Naval Surface Warfare Center, Carderock Division

AMERICA'S FLEET STARTS HERE

10-12 October 2023, AVT- 369, Båstad, Sweden

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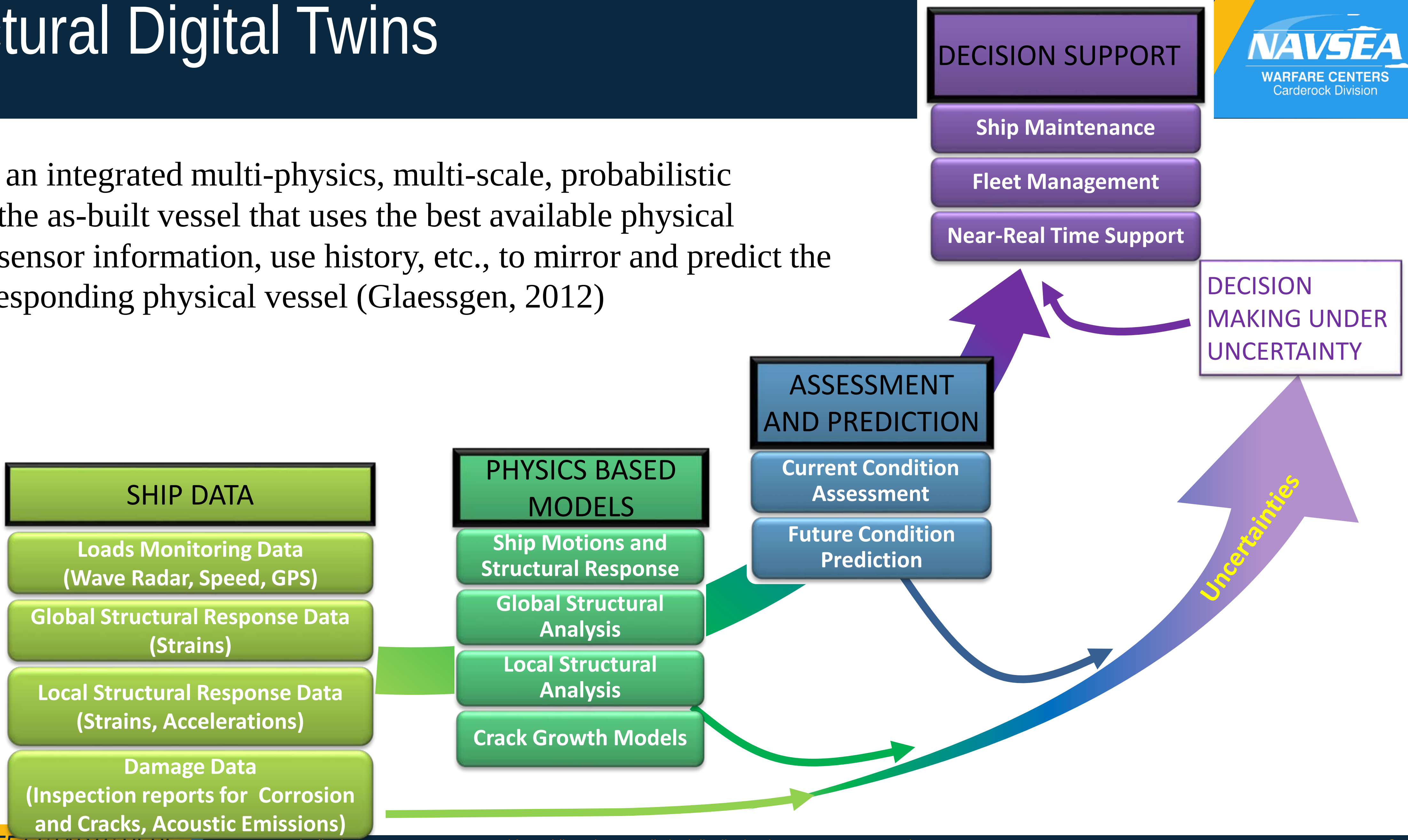
NAVSEA WARFARE CENTERS Carderock Division

On the Application of Structural Digital Twins for Surface Ships for Operational Guidance Support

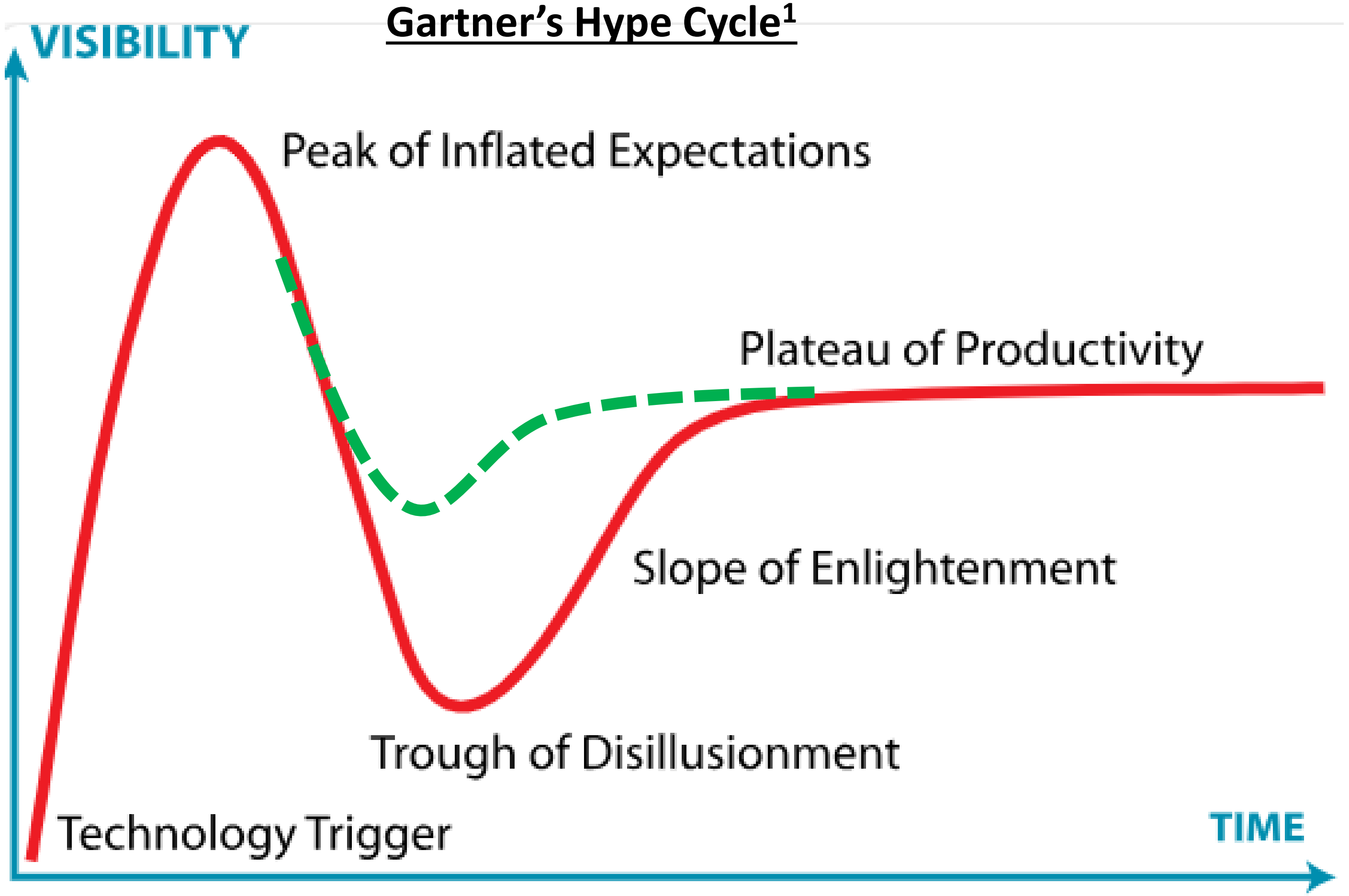
Structural Digital Twins

Digital Twin: an integrated multi-physics, multi-scale, probabilistic simulation of the as-built vessel that uses the best available physical models, data, sensor information, use history, etc., to mirror and predict the life of its corresponding physical vessel (Glaessgen, 2012)



