure for Reliability and Producibility as Early in Design as Possible.** Develop a "Least Work Content" structural design algorithm for implementation in the Navy's ship synthesis model ASSET (Advanced Ship and Submarine Evaluation Tool), and implement an interface of the RA project tools with U.S. Navy early-stage design tools such as RSDE and ISDE via the Navy's LEAPS (Leading Edge Architecture for Prototyping Systems) early stage design product model. The Task 3 results will provide early-stage structural optimization based on reduced work content while ensuring that structural design criteria are met. These developments provide an alternative to the current least weight methodologies.



Early Stage Structural Design Process

- Automatically generates modified finite element segment models to support the structural changes
  - Stiffener spacing
  - Number of frames
- FE Analysis to compute stresses
- DPC100-4 V2 limit state evaluation
- Optimizations automatically iterate to convergence
- Each optimized structural design is saved and has metrics extracted for review

Define Deck, Bulkhead and Girder Locations

Select and Define Critical 2D Stations

Extrude 2D sections to a number of 2.5D MAESTRO segment models

Apply VBM and Design Pressure on a segment model

Iterate number of frames, stiffener spacing

2D Beam analysis or 3D FE Analysis

Structural Evaluation: DPC100-4 V2

Strake Optimization

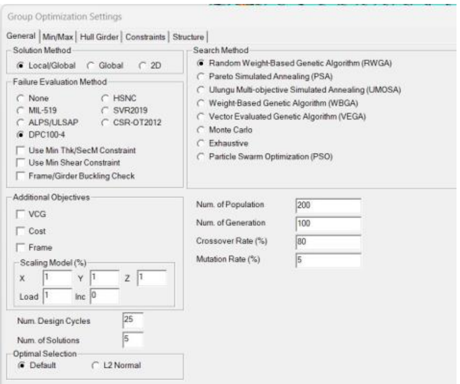
Store Designs

Auto-Change **segment model**, **number of frames**, **stiffener spacing**

Stop

Task 3: Optimize the Structure for Reliability and Producibility as Early in Design as Possible

- **Develop the Least Work-Content Algorithm.** MAESTRO Marine is implementing DPC100 -4 V2 criteria (both traditional 2D based evaluation and FEA based evaluation) into MAESTRO optimization framework



Group Optimization Settings

General | Min/Max | Hull Girder | Constraints | Structure

Solution Method
● Local/Global ○ Global ○ 2D

Failure Evaluation Method
○ None ○ HSNC
○ MIL-519 ○ SVR2019
○ ALPS/ULSAP ○ CSR-OT2012
● DPC100-4
☐ Use Min Thk/SecM Constraint
☐ Use Min Shear Constraint
☐ Frame/Girder Buckling Check

Search Method
● Random Weight-Based Genetic Algorithm (RWGA)
○ Pareto Simulated Annealing (PSA)
○ Ulungu Multi-objective Simulated Annealing (UMOSA)
○ Weight-Based Genetic Algorithm (WBGA)
○ Vector Evaluated Genetic Algorithm (VEGA)
○ Monte Carlo
○ Exhaustive
○ Particle Swarm Optimization (PSO)

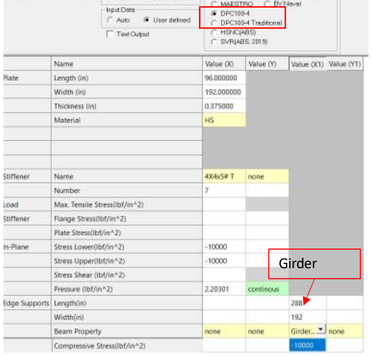
Additional Objectives
☐ VCG
☐ Cost
☐ Frame

Scaling Model (%)
X 1 Y 1 Z 1
Load 1 Inc 0

Num. of Population 200
Num. of Generation 100
Crossover Rate (%) 80
Mutation Rate (%) 5

Num. Design Cycles 25
Num. of Solutions 5

Optimal Selection
● Default ○ L2 Normal



Limit State Creation/Evaluation

Identification
ID 000002

Evaluation Type
● Panel ○ Beam-Column

Input Data
○ Auto ● User defined

☐ Text Output

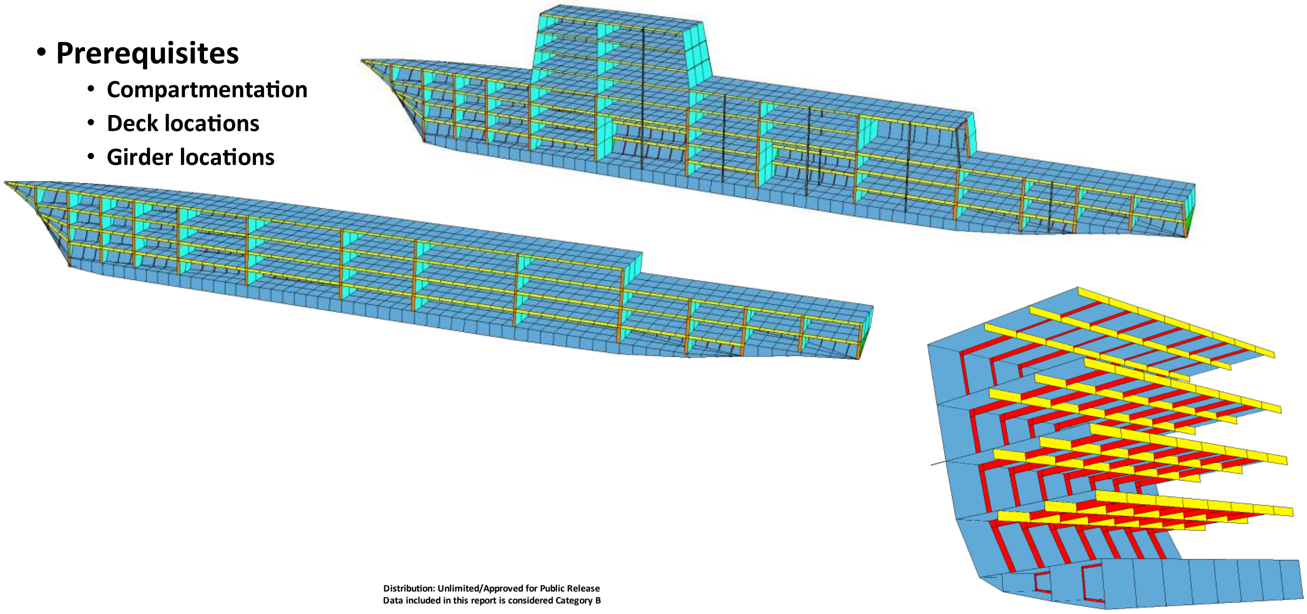
Method
○ ULSAP ○ CSR-OT(2012)
○ MAESTRO ○ BV Naval
● DPC100-4
○ DPC100-4 Traditional
○ HSNC(ABS)
○ SVR(ABS, 2019)

	Name	Value (X)	Value (Y)	Value (X1)	Value (Y1)
Plate	Length (in)	96.000000			
	Width (in)	192.000000			
	Thickness (in)	0.375000			
	Material	HS			
Stiffener	Name	4X4x5# T	none		
	Number	7			
Load	Max. Tensile Stress(lbf/in^2)				
Stiffener	Flange Stress(lbf/in^2)				
	Plate Stress(lbf/in^2)				
In-Plane	Stress Lower(lbf/in^2)	-10000			
	Stress Upper(lbf/in^2)	-10000			
	Stress Shear (lbf/in^2)				
	Pressure (lbf/in^2)	2.20301	continous		
Edge Supports	Length(in)			288	
	Width(in)			192	
	Beam Property	none	none	Girder...	none
	Compressive Stress(lbf/in^2)			-10000	

The Least Work-Content Structural Design Algorithm will be an optimization algorithm that serves as a user-selected switchable alternative to the current structural design algorithm, derived from SSDP, which optimizes for a least-weight structural design.

Early-Stage Structural Design

- **Prerequisites**
  - **Compartmentation**
  - **Deck locations**
  - **Girder locations**



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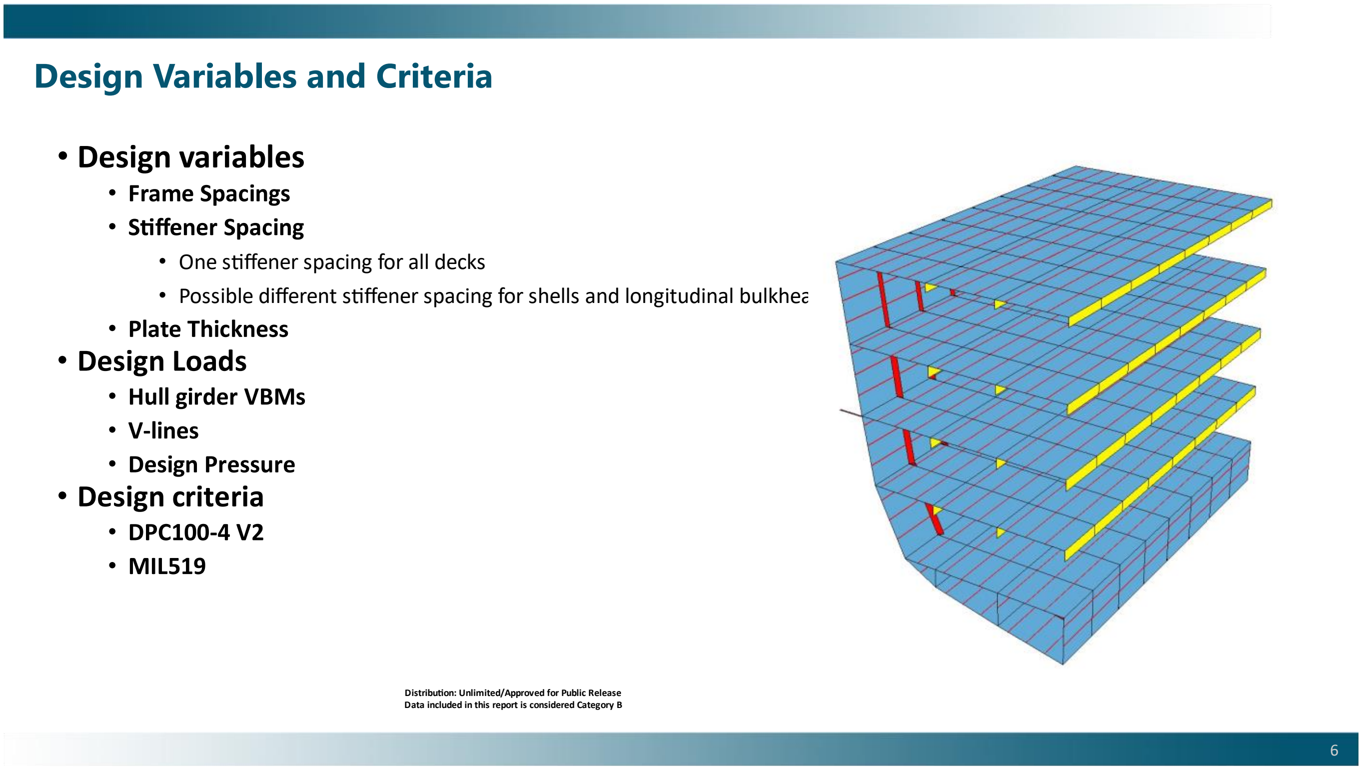

Design Variables and Criteria

- **Design variables**
  - **Frame Spacings**
  - **Stiffener Spacing**
    - One stiffener spacing for all decks
    - Possible different stiffener spacing for shells and longitudinal bulkhea
  - **Plate Thickness**
- **Design Loads**
  - **Hull girder VBMs**
  - **V-lines**
  - **Design Pressure**
- **Design criteria**
  - **DPC100-4 V2**
  - **MIL519**