Motivation

Gartner's Hype Cycle[1]



Reference 1: Linden, A., & Fenn, J. (2003). Understanding Gartner's hype cycles. *Strategic Analysis Report Nº R-20-1971. Gartner, Inc*, *88*, 1423.

Structural Digital Twins

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- ***Digital Twin is a concept so extensive, that, to enable practical development and usage, scoping the twin is essential.***

SHIP DATA
- Loads Monitoring Data (Wave Radar, Speed, GPS)
- Global Structural Response Data (Strains)
- Local Structural Response Data (Strains, Accelerations)
- Damage Data (Inspection reports for Corrosion and Cracks, Acoustic Emissions)

PHYSICS BASED MODELS
- Ship Motions and Structural Response
- Global Structural Analysis
- Local Structural Analysis
- Crack Growth Models

ASSESSMENT AND PREDICTION
- Current Condition Assessment
- Future Condition Prediction

DECISION SUPPORT
- Ship Maintenance
- Fleet Management
- Near-Real Time Support

DECISION MAKING UNDER UNCERTAINTY

Uncertainties

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Outline

- ***Digital Twin is a concept so extensive, that, to enable practical development and usage, scoping the twin is essential.***

1. Defining a digital twin
   A. Objectives
   B. Model Parameters
   C. Constraints
   D. Model
      - Physics-Data Fusion
      - Probabilistic & Predictive
2. Case Study
3. Performance Based Decision Support
4. Conclusion

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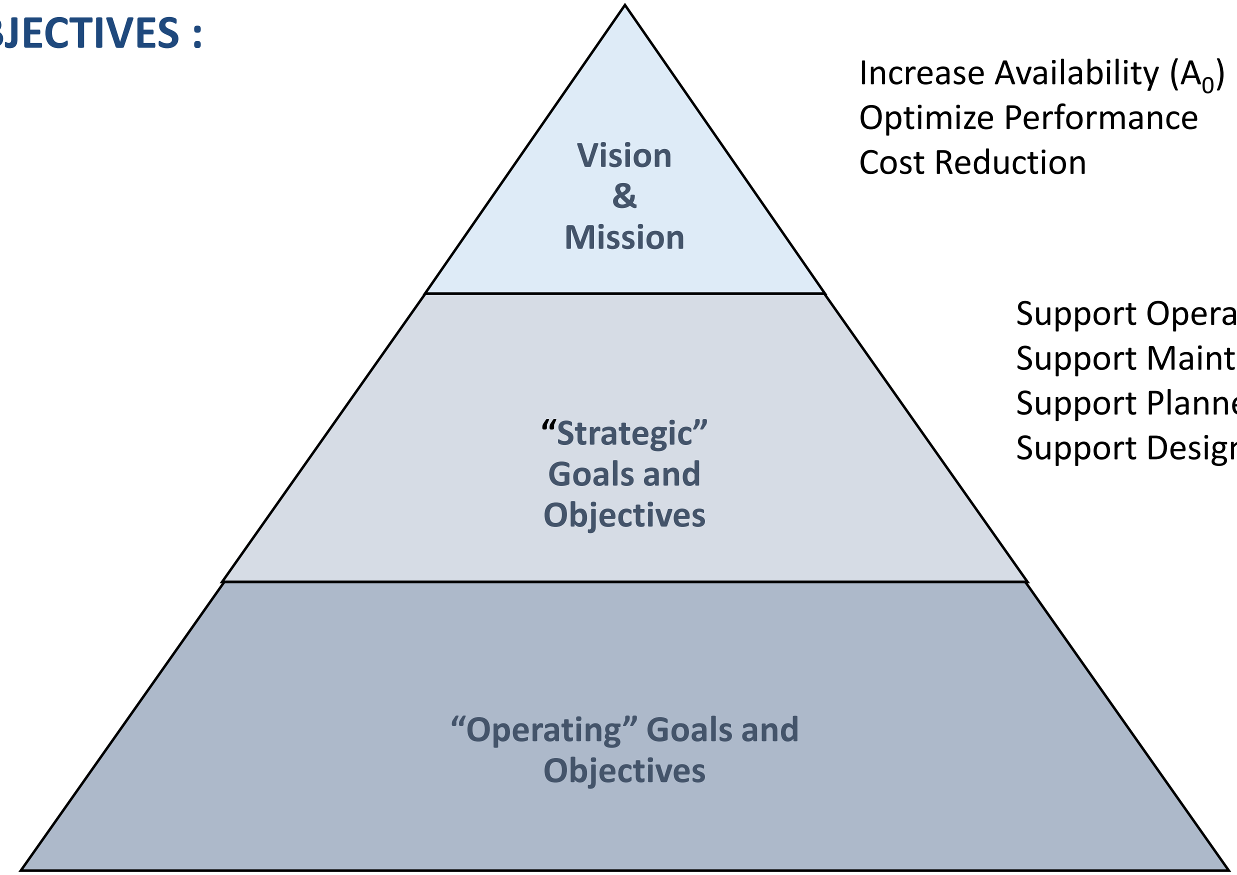
Objectives

HIERARCHY OF OBJECTIVES :



Increase Availability (A_0)
Optimize Performance
Cost Reduction

Support Operator: Operator Guidance, Route Planning
Support Maintainer: Condition Based Maintenance
Support Planner: Fleet / Asset Planning
Support Designer: Enable Optimal Design

Provide decision support with respect to complexity of analysis, the planning time-horizon, resources available, flexibility, level of integration to the decision maker

Objectives

OPERATIONAL OBJECTIVE :

Near Real Time Operational Guidance for the Near Future for a Manned Ship during Routine Operations for Operator Support

Timeliness	+	Use	+	Time Horizon	+	Consequences	+	Operations	+	Level of Integration
Complexity level compliant with resources		What decision is being supported		Immediate actions or longer term routing		Manned Unmanned Autonomous		Routine (Peacetime) Critical (Wartime)		Support Operator Human-in-the-loop Full Decision Authority

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Model Parameters

	Operational Information	*Structures-Intentional Data*
Recurring		• Structural Inspection Data (materials, cracking, deformation, configuration, etc)
Real Time	• True & Relative Wind Data • Air Pressure, Temperature and Humidity • Wave Height, Frequency, Directional Content • Sea Temperature Data • Weather and Wave Forecast • Ballast & Draft • Ship's Position, Attitude, Heading and Velocity	• Strains • Pressure Transducers • Accelerations • Acoustic Emissions
After Data Collection	• Hindcast Data (Wave Height, Frequency, Directional Content, relative headings, speed over ground)	

Model Parameters: How to choose?

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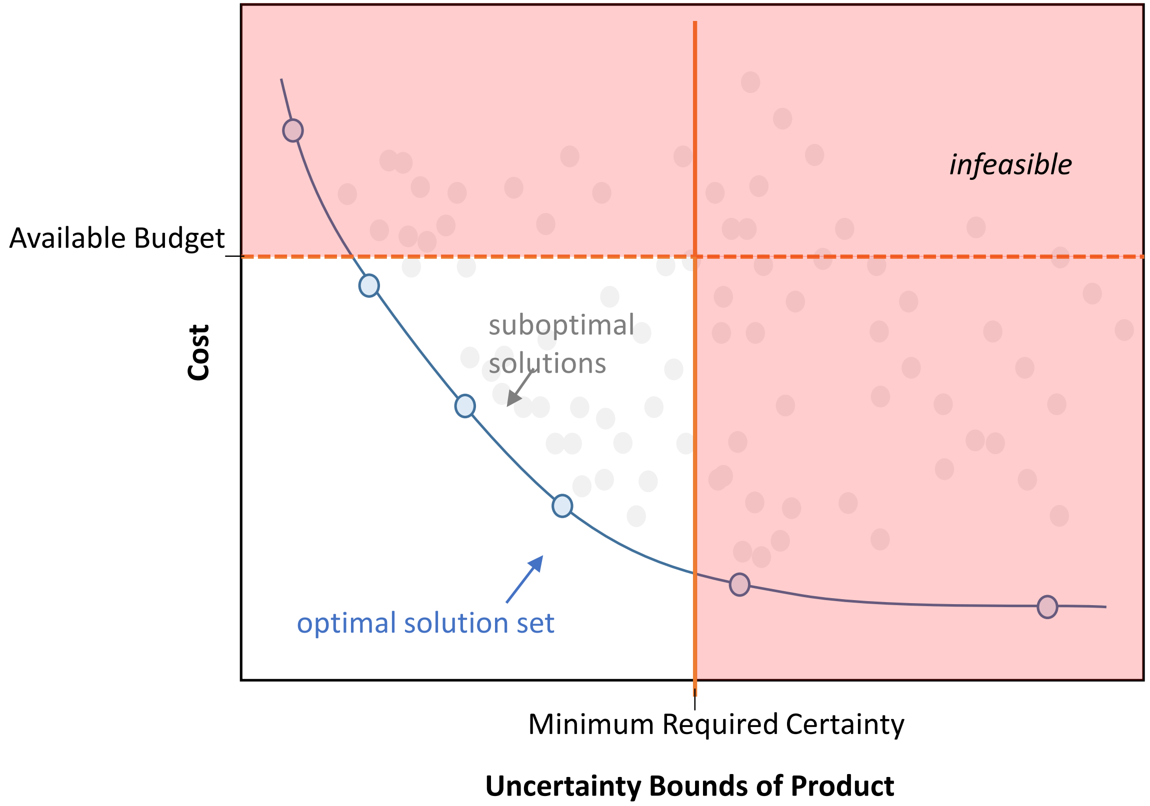
Path 1 – Defining the Parameters, Designing the SDT:

- This path is useful if there is a relatively clear idea of what data set is available. {e.g. a ship has GPS and a gyroscope, the desire/need for a SDT, and limited funding}.
- The design of the SDT may then heavily rely on fusion with physics-based, numerical models, analytical seakeeping models, existing experimental derived databases (i.e., model test data, dedicated trials data, to name a few), climatological models, amongst others.
- The resultant SDT carries the compounded uncertainties from each step in the process, leading to (potentially) high uncertainty bands around the output product of the SDT.

Path 2 – Defining the SDT, Setting the Parameters:

- This path is useful if there is a clear understanding of the SDT output product uncertainty bounds. {e.g. operational guidance with personnel on board where there is a required probability of failure threshold that must be met}
- Then the SDT can be designed such that this requirement is met, exploring the use of input parameters to converge on the required set.



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“Constraints”

When pivoting to the practical development of a functional SDT, the design of the SDT also has to consider the **constraints** of the practical problem:

Location		*Shipboard*	*Land-Based*
Resources: Access to Data	**Quasi-Static Information**	Available	Available
	Monitoring Measurements	Available	Possible
	Summary Data from Digital Twin	Available	Available
	Qualitative Information	Ready Access	Remote Access
	Data from Other Ship Systems	Available	Possible
	External Data Sets (Environmental Forecasts, History, etc.)	Possible	Available
Resources: Computational		Limited	Advanced / Unlimited
Resources: Infrastructure		Wired/Wireless	Digital Communication System

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Digital Twin & Model

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Models

	Loads		Strength		
Low Fidelity	Empirical Equations and/or Theoretical Approximations		Fundamental Theoretical (Section Properties &Ultimate Strength)		
			Coarse Mesh FEM & Linear Static Analysis		
	Frequency Domain Approaches RAOs		Refined Mesh FEM & Linear Static Analysis		
	Time domain simulation model Linear & Nonlinear		Refined Mesh FEM & Nonlinear Static Analysis		
High Fidelity	CFD	FSI	Dynamic Analysis	Local Analysis	Crack Growth
Test Data	Model Test	Full Scale Test	Model Test	Full Scale Test	

Probabilistic & Predictive Models

Ship

Decision Support

Operational Guidance

Condition Based Maintenance

Model: Probabilistic & Predictive

Class Standard	Calculation Period
ABS Hull Condition Monitoring (ABS, 2020)	20-30 min; Rolling basis is accepted
ABS SMART (ABS, 2022)	Not identified
Rules for the Classification of Steel Ships, NR467, Part F (BV, 2022)	Not less than 10 minutes (the recording duration per cycle is to be adapted to produce results that are not to deviate by more than 10% from one wave encounter to the next in steady navigation conditions.)
BV NR675 Additional Service Feature SMART (BV, 2021)	Invokes NR467 - JULY 2022, Part F
DNVGL - Rules for classification: Ships — DNVGL-RU-SHIP Pt.6 Ch.9 (DNV GL, 2017)	Time period for statistics shall be configurable; For predictive assessments, past 4 hours for displacement ships and 30 minutes for high speed vessels.
DNV GL Smart Vessel (DNV GL, 2020)	Invokes DNVGL-RU-SHIP Pt.6 Ch.9 Sec.3,
Lloyds Register, ShipRight, Ship Event Analysis (Llyods Register, 2021)	Not identified
CCS, Rules for Intelligent Ships (CCS, 2020)	Time interval shall be stated in configuration file
CCS, Hull monitoring and assistant decision--making system for operations in ice (CCS, 2018)	*Forecast for the next 1-2 hours
Class NK (Class NK, 2020)	4 hours

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Case Study: Operational Guidance

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- **Model parameters included only structural, retrospective data**
- **Regressive and Machine Learning models were developed around the probabilistic characterization of structural loads acting on a vessel**
  - Models were developed from training data that represented the response data of a notional vessel operating in a seaway.
  - The models were then optimized to support the short term (1-5 minute) prediction accuracy across the training data set.
- **The models were then applied to the remainder of the data set.**
- **Review of the SDT performance highlighted 3 critical scenarios:**
  - *Scenario 1*: a ship entering a storm
  - *Scenario 2*: a ship is operating in a seaway, then turns to continue operations in the same seaway but at a different relative heading.
  - *Scenario 3*: a ship is operating in a seaway, then turns to continue operations in the same seaway but at another relative heading.