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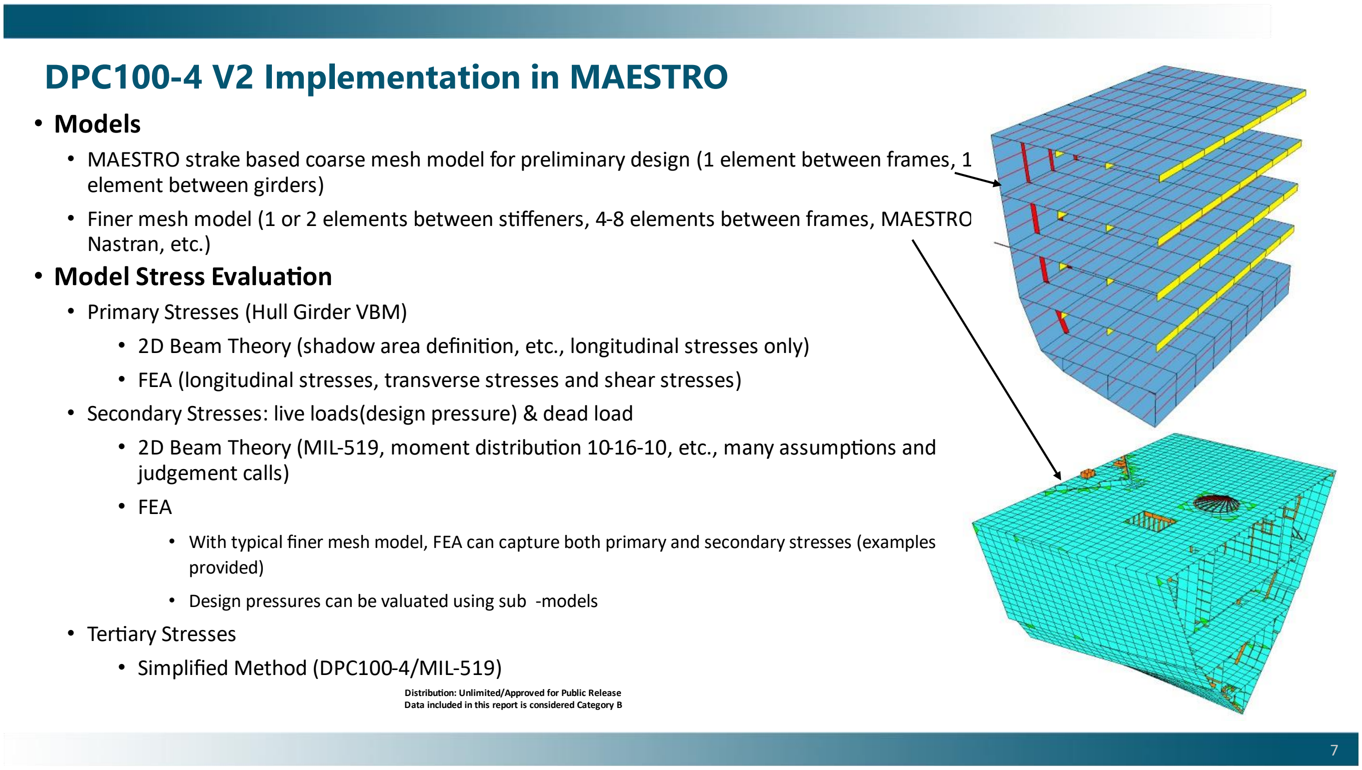

DPC100-4 V2 Implementation in MAESTRO

- **Models**
  - MAESTRO strake based coarse mesh model for preliminary design (1 element between frames, 1 element between girders)
  - Finer mesh model (1 or 2 elements between stiffeners, 4-8 elements between frames, MAESTRO Nastran, etc.)
- **Model Stress Evaluation**
  - Primary Stresses (Hull Girder VBM)
    - 2D Beam Theory (shadow area definition, etc., longitudinal stresses only)
    - FEA (longitudinal stresses, transverse stresses and shear stresses)
  - Secondary Stresses: live loads(design pressure) & dead load
    - 2D Beam Theory (MIL-519, moment distribution 10-16-10, etc., many assumptions and judgement calls)
    - FEA
      - With typical finer mesh model, FEA can capture both primary and secondary stresses (examples provided)
      - Design pressures can be valuated using sub -models
  - Tertiary Stresses
    - Simplified Method (DPC100-4/MIL-519)

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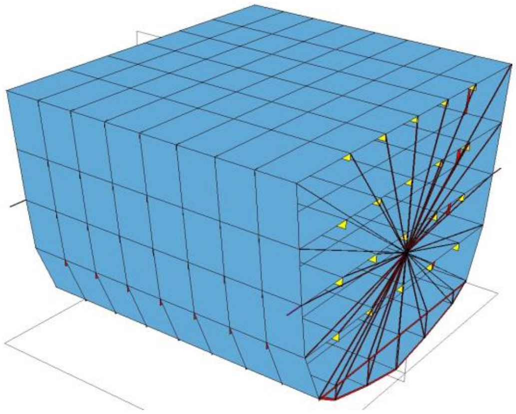
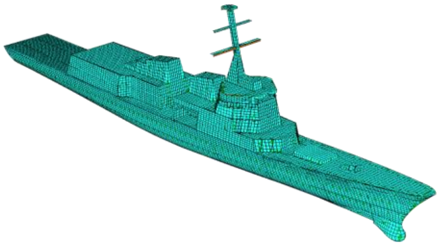
Strake Based Coarse Mesh Optimization (Preliminary Design Stage)

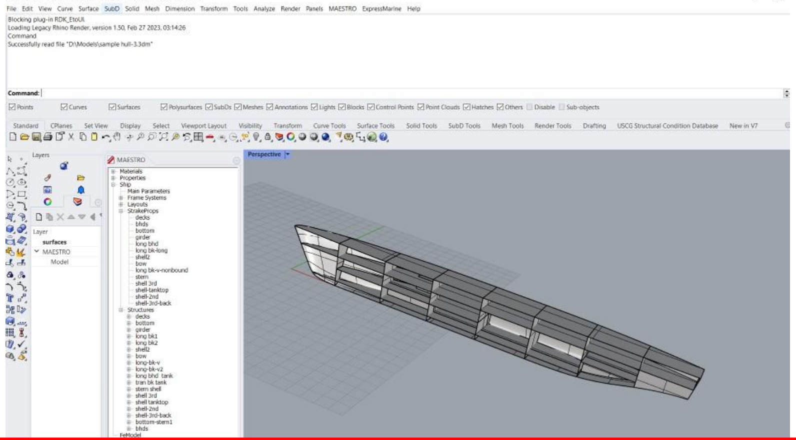
- **Prismatic segment model**
  - Easy to construct
  - Good estimation of 2D cross sectional properties
  - Easy to change frame spacing and stiffener spacing
  - Use DPC100-4 V2 and MIL-519 design criteria
  - Weight, paint area, weld length data are available
- **2D Analysis & Optimization**
  - 2D Analysis (available)
  - DPC100-4 V2 evaluation (under testing)
  - 2D cross section optimization (under development)
- **3D Analysis & Optimization**
  - 3D segment FEA Analysis (available)
  - DPC100-4 V2 evaluation (under testing/integration)
  - 3D multi-objective optimization (under development/integration)



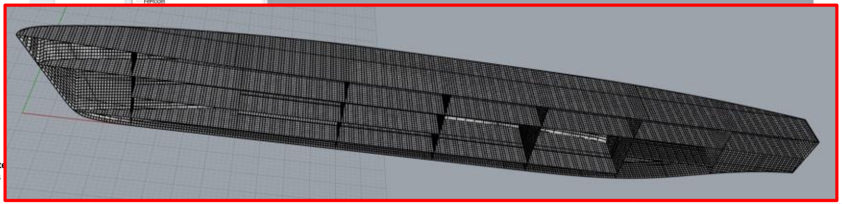
Finer Mesh Analysis and Optimization (Contract Design Stage)

- **Full ship model**
  - Various design loads
  - Frame spacing and stiffener spacing are fixed
  - DPC100-4 limit state evaluation of full ship
  - High fidelity weight, paint area, weld length data
  - Finetune scantling optimization



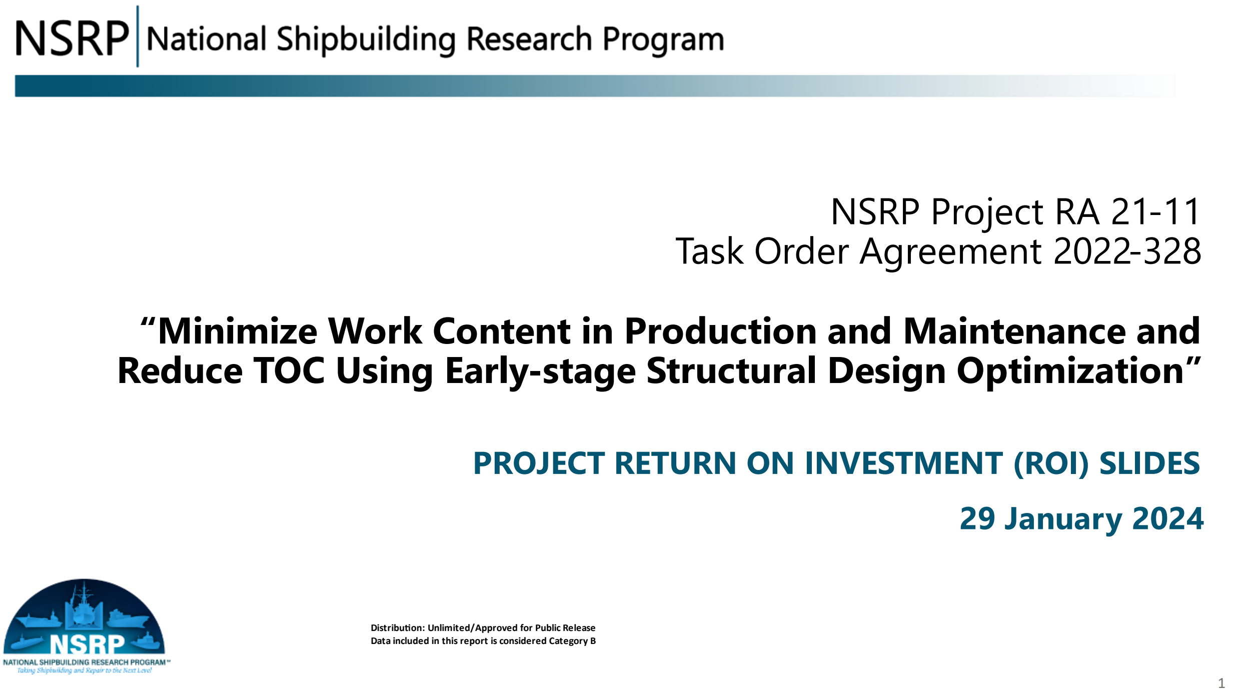


```
Blocking plug-in RDK_EtoUI
Loading Legacy Rhino Render, version 1.50, Feb 27 2023, 03:14:26
Command
Successfully read file "D:\Models\sample hull-3.3dm"
Command:
```



APPENDIX E. RETURN ON INVESTMENT (ROI) DETAILS

The following slides provide additional information and background data related to the assessment of the project's Return on Investment (ROI).