Case Study: Results - Scenario 1

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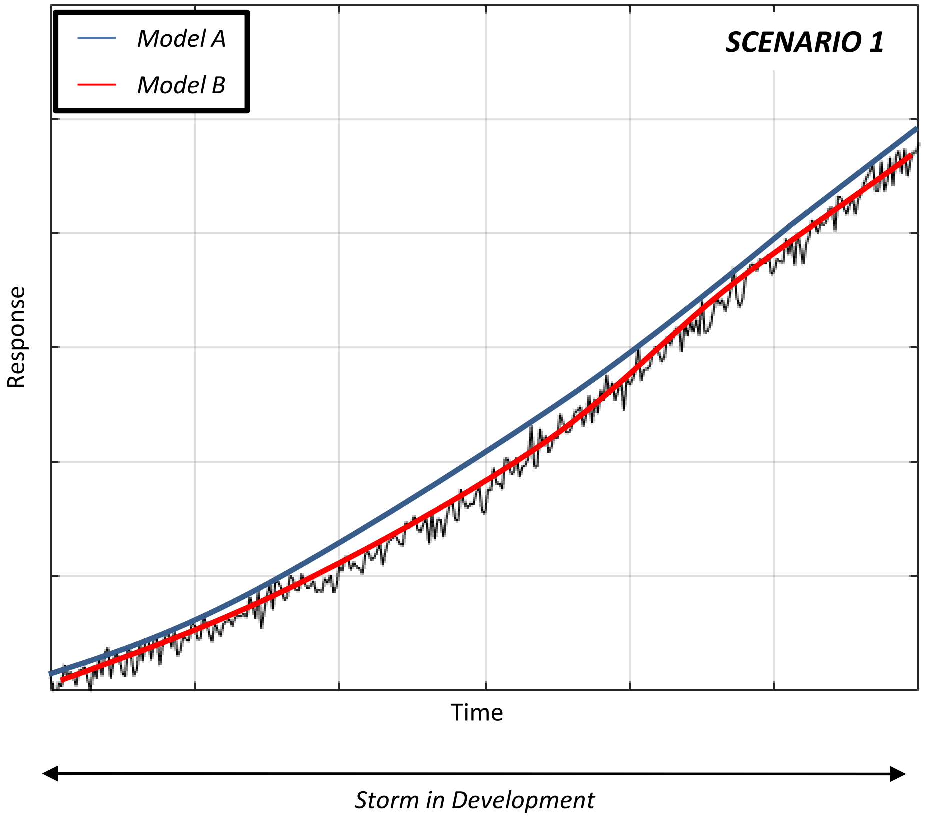
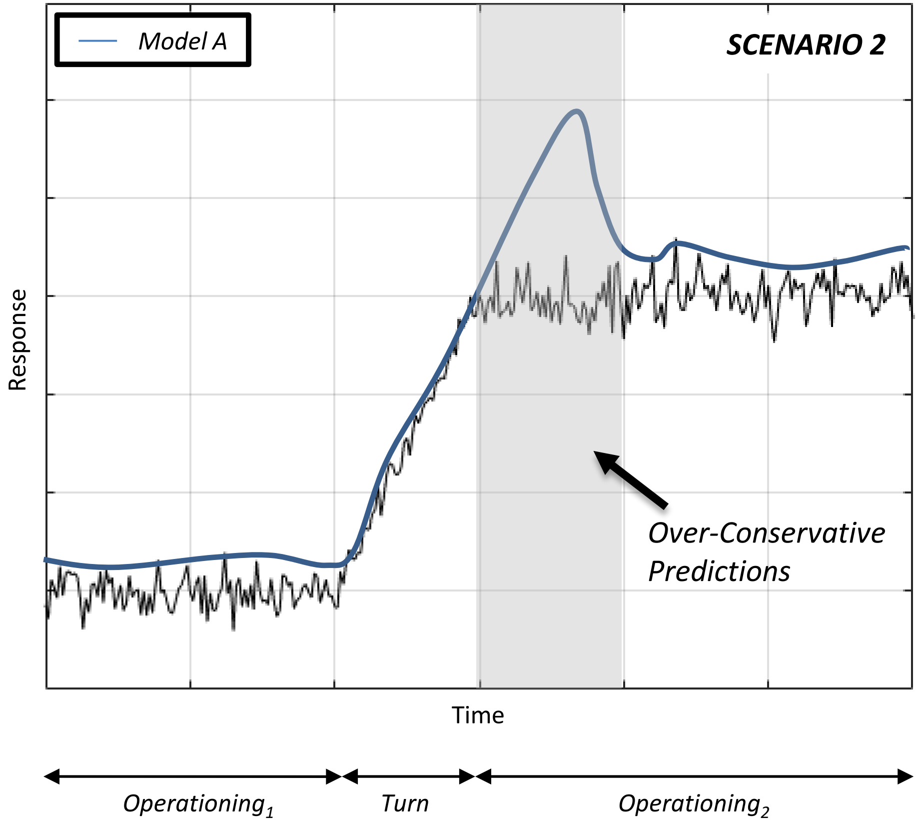
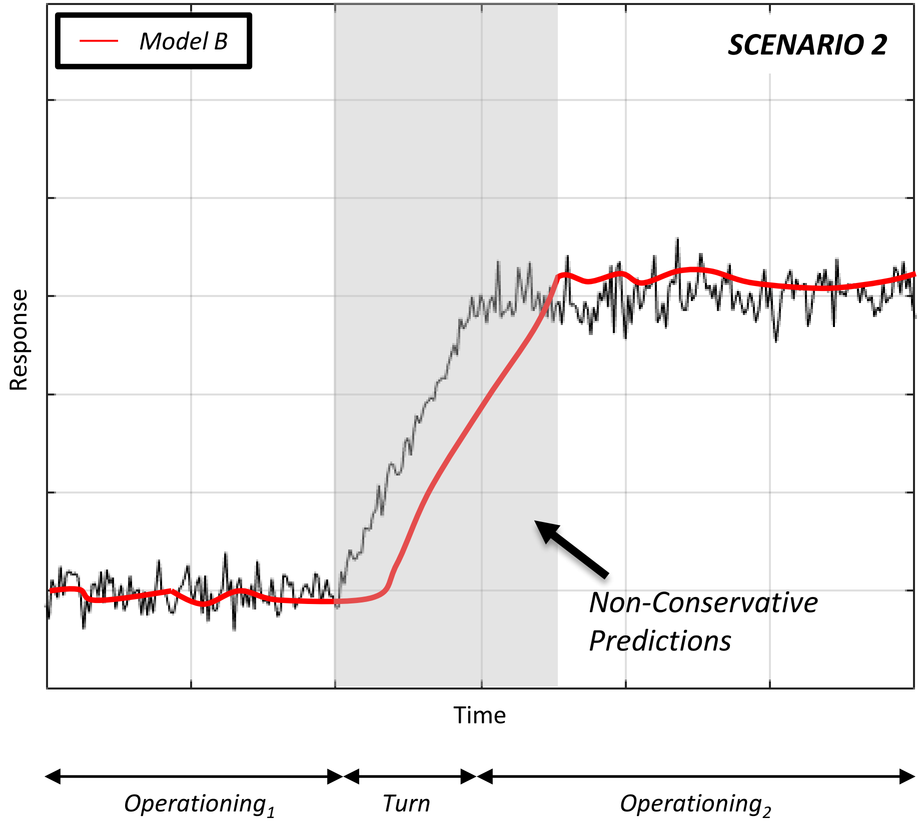
- Scenario 1: an example of the ship operating and entering a storm



Case Study: Results - Scenario 2

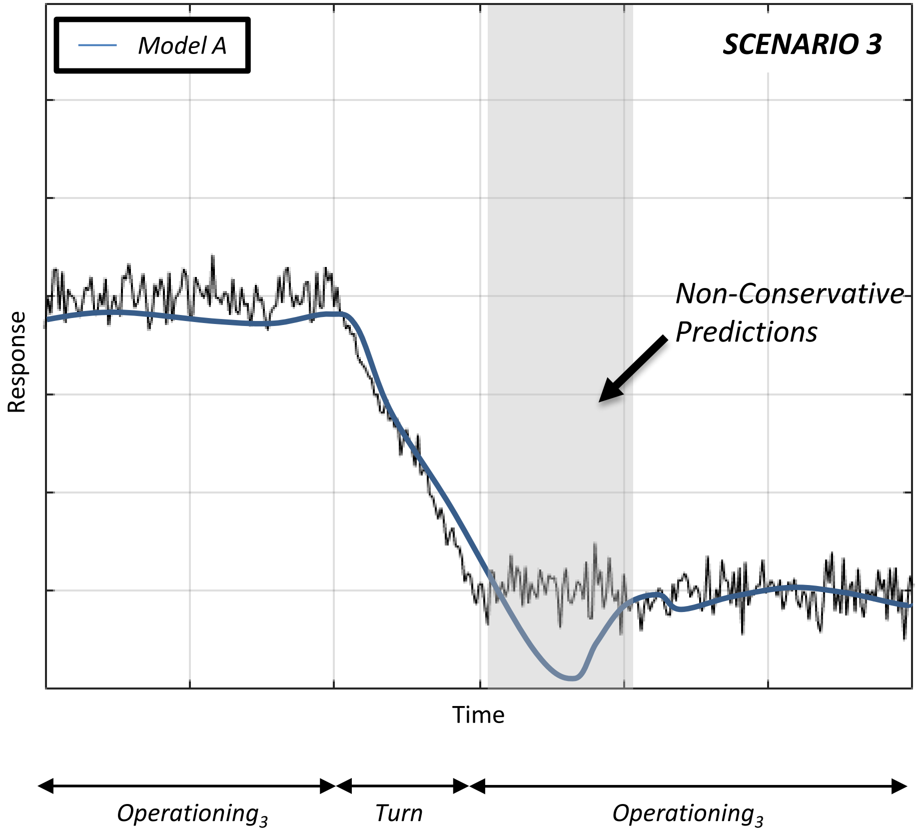
- Scenario 2: a ship is operating in a seaway, then turns to continue operations in the same seaway but at a different relative heading.

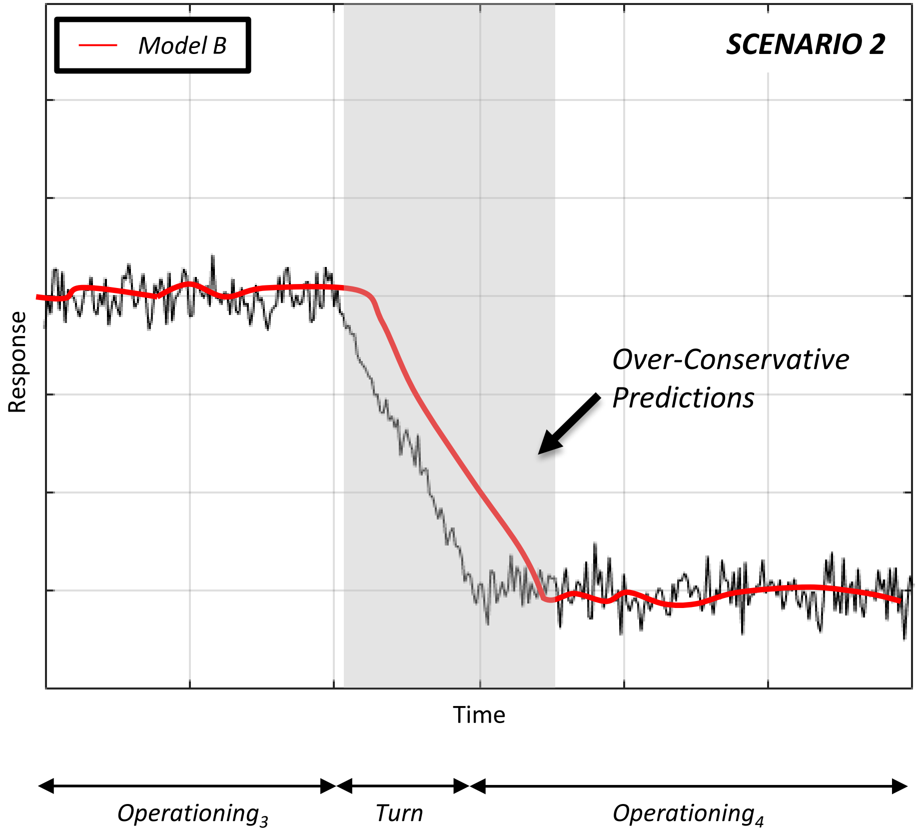




Case Study: Results - Scenario 3

- Scenario 3: a ship is operating in a seaway, then turns to continue operations in the same seaway but at another relative heading.