NSRP | National Shipbuilding Research Program

NSRP Project RA 21-11
Task Order Agreement 2022-328

"Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization"

PROJECT RETURN ON INVESTMENT (ROI) SLIDES

29 January 2024

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NSRP RA 21-11 Project Team: Software Developers; Major Shipbuilder; U.S. Navy; U.S. Coast Guard; ABS; Lean Design, Production and Ship Design Expertise

Project Team Members:

- **MAESTRO Marine LLC**
  - *Project Lead; Naval Architects and Software Developers*
- **Austal USA**
  - *Shipbuilder with strong Concept/Preliminary through Functional and Detail Design*
- **NSWC Carderock Division, Code 65**
  - *U.S. Navy organization for structural design tools*
- **U.S. Coast Guard, Surface Forces Logistics Center**
  - *Depot Level USCG Maintenance and Engineering Center*
- **American Bureau of Shipping**
  - *Major U.S. Ship Classification Society and Technical/Safety Authority*
- **Robert Keane – Ship Design USA, Inc.**
  - *Former U.S. Navy Chief Naval Architect; Advisor for ship design tools and methods*
- **P. Jaquith & Associates**
  - *SME in Lean Design and Design for Production*
- **SPAR Associates, Inc.**
  - *SME's in ship cost-estimating and production planning*

The project team represents the U.S. shipbuilding enterprise:

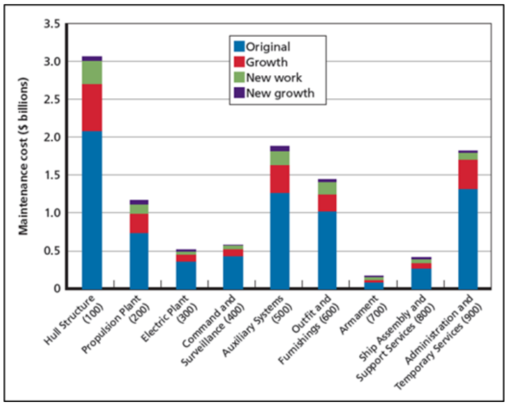
- Key shipbuilder
- U.S. Navy and U.S. Coast Guard ship designers, owners and operators
- Major U.S. Ship Classification society
- Ship design, production and cost estimating specialists
- And is primed by the developers of the software being leveraged for the project.

NSRP RA 21-11 Project Rationale

Project Rationale

- Reduce ship construction costs with Lean Design principles while improving in-service structural performance
- U.S. Government Accountability Office (GAO) reported in its March 2020 GAO-20-2 Report, "Increasing Focus on Sustainment Early in the Acquisition Process Could Save Billions"
- The GAO found that in the seven-year period from 2012-2018, the Navy experienced over 27,000 days of unexpected maintenance delays across all of its ship classes—delays that increase sustainment costs and degrade readiness.

The project addresses these issues with enhanced design tools for early-stage structural design to augment traditional and less flexible methods.



Group 100 Hull Structures @ $3B+ Leads U.S. Navy Surface Ship Depot Maintenance Costs by ESWBS, 2003-2015 ***[2017 RAND Report 1187]***

Project Objectives: during early -design use principles of Lean Design and higher fidelity, physics-based structural analysis to optimize structural scantlings for least work content, producibility, reduced acquisition cost, and more robust performance in -service

Project Objectives

- Assure that structural design criteria are met while improving structural producibility and reducing design-build cycle time.
- Improve structural design and service-life assessment to reduce in-service corrosion, heavy weather damage, and structural fatigue cracking while mitigating excessive structural repair and maintenance costs and increasing ship availability.
- Provide comprehensive structural design space exploration capability for U.S. Navy and shipbuilder early-stage ship design processes resulting in robust structures with reduced acquisition and Total Ownership Costs (TOC).

The state of structural design practice today is largely unchanged from the early-stage structural design processes developed decades ago and still in use for ship design today.

Past structural designs for today's fleet have not withstood the demanding operating environment, resulting in excessive TOC and lost availability

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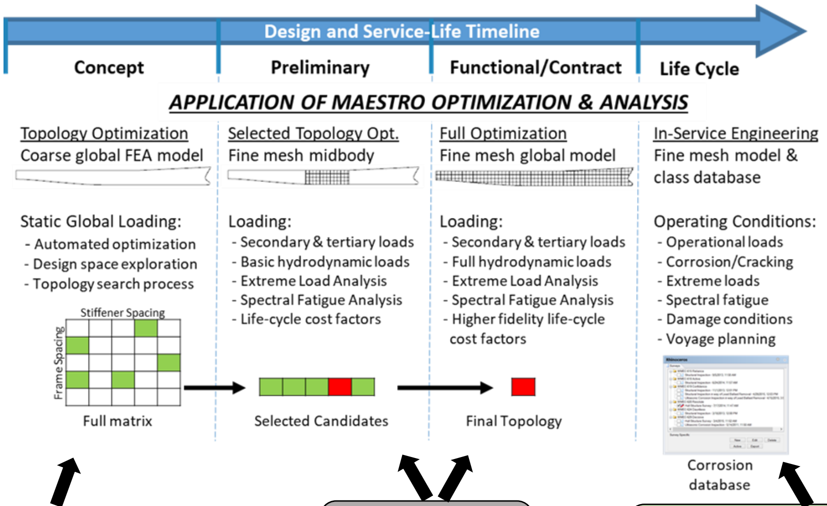
NSRP RA 21-11 Project Technology Transfer Approach: Provide Higher-Fidelity Structural Engineering from Concept Design though the Full Life-Cycle

Project focus is on extending the use of finite element analysis and enhanced software tools into early-stage design and also into the in-service phase of the life-cycle

The project software tools also increase the productivity of the structural engineers by seamlessly integrating hydrodynamic loading analysis and mapping the hydrodynamic loads accurately to the finite element model for analysis.



APPLICATION OF MAESTRO OPTIMIZATION & ANALYSIS

Concept: Topology Optimization; Coarse global FEA model

Static Global Loading:
- Automated optimization
- Design space exploration
- Topology search process

Full matrix

Preliminary: Selected Topology Opt.; Fine mesh midbody

Loading:
- Secondary & tertiary loads
- Basic hydrodynamic loads
- Extreme Load Analysis
- Spectral Fatigue Analysis
- Life-cycle cost factors

Selected Candidates

Functional/Contract: Full Optimization; Fine mesh global model

Loading:
- Secondary & tertiary loads
- Full hydrodynamic loads
- Extreme Load Analysis
- Spectral Fatigue Analysis
- Higher fidelity life-cycle cost factors

Final Topology

Life Cycle: In-Service Engineering; Fine mesh model & class database

Operating Conditions:
- Operational loads
- Corrosion/Cracking
- Extreme loads
- Spectral fatigue
- Damage conditions
- Voyage planning

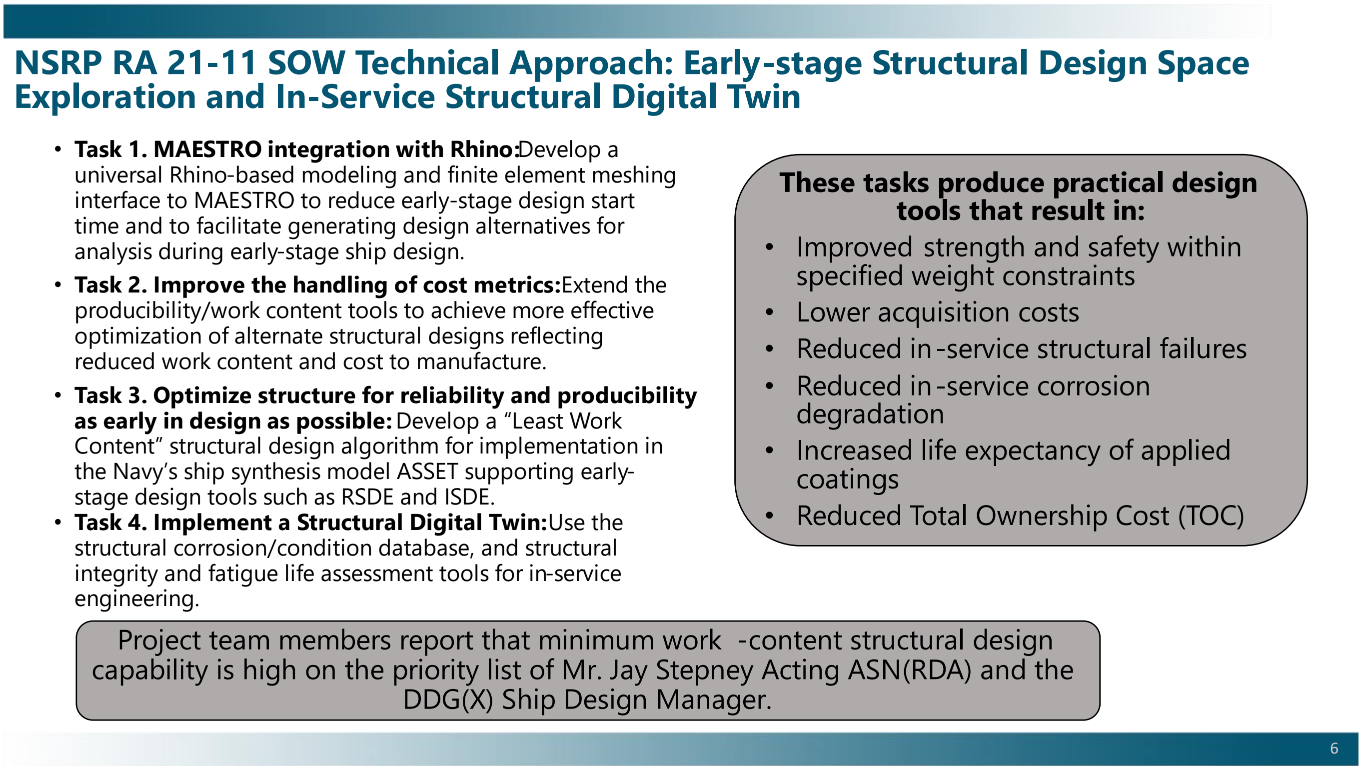
Corrosion database

Early-Stage Structural Design Space Exploration

Current use/applications of the baseline tools

Digital Twin Application to In-Service Engineering

or Public Release
dered Category B



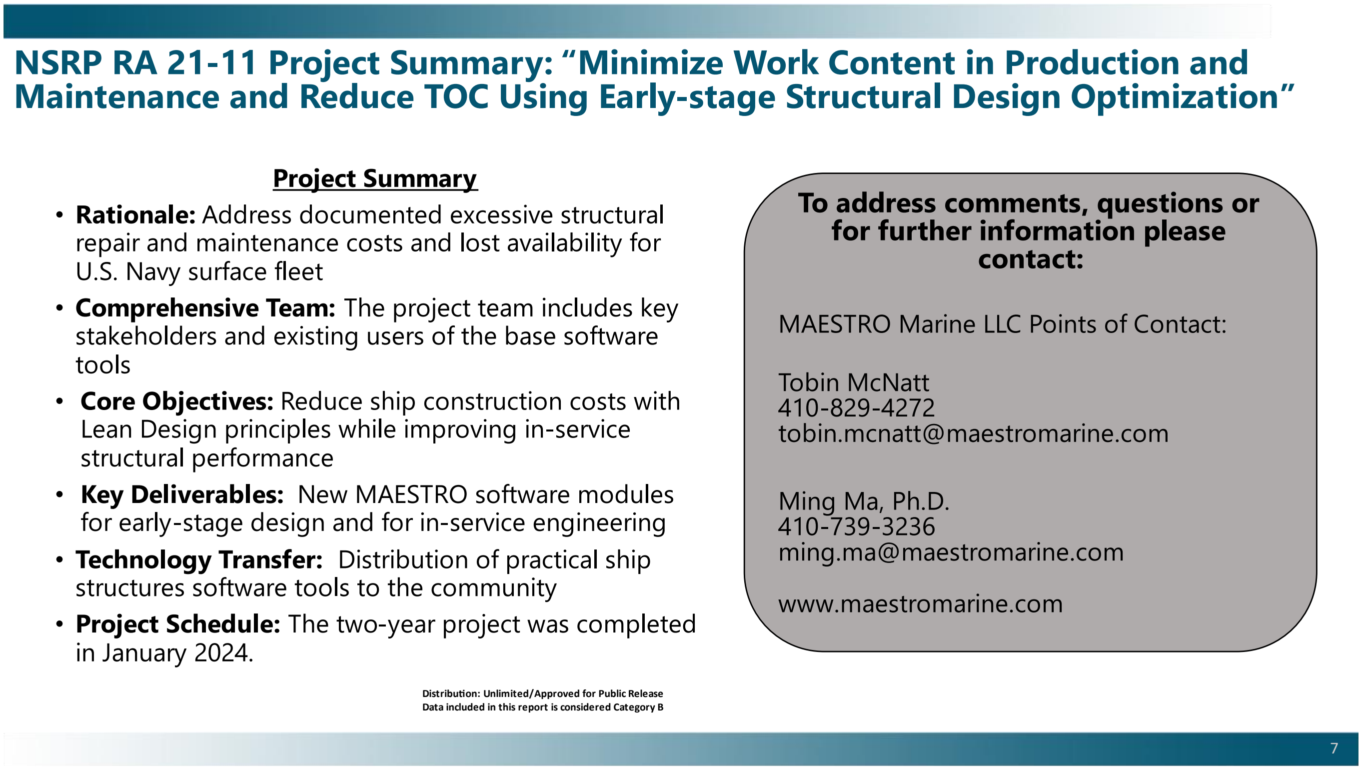
NSRP RA 21-11 SOW Technical Approach: Early-stage Structural Design Space Exploration and In-Service Structural Digital Twin