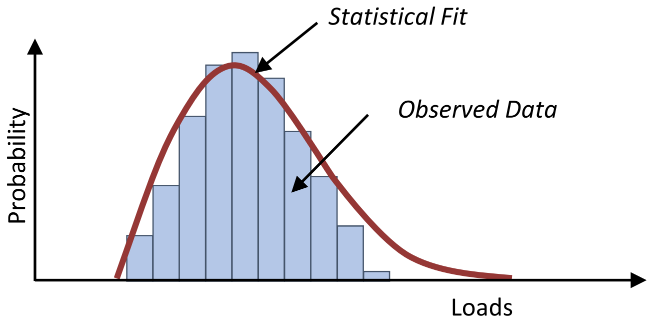


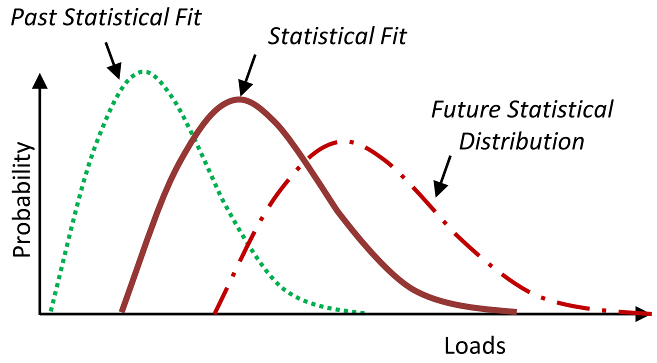
Uncertainties: Loads

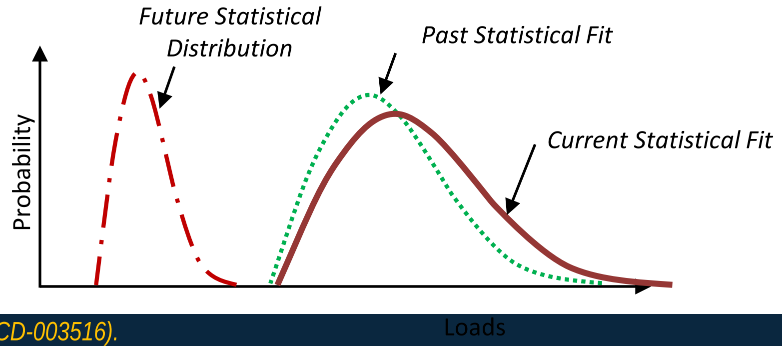
- **Natural Variability**:
  The seaway is a random field in which the ship operates. Thus, if the seaway remains stationary (in mathematical sense), the ships response can be defined as a random process and/or random variable.

- **Evolution of Environment**:
  The climatology of the ocean leads to the development and dissipation of storms. This is a continuous process that can lead to a ship's response also evolving with the environment. This is a gradual change in the ship's statistical response characteristics.

- **Abrupt Changes**:
  Changes in the ships' course or speed represent abrupt changes in states. The passage out of or into sheltered areas lead to relatively abrupt changes in the seaway.







Case Study - Findings

- Models driven by **retrospective (response) data have challenges** with abrupt changes in the response (such as those stemming from turns, changes in speed, or emergence from (or entrance into) a sheltered area.

- A **robust SDT solution should account for and be able to adapt to the variability in vessel operation** and response (sea state, speed, heading, storm evolution, route, etc).

- Complex structural systems, like ship hulls, should be assessed on the system level: The **Structural Digital Twin should account for relevant response and/or performance metrics and system level assessment**.

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Performance Based Decision Support

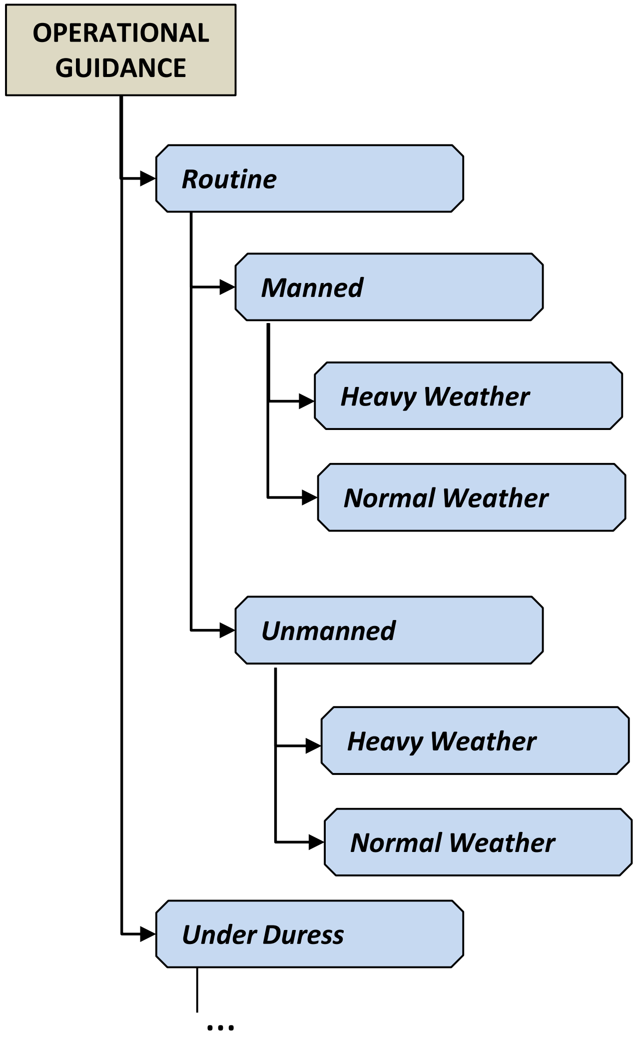
Performance-based decision support first involves the identification of the state that the vessel is in:

- Routine / Under Duress (Peacetime / Wartime)
- Manned / Unmanned
- "Normal Weather" / "Heavy Weather" (Day-to-Day / Near & Hurricanes)

This helps establish the imperative for operations, consequences, and risk tolerances.

This paper puts forth a logic tree framework for use when developing SDT solutions:

- Routine – Manned - Normal Weather
- Routine – Manned - Heavy Weather
- Routine – Unmanned - Normal Weather
- Routine – Unmanned - Heavy Weather
- Under Duress – Manned - Normal Weather
- Under Duress – Manned - Heavy Weather
- Under Duress – Unmanned - Normal Weather
- Under Duress – Unmanned - Heavy Weather



Performance Based Decision Support: Logic Tree (cont.)