- **Task 1. MAESTRO integration with Rhino:** Develop a universal Rhino-based modeling and finite element meshing interface to MAESTRO to reduce early-stage design start time and to facilitate generating design alternatives for analysis during early-stage ship design.
- **Task 2. Improve the handling of cost metrics:** Extend the producibility/work content tools to achieve more effective optimization of alternate structural designs reflecting reduced work content and cost to manufacture.
- **Task 3. Optimize structure for reliability and producibility as early in design as possible:** Develop a "Least Work Content" structural design algorithm for implementation in the Navy's ship synthesis model ASSET supporting early-stage design tools such as RSDE and ISDE.
- **Task 4. Implement a Structural Digital Twin:** Use the structural corrosion/condition database, and structural integrity and fatigue life assessment tools for in-service engineering.

These tasks produce practical design tools that result in:

- Improved strength and safety within specified weight constraints
- Lower acquisition costs
- Reduced in-service structural failures
- Reduced in-service corrosion degradation
- Increased life expectancy of applied coatings
- Reduced Total Ownership Cost (TOC)

Project team members report that minimum work-content structural design capability is high on the priority list of Mr. Jay Stepney Acting ASN(RDA) and the DDG(X) Ship Design Manager.



NSRP RA 21-11 Project Summary: "Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-stage Structural Design Optimization"

Project Summary

- **Rationale:** Address documented excessive structural repair and maintenance costs and lost availability for U.S. Navy surface fleet
- **Comprehensive Team:** The project team includes key stakeholders and existing users of the base software tools
- **Core Objectives:** Reduce ship construction costs with Lean Design principles while improving in-service structural performance
- **Key Deliverables:** New MAESTRO software modules for early-stage design and for in-service engineering
- **Technology Transfer:** Distribution of practical ship structures software tools to the community
- **Project Schedule:** The two-year project was completed in January 2024.

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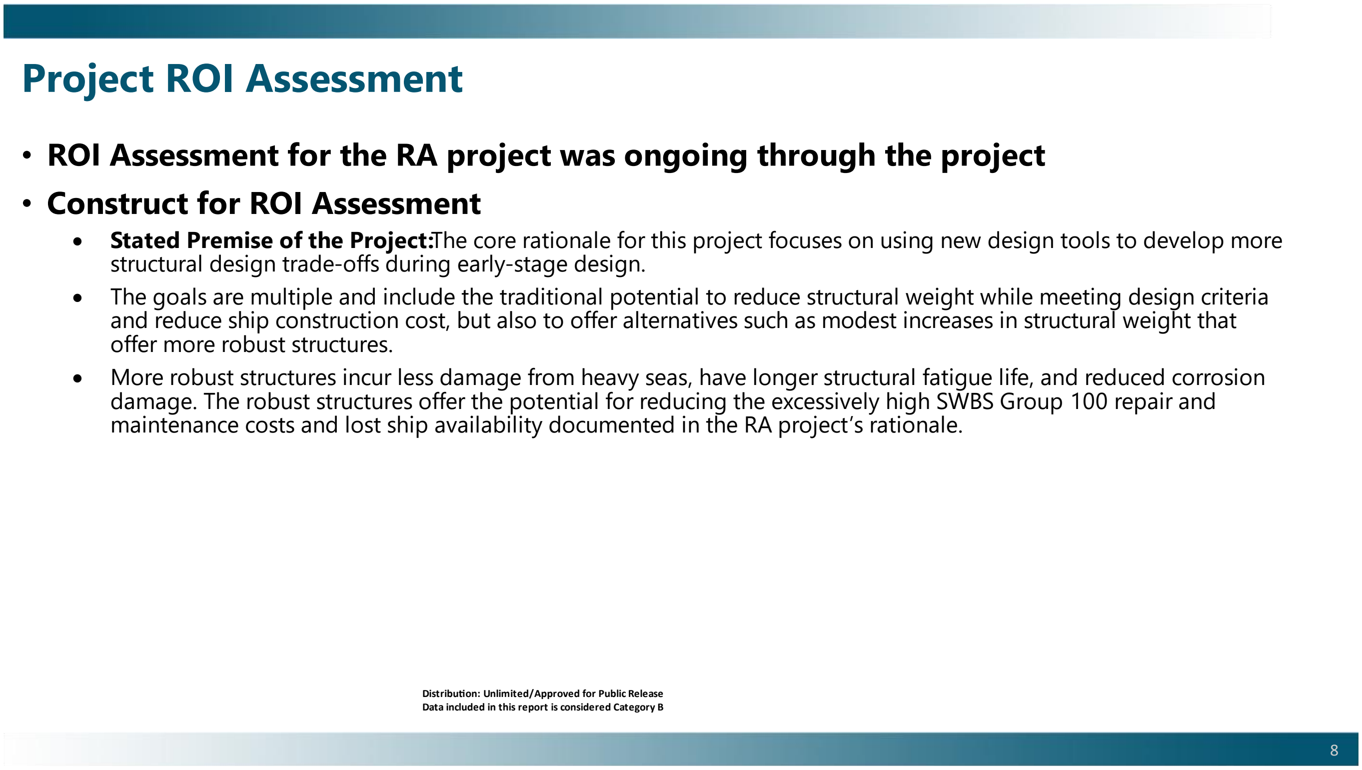
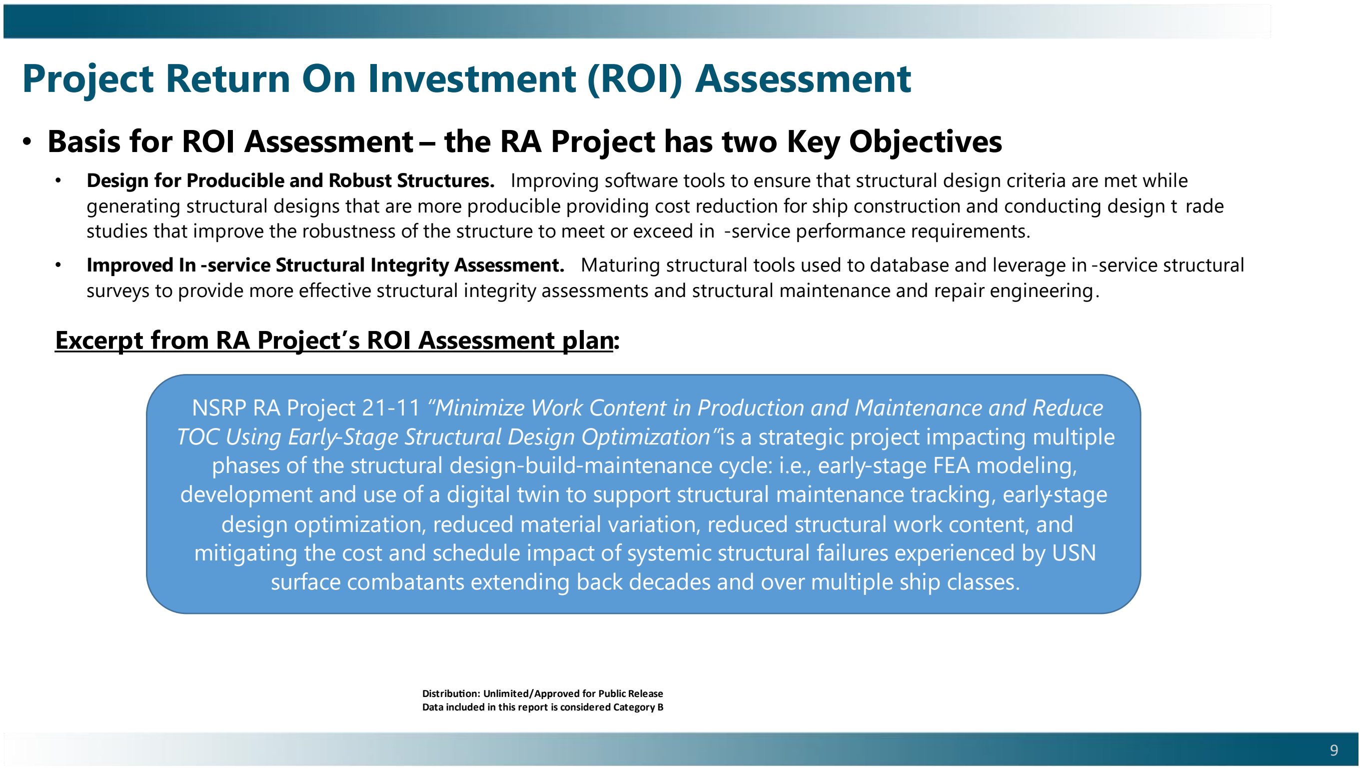


Project ROI Assessment

- **ROI Assessment for the RA project was ongoing through the project**
- **Construct for ROI Assessment**
  - **Stated Premise of the Project:** The core rationale for this project focuses on using new design tools to develop more structural design trade-offs during early-stage design.
  - The goals are multiple and include the traditional potential to reduce structural weight while meeting design criteria and reduce ship construction cost, but also to offer alternatives such as modest increases in structural weight that offer more robust structures.
  - More robust structures incur less damage from heavy seas, have longer structural fatigue life, and reduced corrosion damage. The robust structures offer the potential for reducing the excessively high SWBS Group 100 repair and maintenance costs and lost ship availability documented in the RA project's rationale.



Project Return On Investment (ROI) Assessment

- **Basis for ROI Assessment – the RA Project has two Key Objectives**
  - **Design for Producible and Robust Structures.** Improving software tools to ensure that structural design criteria are met while generating structural designs that are more producible providing cost reduction for ship construction and conducting design trade studies that improve the robustness of the structure to meet or exceed in-service performance requirements.
  - **Improved In-service Structural Integrity Assessment.** Maturing structural tools used to database and leverage in-service structural surveys to provide more effective structural integrity assessments and structural maintenance and repair engineering.