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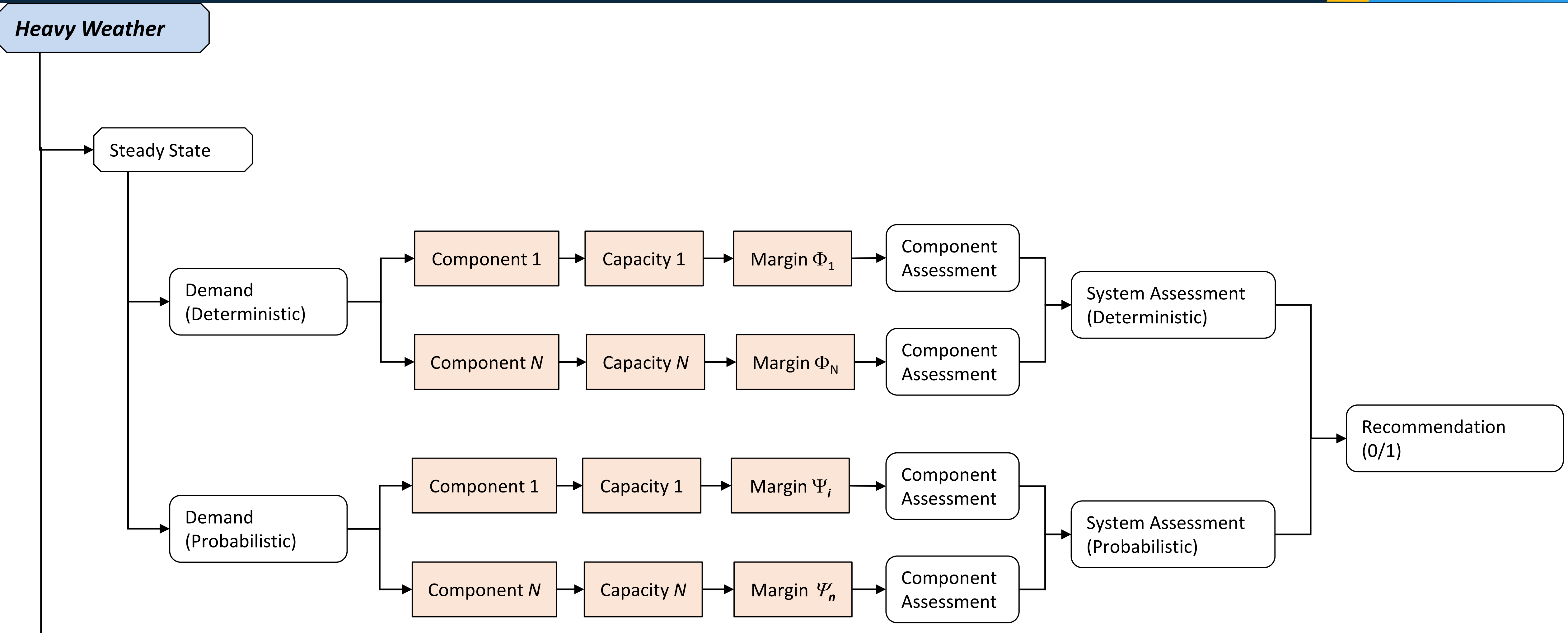
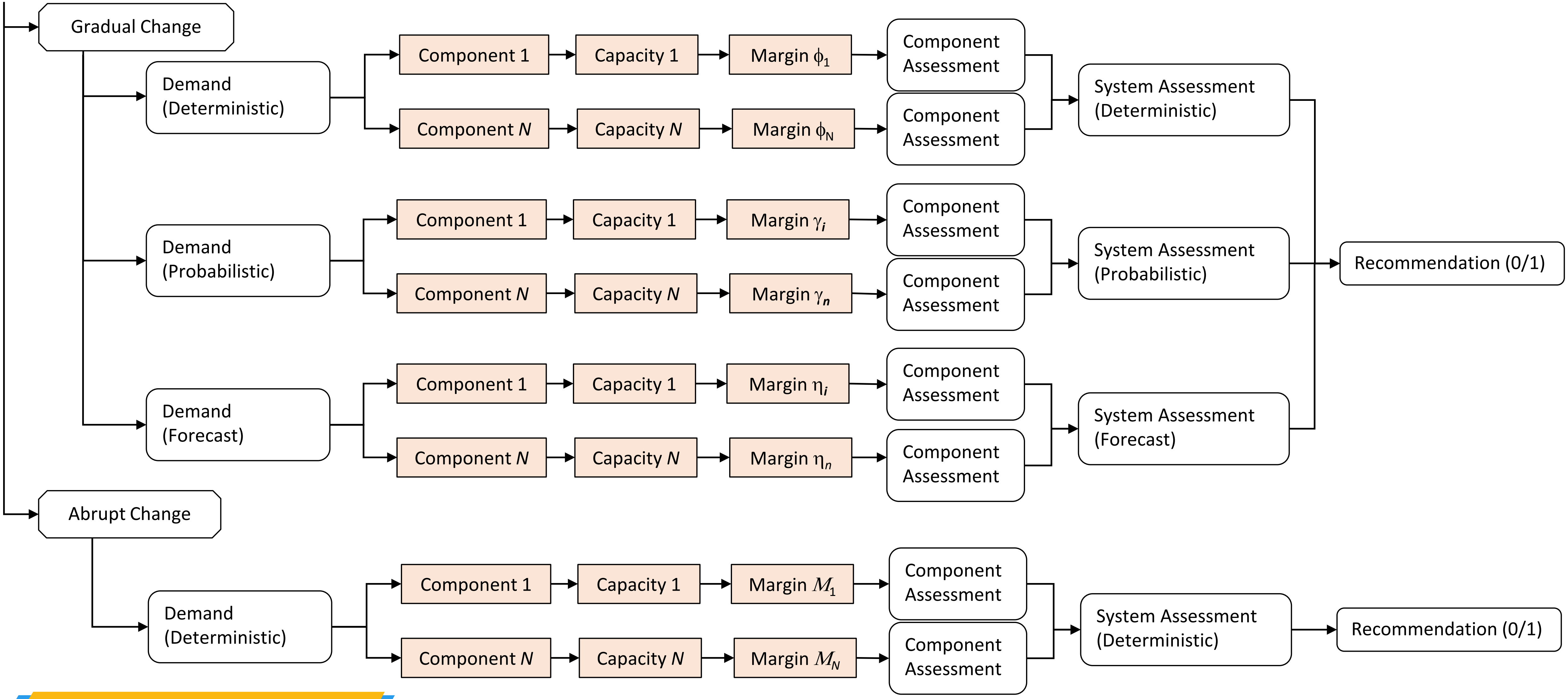


Performance Based Decision Support: Logic Tree (cont.)



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Summary

- ***Developing a Structural Digital Twin: A clear understanding of the objectives, resources, model parameters, and risk tolerances is essential.***
  - The **objective** is essential to both down scope to a tractable problem and define system requirements. As proposed in this paper, this includes the intended use, the timeliness of the outputs, the time horizon used for the assessments, the consequences of failure, the type of operations (peacetime, wartime, both), and the level of integration of the SDT with humans.
  - The resources establish the **constraints** to the SDT design problem, and the **model parameters** are the input variables needed.
  - The definition of the constraints and model parameters becomes an **iterative process with cost and the uncertainty bounds** of the SDT as conflicting objectives that are trying to be jointly optimized.
- ***Case Study: A robust SDT solution accounts for the variability in vessel operation and response (sea state, speed, heading, storm evolution, route, etc).***
  - This paper discussed some of the trappings when using only retrospective data as model parameters for the digital twin. The case study demonstrated that these types of models have challenges with abrupt changes in the response (such as those stemming from turns, changes in speed, or emergence from (or entrance into) a sheltered area.
- ***This paper put forth the use of performance-based structural engineering concepts to support Structural Digital Twins.***
  - Is reliant on the ability to identify which branch it should be in (if the environment and operations are steady, evolving continuously, or abruptly changing)
  - Enables risk based decisions

Acknowledgements

ONR Sponsor: Dr. Paul Hess & Dr. Jessica Dibelka

Research Team: William Whitmore, Nathan Nelson, and Dr. Kevin Augustyn

Ship Structure Committee SR 1482: Digital Twin Methodologies for the Integration of Hull Monitoring Systems with Physics-Based Models

Questions?