Excerpt from RA Project's ROI Assessment plan:

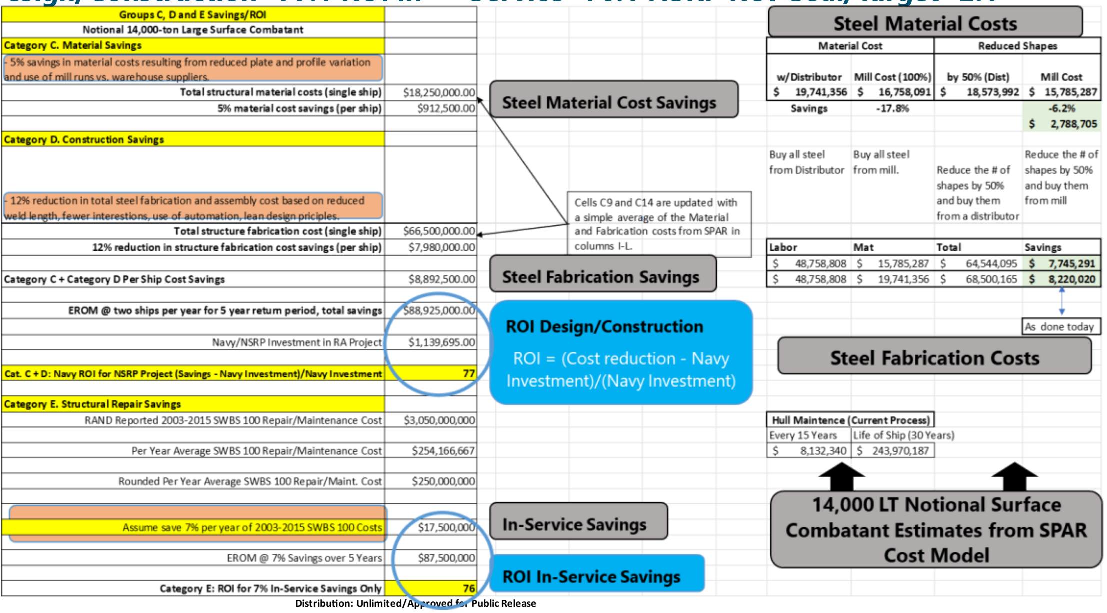
NSRP RA Project 21-11 *"Minimize Work Content in Production and Maintenance and Reduce TOC Using Early-Stage Structural Design Optimization"* is a strategic project impacting multiple phases of the structural design-build-maintenance cycle: i.e., early-stage FEA modeling, development and use of a digital twin to support structural maintenance tracking, early-stage design optimization, reduced material variation, reduced structural work content, and mitigating the cost and schedule impact of systemic structural failures experienced by USN surface combatants extending back decades and over multiple ship classes.

Project ROI Quick Look – Bottom Line Up Front (BLUF)

- **Project ROI Assessment/Calculation**
  - Project ROI assessments were made for the project in two aspects of the ship life-cycle: **Design/Construction** and **In-Service Repairs** for SWBS Group 100. Both resulted in high ROI scores of 77:1 and 76:1 respectively.
- **NSRP ROI Calculation Basis**
  - NSRP ROI = (Cost reduction - Navy Investment)/(Navy Investment)
    - Cost Reduction = cost savings and cost avoidance resulting from implementation of the project
    - Navy Investment = NSRP program funding approved for the project = $1,139,695.00
- **Project Design/Construction ROI Assessment: ROI=77:1**
  - Cost Reduction = $88,925,000.00 (EROM Five-year return period)(see next slide)
- **Project In-Service ROI Assessment: ROI=76:1**
  - Cost Reduction = $87,500.000.00 (EROM Five-year return period) (see next slide)

These ROI Assessments far exceed the NSRP target value of 2:1

Project Return On Investment (ROI) Assessment - NSRP RA 21-11 ROI Calculations and Results ROI Design/Construction=77:1 ROI In-Service=76:1 NSRP ROI Goal/Target=2:1



Groups C, D and E Savings/ROI	
Notional 14,000-ton Large Surface Combatant	
Category C. Material Savings	
- 5% savings in material costs resulting from reduced plate and profile variation and use of mill runs vs. warehouse suppliers.	
Total structural material costs (single ship)	$18,250,000.00
5% material cost savings (per ship)	$912,500.00
Category D. Construction Savings	
- 12% reduction in total steel fabrication and assembly cost based on reduced weld length, fewer interestions, use of automation, lean design priciples.	
Total structure fabrication cost (single ship)	$66,500,000.00
12% reduction in structure fabrication cost savings (per ship)	$7,980,000.00
Category C + Category D Per Ship Cost Savings	$8,892,500.00
EROM @ two ships per year for 5 year return period, total savings	$88,925,000.00
Navy/NSRP Investment in RA Project	$1,139,695.00
Cat. C + D: Navy ROI for NSRP Project (Savings - Navy Investment)/Navy Investment	77
Category E. Structural Repair Savings	
RAND Reported 2003-2015 SWBS 100 Repair/Maintenance Cost	$3,050,000,000
Per Year Average SWBS 100 Repair/Maintenance Cost	$254,166,667
Rounded Per Year Average SWBS 100 Repair/Maint. Cost	$250,000,000
Assume save 7% per year of 2003-2015 SWBS 100 Costs	$17,500,000
EROM @ 7% Savings over 5 Years	$87,500,000
Category E: ROI for 7% In-Service Savings Only	76

Steel Material Cost Savings

Cells C9 and C14 are updated with a simple average of the Material and Fabrication costs from SPAR in columns I-L.

Steel Fabrication Savings

ROI Design/Construction

ROI = (Cost reduction - Navy Investment)/(Navy Investment)

In-Service Savings

ROI In-Service Savings

Steel Material Costs

Material Cost		Reduced Shapes	
w/Distributor	Mill Cost (100%)	by 50% (Dist)	Mill Cost
$ 19,741,356	$ 16,758,091	$ 18,573,992	$ 15,785,287
Savings	-17.8%		-6.2%
			$ 2,788,705
Buy all steel from Distributor	Buy all steel from mill.	Reduce the # of shapes by 50% and buy them from a distributor	Reduce the # of shapes by 50% and buy them from mill

Labor	Mat	Total	Savings
$ 48,758,808	$ 15,785,287	$ 64,544,095	$ 7,745,291
$ 48,758,808	$ 19,741,356	$ 68,500,165	$ 8,220,020

As done today

Steel Fabrication Costs

Hull Maintence (Current Process)	
Every 15 Years	Life of Ship (30 Years)
$ 8,132,340	$ 243,970,187

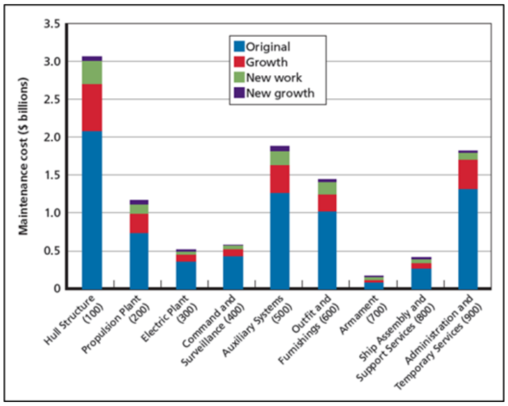
14,000 LT Notional Surface Combatant Estimates from SPAR Cost Model

Project Return On Investment (ROI) Assessment - Numerous DoD Studies Document Excessive Ship Structural Degradation and Related Repair and Maintenance Costs

Project Cost Savings Objectives

- Reduce ship construction costs with Lean Design principles while improving in-service structural performance
- U.S. Government Accountability Office (GAO) reported in its March 2020 GAO-20-2 Report, "Increasing Focus on Sustainment Early in the Acquisition Process Could Save Billions"
- Structural failure has been a serious problem on FFG 7, CG 47/52 and DDG 51 Classes; this can be mitigated by MAESTRO design optimization for combined loads.
- Corrosion continues to be a significant ongoing cost:
- Added fatigue damage margin and corrosion margin is one mitigation strategy
- Coating/production friendly construction details is another mitigation strategy
- Designing for coating and maintenance is a third mitigation strategy

The RA project addresses these issues with enhanced design tools for early-stage structural design to augment traditional and less flexible methods.



Group 100 Hull Structures Leads U.S. Navy Surface Ship Depot Maintenance Costs by ESWBS, 2003-2015 ***[2017 RAND Report 1187]***

Phase 3 – Return On Investment (ROI) Assessment
NSRP RA 21-11 ROI Assessment/Calculation Approach

- **Project ROI Construct**
  - The project has two distinct phases of ROI : **Design/Construction** and **In-Service**
  - Pete Jaquith wrote a recommended approach for the project ROI calculation
  - Six categories of savings or cost avoidance were identified
- **Six categories of ROI savings or cost avoidance were identified:**
  - **Category A. Early -Stage FEA Modeling Savings** – Early-stage design analysis savings resulting from new MAESTRO modeling and analysis tools (assess in Phase 4).
  - **Category B. Digital Twin Development Savings** – Digital twin development and maintenance savings resulting from new MAESTRO modeling and analysis tools (assess in Phase 4).
  - **Category C. Material Savings** – Using the SPAR Cost Model estimate the total steel cost (assume an all HSLA 65 ship), based on the work demonstrated on earlier projects a 5% savings in material cost is recommended resulting from reduced plate and profile variation and the ability to use mill runs vs. warehouse suppliers.
  - **Category D. Construction Savings** – Using the SPAR Cost Model estimate the total steel fabrication and assembly labor cost (include supervision and support), based on the work demonstrated on earlier projects (up to 28% reduction in total weld length) a 10% -15% reduction in total steel fabrication and assembly cost is recommended.
  - **Category E. Structural Repair Savings** – Obtain from NSWC Carderock or ASN's Office the structural repair cost and time out of service for DDG 51 Flight I and II structural failures (Bob Keane is working this), ratio these up to reflect a 14,000 -ton Large Surface Combatant. The Group 100 Structures maintenance and repair costs documented in major U.S. Navy and USCG reports are being used to recommend that through MAESTRO FEA optimization starting in early -stage design this cost can be reduced by at least 5% -10%.
  - **Category F. Life -Cycle Structural Maintenance Savings** – Life-cycle structural damage and maintenance savings resulting from new MAESTRO digital twin modeling and analysis tools (assess in Phase 4).

Project Return On Investment (ROI) Assessment NSRP RA 21-11 ROI Assessment Approach

- **ROI savings or cost avoidance: Categories C, D and E from Peter Jaquith's White Paper were selected for the ROI Assessment/Calculation:**
  - **Category C. Material Savings** – Using the SPAR Cost Model estimate the total steel cost (assume an all HSLA 65 ship), based on the work demonstrated under the project a 5% savings is recommended in material cost resulting from reduced plate and profile variation and the ability to use mill runs vs. warehouse suppliers.
  - **Category D. Construction Savings** – Using the SPAR Cost Model estimate the total steel fabrication and assembly labor cost (include supervision and support), based on the work demonstrated under the project (up to 28% reduction in total weld length) taking a 10% - 15% reduction in total steel fabrication and assembly cost is recommended.
  - **Category E. Structural Repair Savings** – A request has been placed with NSWC Carderock and ASN's Office for the structural repair cost and time out of service for DDG 51 Flight I and II structural failures (Bob Keane is working this). The documented Group 100 structures maintenance and repair costs documented in major U.S. Navy and USCG reports are being used to recommend that through MAESTRO FEA optimization starting in early-stage design this cost can be reduced by at least 5%-10%.
- **ROI Case Study and Assessment**
  - Use a 14,000-ton Large Surface Combatant assuming a 30 ship buy.
  - Categories C and D can be combined to apply to the **Design and Construction** Phase of the life-cycle.
  - Category E can be applied to the **In-Service** Phase of the life-cycle.

Project Return On Investment (ROI) Assessment NSRP RA 21-11 ROI Assessment Approach

- **ROI Construct**
  - The project has two phases of ROI**: Design/Construction**and **In-Service**
  - ROI Assessment work has focused on three categories of cost savings: saving structural material cost, saving structural fabrication cost, and reducing in-service structural repair costs.
- **Examples of Design/Construction Savings for a specific ship design :**
  - Reduced structural weight by 5% or by 8%
  - Reduced numbers of plate and profile types/sizes: e.g., from 30 plates to 20 plates and 60 profiles to 40 profiles
  - Reduced weld length for the overall design by, e.g., 5% or 10%
- **Examples of In-Service Savings**
  - Navy and Coast Guard have existing data/studies to document the cost and potential cost reductions
  - The Project premise includes less heavy weather damage, extended fatigue life, and reduced corrosion damage.
  - The project rationale uses the Rand and similar reports as a benchmark. The project Team is postulating a modest (e.g., 5% - 10%) reduction in SWBS Group 100 repair and maintenance costs.

Project ROI Assessment

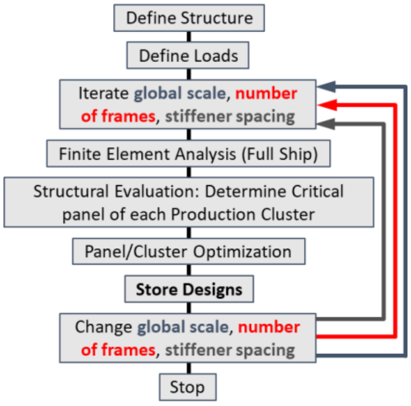
- **Examples of Design/Construction Savings for a specific ship design :**
    - SPAR has developed a notional 14,000 LT surface combatant using their work-content cost model
    - This model is be used to estimate Group 100 structural material and fabrication costs
    - These costs with modest % savings are used to develop ROI for reduced structural material cost and reduced structural fabrication costs
    - Project ROI calculations show strong/high ROI values.
- **Examples of In-Service Savings**
    - Navy and Coast Guard have existing data/studies to document the cost and potential cost reductions
    - Studies support structural repairs being driven by heavy weather damage, structural fatigue cracking, and corrosion induced structural damage
    - Annual costs of structural repairs are estimated based on the studies
    - A reduction in these SWBS Group 100 repair and maintenance costs of 5%- 10% is used to assess the project's potential ROI associated with reducing cost of in-service structural repairs.
    - Project ROI calculations show strong/high ROI values.

Project Return On Investment (ROI) Assessment - Numerous DoD Studies Document Excessive Ship Structural Degradation and Related Repair and Maintenance Costs

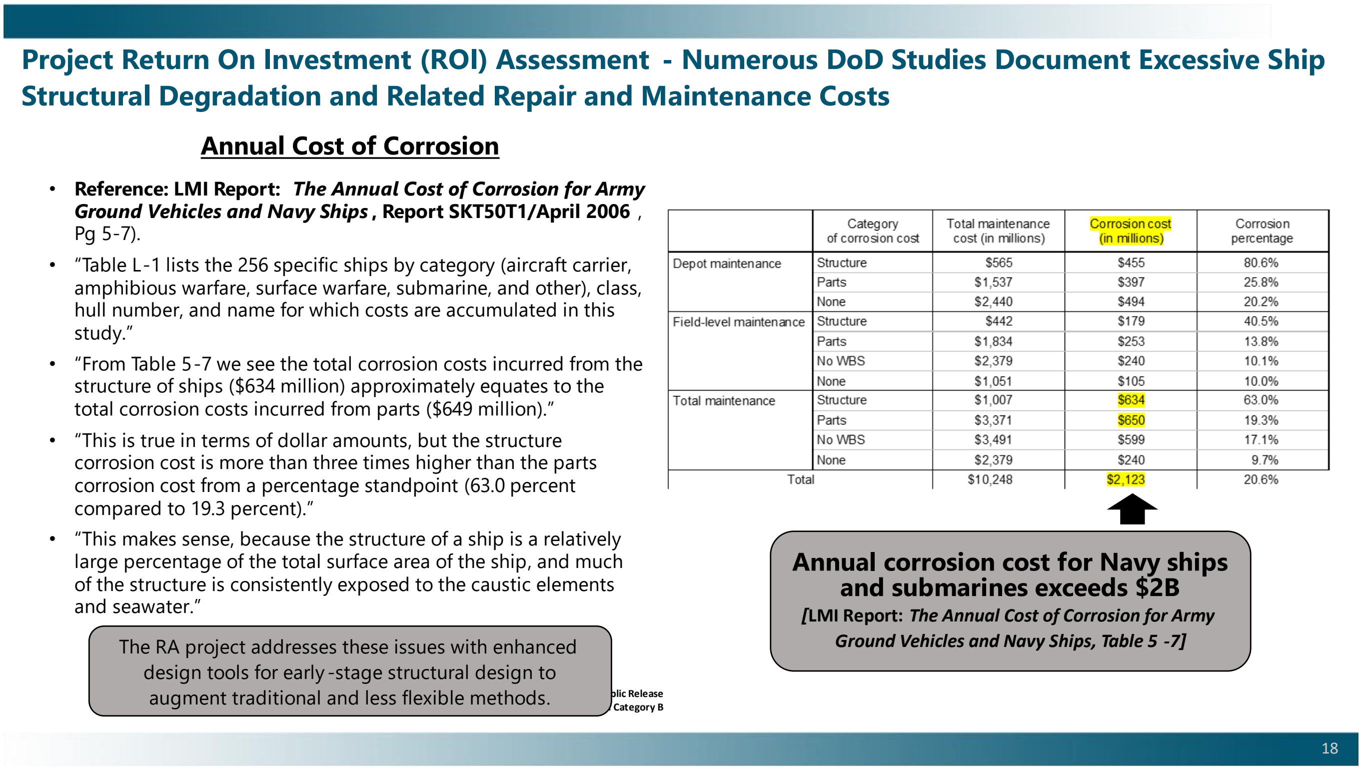
Structural Design Directly Affects Corrosion

- **Ship Structure Committee Report SSC -397** titled: "Commercial Ship Design and Fabrication for Corrosion Control", dated 24 Sep 1996, has significant material connecting structural design with in-service corrosion control.
- SSC-397 is equally relevant to U.S. Navy ships. Much of the relationship between structural design, including arrangements, and corrosion control is fundamentally lean design principles.
- Section 4.1.2 of the SSC -397 report is titled "Optimization of Structural Design" and addresses topics including: Longitudinal Strength, Buckling and Local Strength, Flexibility of Bulkhead Panels, Thickness Considerations, and Material Considerations.
- These are all topics that fall within the scope of using MAESTRO for optimized design. These topics are also revisited and summarized in the report's Section 6. Recommendations.

The RA project addresses these issues with enhanced design tools for early-stage structural design to optimize the complex combination of structural strength, buckling, and materials.



**NSRP RA 21-11 Project Tools
Ship Structural Optimization**



Project Return On Investment (ROI) Assessment - Numerous DoD Studies Document Excessive Ship Structural Degradation and Related Repair and Maintenance Costs

Annual Cost of Corrosion

- **Reference: LMI Report: *The Annual Cost of Corrosion for Army Ground Vehicles and Navy Ships*, Report SKT50T1/April 2006**, Pg 5-7).
- "Table L-1 lists the 256 specific ships by category (aircraft carrier, amphibious warfare, surface warfare, submarine, and other), class, hull number, and name for which costs are accumulated in this study."
- "From Table 5-7 we see the total corrosion costs incurred from the structure of ships ($634 million) approximately equates to the total corrosion costs incurred from parts ($649 million)."
- "This is true in terms of dollar amounts, but the structure corrosion cost is more than three times higher than the parts corrosion cost from a percentage standpoint (63.0 percent compared to 19.3 percent)."
- "This makes sense, because the structure of a ship is a relatively large percentage of the total surface area of the ship, and much of the structure is consistently exposed to the caustic elements and seawater."

	Category of corrosion cost	Total maintenance cost (in millions)	Corrosion cost (in millions)	Corrosion percentage
Depot maintenance	Structure	$565	$455	80.6%
	Parts	$1,537	$397	25.8%
	None	$2,440	$494	20.2%
Field-level maintenance	Structure	$442	$179	40.5%
	Parts	$1,834	$253	13.8%
	No WBS	$2,379	$240	10.1%
	None	$1,051	$105	10.0%
Total maintenance	Structure	$1,007	$634	63.0%
	Parts	$3,371	$650	19.3%
	No WBS	$3,491	$599	17.1%
	None	$2,379	$240	9.7%
Total		$10,248	$2,123	20.6%

Annual corrosion cost for Navy ships and submarines exceeds $2B

[LMI Report: The Annual Cost of Corrosion for Army Ground Vehicles and Navy Ships, Table 5 -7]

The RA project addresses these issues with enhanced design tools for early-stage structural design to augment traditional and less flexible methods.

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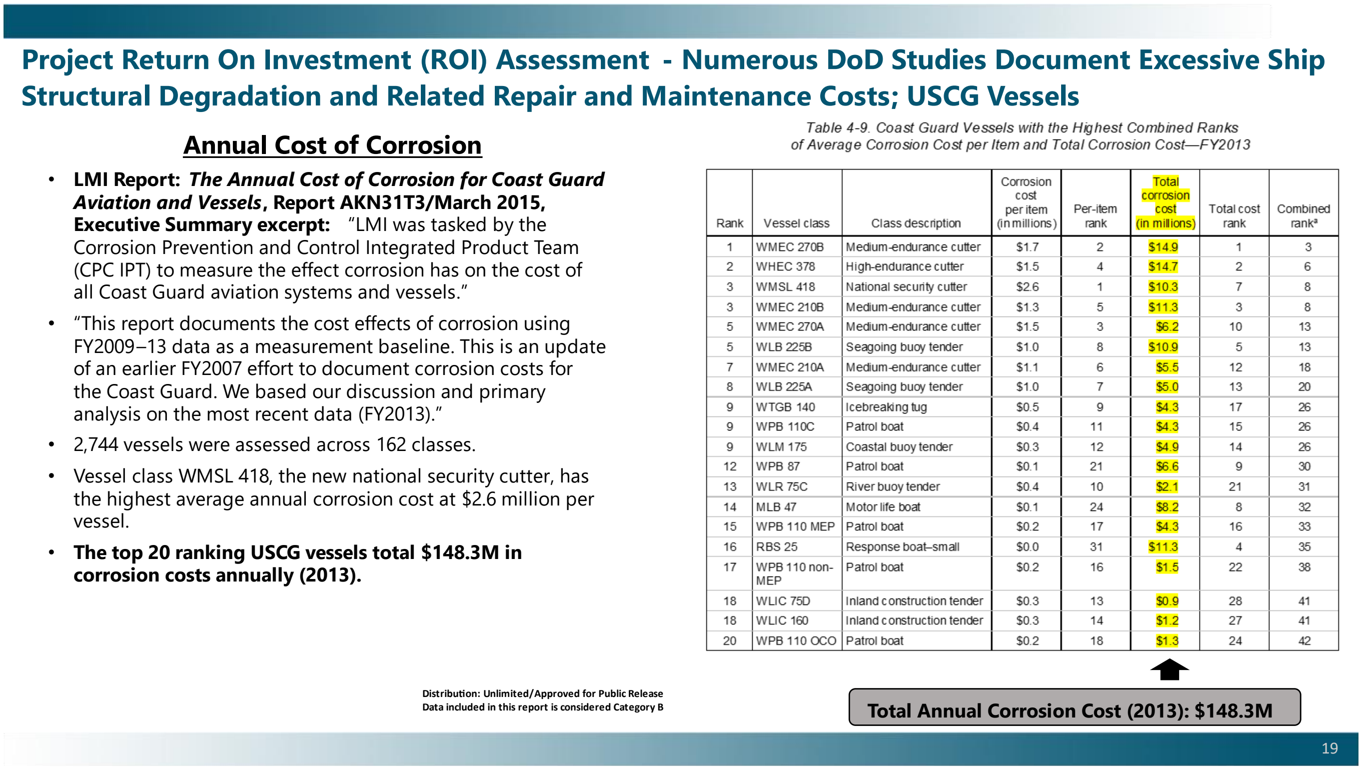
18



Project Return On Investment (ROI) Assessment - Numerous DoD Studies Document Excessive Ship Structural Degradation and Related Repair and Maintenance Costs; USCG Vessels

Annual Cost of Corrosion

- **LMI Report: *The Annual Cost of Corrosion for Coast Guard Aviation and Vessels*, Report AKN31T3/March 2015, Executive Summary excerpt:** "LMI was tasked by the Corrosion Prevention and Control Integrated Product Team (CPC IPT) to measure the effect corrosion has on the cost of all Coast Guard aviation systems and vessels."
- "This report documents the cost effects of corrosion using FY2009–13 data as a measurement baseline. This is an update of an earlier FY2007 effort to document corrosion costs for the Coast Guard. We based our discussion and primary analysis on the most recent data (FY2013)."
- 2,744 vessels were assessed across 162 classes.
- Vessel class WMSL 418, the new national security cutter, has the highest average annual corrosion cost at $2.6 million per vessel.
- **The top 20 ranking USCG vessels total $148.3M in corrosion costs annually (2013).**