Backup

Objectives: Class Standards & Guidance

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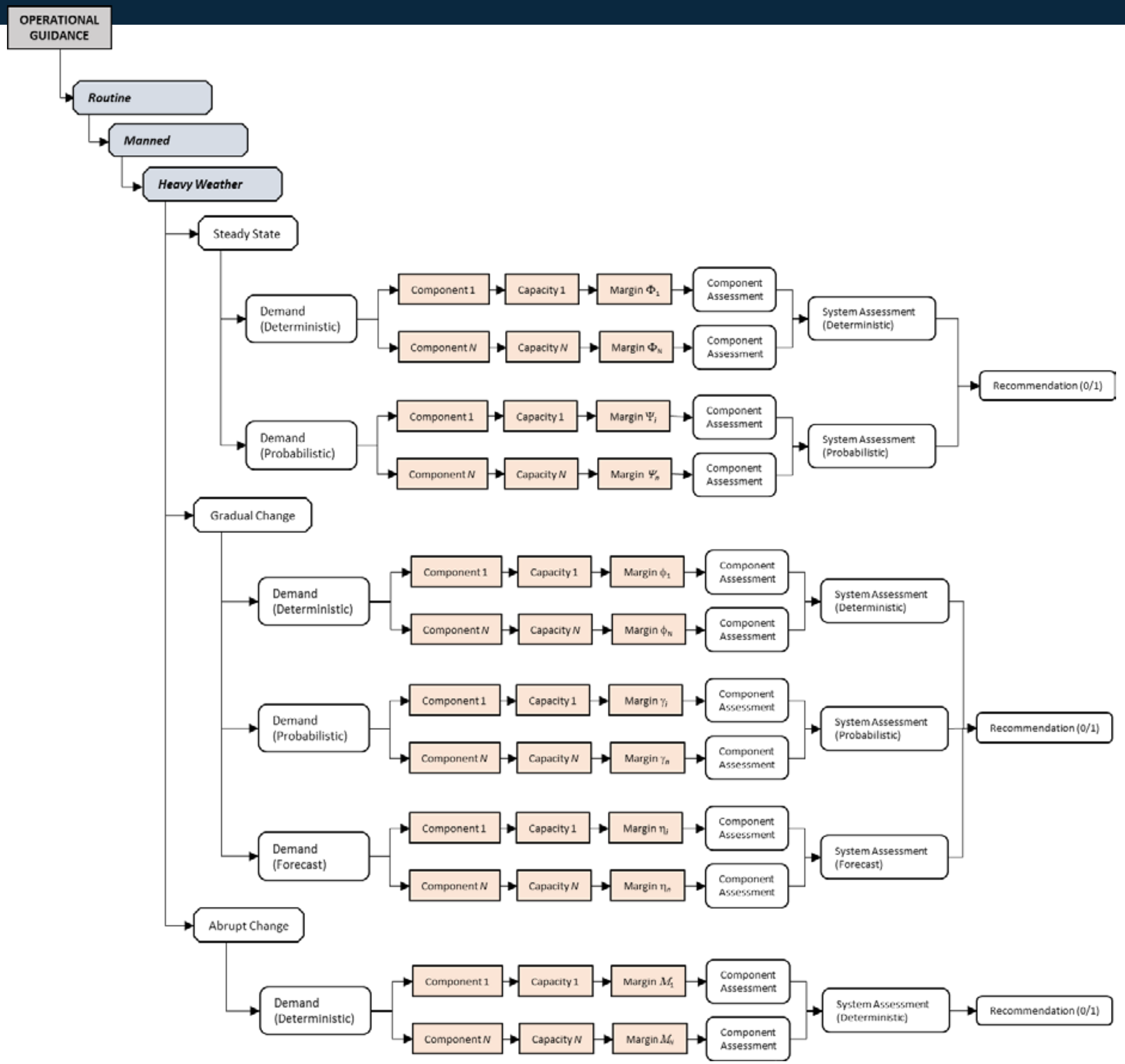
Class Standard	Objective/Description
ABS Hull Condition Monitoring (ABS, 2020)	Hull Condition Monitoring (HCM) is to monitor, visualize, and trend parameters relevant to environment, structural loads, and responses through sensor-based measurements. HCM typically involves onboard and/or onshore reporting and threshold-based alarms for operational guidance and post-voyage analysis.
ABS SMART (ABS, 2022)	Provide the crew and support personnel with key information to aid in decision making. Use common smart functions that include structural and machinery health monitoring, asset efficiency monitoring, operational performance management, and crew assistance and augmentation to support vessel operations. SHM provides structural health diagnostics and prognostics through correlation of various parameters and integration with analysis and simulation. - HCM handles parameter-based monitoring and covers the loads, responses, and identifiable damages from direct sensor measurements at certain sensor installed locations
Rules for the Classification of Steel Ships, NR467 - JULY 2022, Part F, Additional Class Notations (BV, 2022)	Hull Monitoring System is a system which: - Provides real-time data to the Master and officers of the ship on hull girder longitudinal stresses and vertical accelerations the ship experiences while navigating and during loading and unloading operations in harbor. - Allows the real-time data to be condensed into a set of essential statistical results. The set is to be periodically updated, displayed, and stored on a removable medium.
BV NR675 Additional Service Feature SMART (BV, 2021)	A smart system is defined as a computer-based system that incorporate functions for the collection, transmission, analysis, and visualization of data. A function is a defined objective or characteristic action of a system or component. Smart functions may include operational information such as monitoring, decision making support, remote monitoring, as well as maintenance

Class Standard	Objective/Description
DNVGL-RU-SHIP Pt.6 Ch.9 (DNV GL, 2017)	The system shall give warning when stress levels and the frequency and magnitude of ship accelerations approach levels that require corrective action. The owner shall decide how the hull monitoring system should be configured, i.e., which features to be included and how the measured and processed data shall be use intended as an aid to the master's judgement and not as a substitute.
DNV GL Smart Vessel (DNV GL, 2020)	Use data and information to further optimize vessels' operations and reduce the environmental footprint. Operation and maintenance - hull and structure (OPH) enhancements include solutions that use data as an important element and provide options related to structural integrity management
Lloyds Register, ShipRight, Ship Event Analysis (Llyods Register, 2021)	Provide warning to ship's personnel that stress levels or the frequency and magnitude of slamming motions are approaching a level where corrective action is advisable
CCS, Rules for Intelligent Ships (CCS, 2020)	To provide assistant decision-making for hull and deck machinery maintenance and structural renewal during in-service period of the ship based on the establishment and maintenance of hull database system and three-dimensional hull structural models.
Class NK (Class NK, 2020)	To monitor the behavior of hull girders during navigation, loading and unloading, and to provide real-time information on stress levels due to longitudinal bending moments and acceleration levels due to ship motion. Information is to be intended to aid the judgment of Shipmasters and crew members during navigational operations, it is not intended to be a substitute for the judgment and the responsibility of Shipmasters.


OPERATIONAL GUIDANCE
Routine
Manned
Heavy Weather
Steady State
Demand (Deterministic)
Component 1
Capacity 1
Margin Φ_1
Component Assessment
Component N
Capacity N
Margin Φ_N
Component Assessment
System Assessment (Deterministic)
Recommendation (0/1)
Demand (Probabilistic)
Component 1
Capacity 1
Margin Ψ_1
Component Assessment
Component N
Capacity N
Margin Ψ_n
Component Assessment
System Assessment (Probabilistic)
Gradual Change
Demand (Deterministic)
Component 1
Capacity 1
Margin ϕ_1
Component Assessment
Component N
Capacity N
Margin ϕ_N
Component Assessment
System Assessment (Deterministic)
Demand (Probabilistic)
Component 1
Capacity 1
Margin γ_1
Component Assessment
Component N
Capacity N
Margin γ_n
Component Assessment
System Assessment (Probabilistic)
Recommendation (0/1)
Demand (Forecast)
Component 1
Capacity 1
Margin η_1
Component Assessment
Component N
Capacity N
Margin η_n
Component Assessment
System Assessment (Forecast)
Abrupt Change
Demand (Deterministic)
Component 1
Capacity 1
Margin M_1
Component Assessment
Component N
Capacity N
Margin M_N
Component Assessment
System Assessment (Deterministic)
Recommendation (0/1)

Performance Based Decision Support: Logic Tree