Table 4-9. Coast Guard Vessels with the Highest Combined Ranks of Average Corrosion Cost per Item and Total Corrosion Cost—FY2013

Rank	Vessel class	Class description	Corrosion cost per item (in millions)	Per-item rank	Total corrosion cost (in millions)	Total cost rank	Combined rank^a
1	WMEC 270B	Medium-endurance cutter	$1.7	2	$14.9	1	3
2	WHEC 378	High-endurance cutter	$1.5	4	$14.7	2	6
3	WMSL 418	National security cutter	$2.6	1	$10.3	7	8
3	WMEC 210B	Medium-endurance cutter	$1.3	5	$11.3	3	8
5	WMEC 270A	Medium-endurance cutter	$1.5	3	$6.2	10	13
5	WLB 225B	Seagoing buoy tender	$1.0	8	$10.9	5	13
7	WMEC 210A	Medium-endurance cutter	$1.1	6	$5.5	12	18
8	WLB 225A	Seagoing buoy tender	$1.0	7	$5.0	13	20
9	WTGB 140	Icebreaking tug	$0.5	9	$4.3	17	26
9	WPB 110C	Patrol boat	$0.4	11	$4.3	15	26
9	WLM 175	Coastal buoy tender	$0.3	12	$4.9	14	26
12	WPB 87	Patrol boat	$0.1	21	$6.6	9	30
13	WLR 75C	River buoy tender	$0.4	10	$2.1	21	31
14	MLB 47	Motor life boat	$0.1	24	$8.2	8	32
15	WPB 110 MEP	Patrol boat	$0.2	17	$4.3	16	33
16	RBS 25	Response boat–small	$0.0	31	$11.3	4	35
17	WPB 110 non-MEP	Patrol boat	$0.2	16	$1.5	22	38
18	WLIC 75D	Inland construction tender	$0.3	13	$0.9	28	41
18	WLIC 160	Inland construction tender	$0.3	14	$1.2	27	41
20	WPB 110 OCO	Patrol boat	$0.2	18	$1.3	24	42

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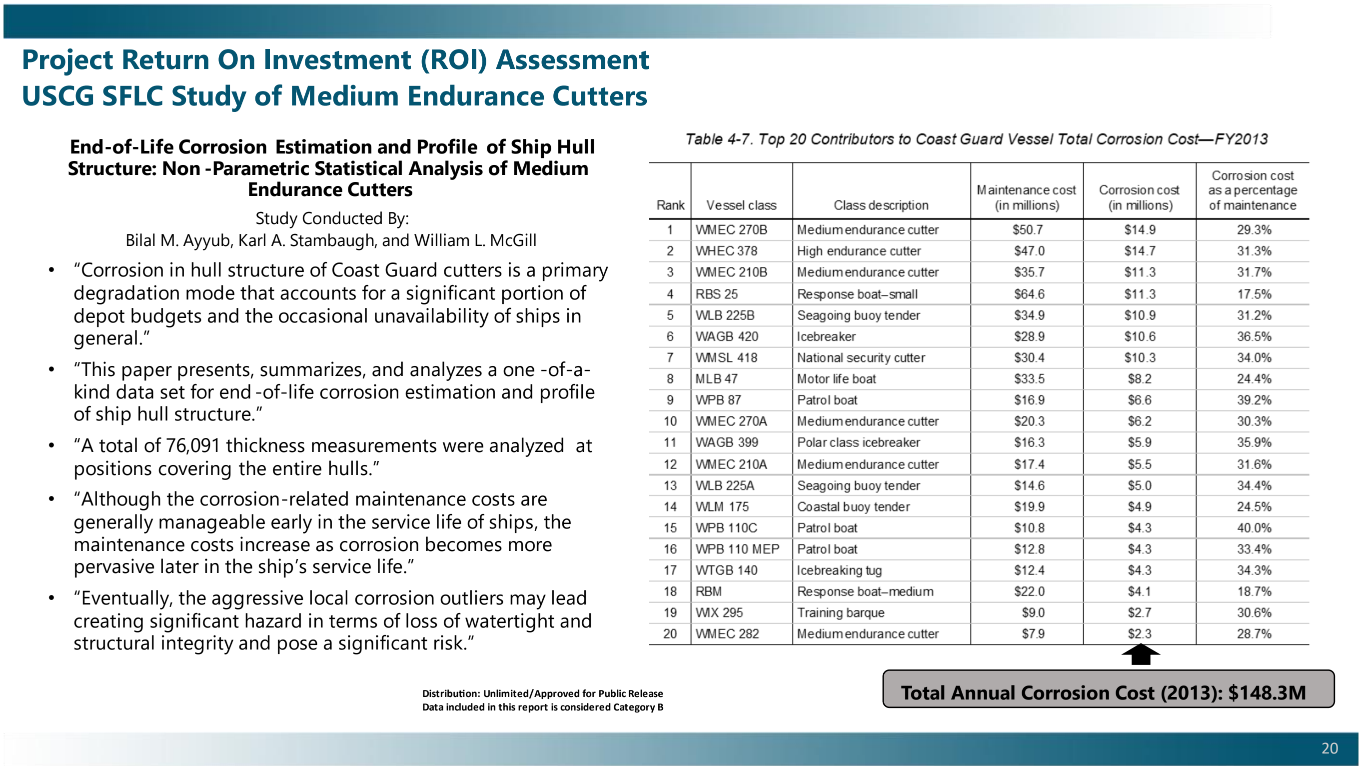
Total Annual Corrosion Cost (2013): $148.3M

19



Project Return On Investment (ROI) Assessment
USCG SFLC Study of Medium Endurance Cutters

End-of-Life Corrosion Estimation and Profile of Ship Hull Structure: Non-Parametric Statistical Analysis of Medium Endurance Cutters

Study Conducted By:
Bilal M. Ayyub, Karl A. Stambaugh, and William L. McGill

- "Corrosion in hull structure of Coast Guard cutters is a primary degradation mode that accounts for a significant portion of depot budgets and the occasional unavailability of ships in general."
- "This paper presents, summarizes, and analyzes a one-of-a-kind data set for end-of-life corrosion estimation and profile of ship hull structure."
- "A total of 76,091 thickness measurements were analyzed at positions covering the entire hulls."
- "Although the corrosion-related maintenance costs are generally manageable early in the service life of ships, the maintenance costs increase as corrosion becomes more pervasive later in the ship's service life."
- "Eventually, the aggressive local corrosion outliers may lead creating significant hazard in terms of loss of watertight and structural integrity and pose a significant risk."

Table 4-7. Top 20 Contributors to Coast Guard Vessel Total Corrosion Cost—FY2013

Rank	Vessel class	Class description	Maintenance cost (in millions)	Corrosion cost (in millions)	Corrosion cost as a percentage of maintenance
1	WMEC 270B	Medium endurance cutter	$50.7	$14.9	29.3%
2	WHEC 378	High endurance cutter	$47.0	$14.7	31.3%
3	WMEC 210B	Medium endurance cutter	$35.7	$11.3	31.7%
4	RBS 25	Response boat–small	$64.6	$11.3	17.5%
5	WLB 225B	Seagoing buoy tender	$34.9	$10.9	31.2%
6	WAGB 420	Icebreaker	$28.9	$10.6	36.5%
7	WMSL 418	National security cutter	$30.4	$10.3	34.0%
8	MLB 47	Motor life boat	$33.5	$8.2	24.4%
9	WPB 87	Patrol boat	$16.9	$6.6	39.2%
10	WMEC 270A	Medium endurance cutter	$20.3	$6.2	30.3%
11	WAGB 399	Polar class icebreaker	$16.3	$5.9	35.9%
12	WMEC 210A	Medium endurance cutter	$17.4	$5.5	31.6%
13	WLB 225A	Seagoing buoy tender	$14.6	$5.0	34.4%
14	WLM 175	Coastal buoy tender	$19.9	$4.9	24.5%
15	WPB 110C	Patrol boat	$10.8	$4.3	40.0%
16	WPB 110 MEP	Patrol boat	$12.8	$4.3	33.4%
17	WTGB 140	Icebreaking tug	$12.4	$4.3	34.3%
18	RBM	Response boat–medium	$22.0	$4.1	18.7%
19	WIX 295	Training barque	$9.0	$2.7	30.6%
20	WMEC 282	Medium endurance cutter	$7.9	$2.3	28.7%

Total Annual Corrosion Cost (2013): $148.3M

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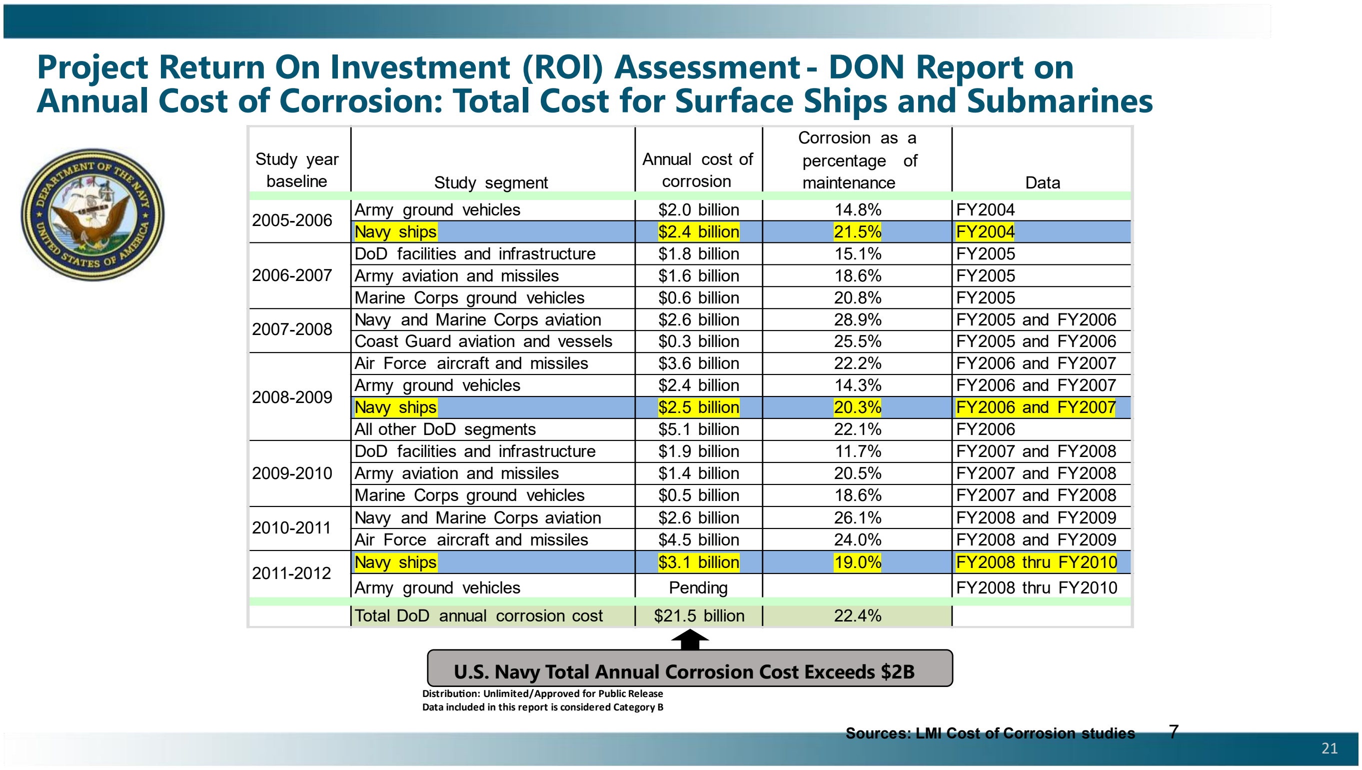
20



Project Return On Investment (ROI) Assessment - DON Report on Annual Cost of Corrosion: Total Cost for Surface Ships and Submarines

Study year baseline	Study segment	Annual cost of corrosion	Corrosion as a percentage of maintenance	Data
2005-2006	Army ground vehicles	$2.0 billion	14.8%	FY2004
	Navy ships	$2.4 billion	21.5%	FY2004
2006-2007	DoD facilities and infrastructure	$1.8 billion	15.1%	FY2005
	Army aviation and missiles	$1.6 billion	18.6%	FY2005
	Marine Corps ground vehicles	$0.6 billion	20.8%	FY2005
2007-2008	Navy and Marine Corps aviation	$2.6 billion	28.9%	FY2005 and FY2006
	Coast Guard aviation and vessels	$0.3 billion	25.5%	FY2005 and FY2006
2008-2009	Air Force aircraft and missiles	$3.6 billion	22.2%	FY2006 and FY2007
	Army ground vehicles	$2.4 billion	14.3%	FY2006 and FY2007
	Navy ships	$2.5 billion	20.3%	FY2006 and FY2007
	All other DoD segments	$5.1 billion	22.1%	FY2006
2009-2010	DoD facilities and infrastructure	$1.9 billion	11.7%	FY2007 and FY2008
	Army aviation and missiles	$1.4 billion	20.5%	FY2007 and FY2008
	Marine Corps ground vehicles	$0.5 billion	18.6%	FY2007 and FY2008
2010-2011	Navy and Marine Corps aviation	$2.6 billion	26.1%	FY2008 and FY2009
	Air Force aircraft and missiles	$4.5 billion	24.0%	FY2008 and FY2009
2011-2012	Navy ships	$3.1 billion	19.0%	FY2008 thru FY2010
	Army ground vehicles	Pending		FY2008 thru FY2010
	Total DoD annual corrosion cost	$21.5 billion	22.4%	

U.S. Navy Total Annual Corrosion Cost Exceeds $2B

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Sources: LMI Cost of Corrosion studies 7

21

Tobin Mcnatt

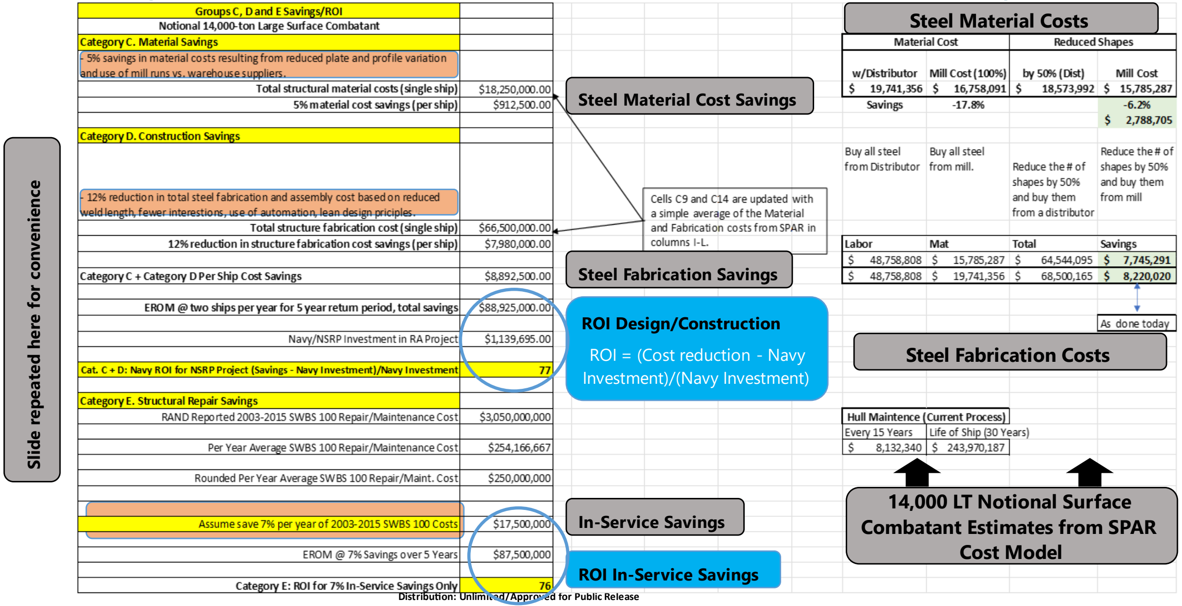
Project ROI Assessment – USCG Surface Forces Logistics Center (SFLC) Technical Input Regarding Targeted Cost Reductions

SFLC Technical Input:

- SFLC agrees with Design & Construction cost savings from structural weight savings and production efficiency gains, acknowledging that the shipyard is more competitive, and savings are also passed to the customers (Navy and USCG).
- SFLC agrees with Category E. In-Service Repair cost savings of 5% to 10%."
- Cites USCG is using a Spectral Fatigue Analysis (SFA) approach to fatigue for recent ship acquisitions, which the project team is testing in Case Studies and recommending for use earlier in design.

USCG Island-Class Patrol Boat

Project Return On Investment (ROI) Assessment - NSRP RA 21-11 ROI Calculations and Results ROI Design/Construction=77:1 ROI In -Service=76:1 NSRP ROI Goal/Target=2:1



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Groups C, D and E Savings/ROI	
Notional 14,000-ton Large Surface Combatant	
Category C. Material Savings	
- 5% savings in material costs resulting from reduced plate and profile variation and use of mill runs vs. warehouse suppliers.	
Total structural material costs (single ship)	$18,250,000.00
5% material cost savings (per ship)	$912,500.00
Category D. Construction Savings	
- 12% reduction in total steel fabrication and assembly cost based on reduced weld length, fewer interestions, use of automation, lean design priciples.	
Total structure fabrication cost (single ship)	$66,500,000.00
12% reduction in structure fabrication cost savings (per ship)	$7,980,000.00
Category C + Category D Per Ship Cost Savings	$8,892,500.00
EROM @ two ships per year for 5 year return period, total savings	$88,925,000.00
Navy/NSRP Investment in RA Project	$1,139,695.00
Cat. C + D: Navy ROI for NSRP Project (Savings - Navy Investment)/Navy Investment	77
Category E. Structural Repair Savings	
RAND Reported 2003-2015 SWBS 100 Repair/Maintenance Cost	$3,050,000,000
Per Year Average SWBS 100 Repair/Maintenance Cost	$254,166,667
Rounded Per Year Average SWBS 100 Repair/Maint. Cost	$250,000,000
Assume save 7% per year of 2003-2015 SWBS 100 Costs	$17,500,000
EROM @ 7% Savings over 5 Years	$87,500,000
Category E: ROI for 7% In-Service Savings Only	76

Steel Material Cost Savings

Cells C9 and C14 are updated with a simple average of the Material and Fabrication costs from SPAR in columns I-L.

Steel Fabrication Savings

ROI Design/Construction

ROI = (Cost reduction - Navy Investment)/(Navy Investment)

In-Service Savings

ROI In-Service Savings

Steel Material Costs

Material Cost		Reduced Shapes	
w/Distributor	Mill Cost (100%)	by 50% (Dist)	Mill Cost
$ 19,741,356	$ 16,758,091	$ 18,573,992	$ 15,785,287
Savings	-17.8%		-6.2%
			$ 2,788,705
Buy all steel from Distributor	Buy all steel from mill.	Reduce the # of shapes by 50% and buy them from a distributor	Reduce the # of shapes by 50% and buy them from mill

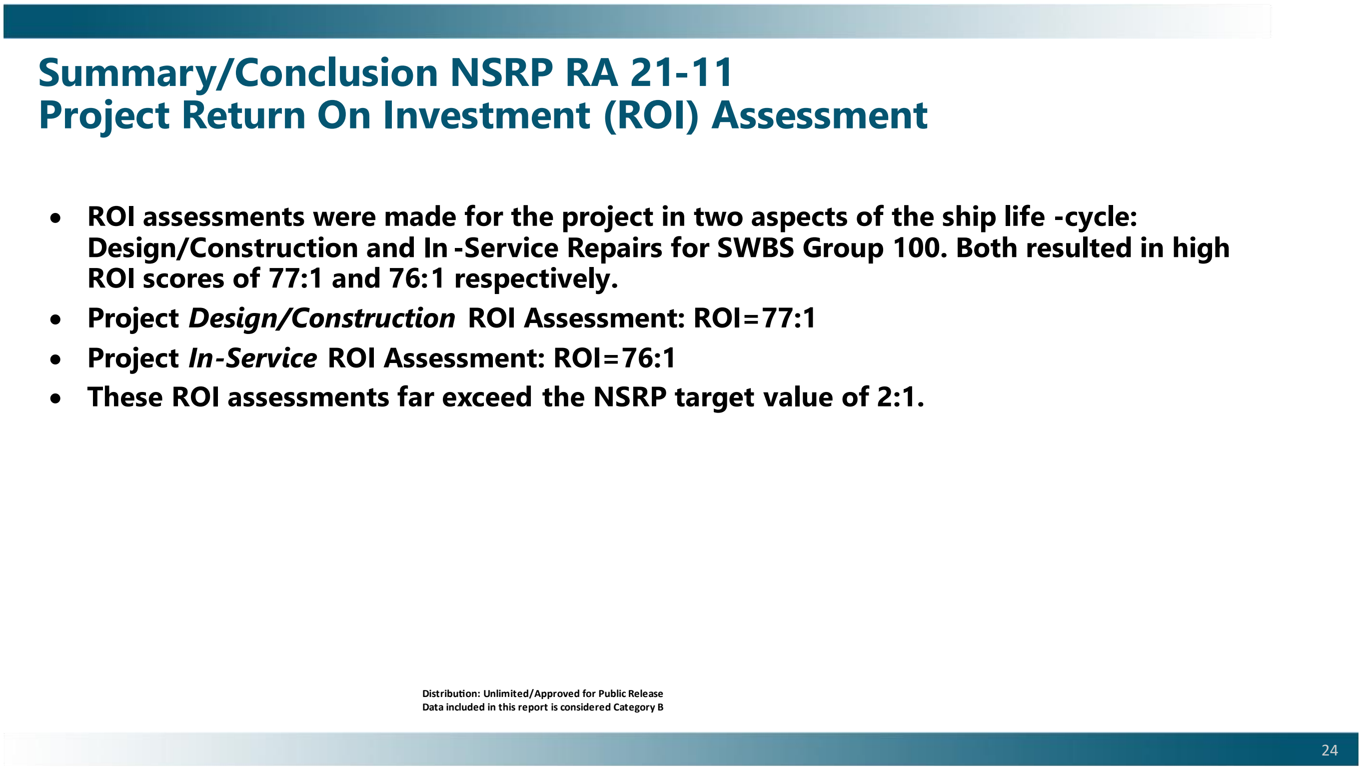
Labor	Mat	Total	Savings
$ 48,758,808	$ 15,785,287	$ 64,544,095	$ 7,745,291
$ 48,758,808	$ 19,741,356	$ 68,500,165	$ 8,220,020

As done today

Steel Fabrication Costs

Hull Maintence (Current Process)	
Every 15 Years	Life of Ship (30 Years)
$ 8,132,340	$ 243,970,187

14,000 LT Notional Surface Combatant Estimates from SPAR Cost Model



Summary/Conclusion NSRP RA 21-11
Project Return On Investment (ROI) Assessment

- **ROI assessments were made for the project in two aspects of the ship life -cycle: Design/Construction and In -Service Repairs for SWBS Group 100. Both resulted in high ROI scores of 77:1 and 76:1 respectively.**
- **Project *Design/Construction* ROI Assessment: ROI=77:1**
- **Project *In-Service* ROI Assessment: ROI=76:1**
- **These ROI assessments far exceed the NSRP target value of 2:1.**

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24