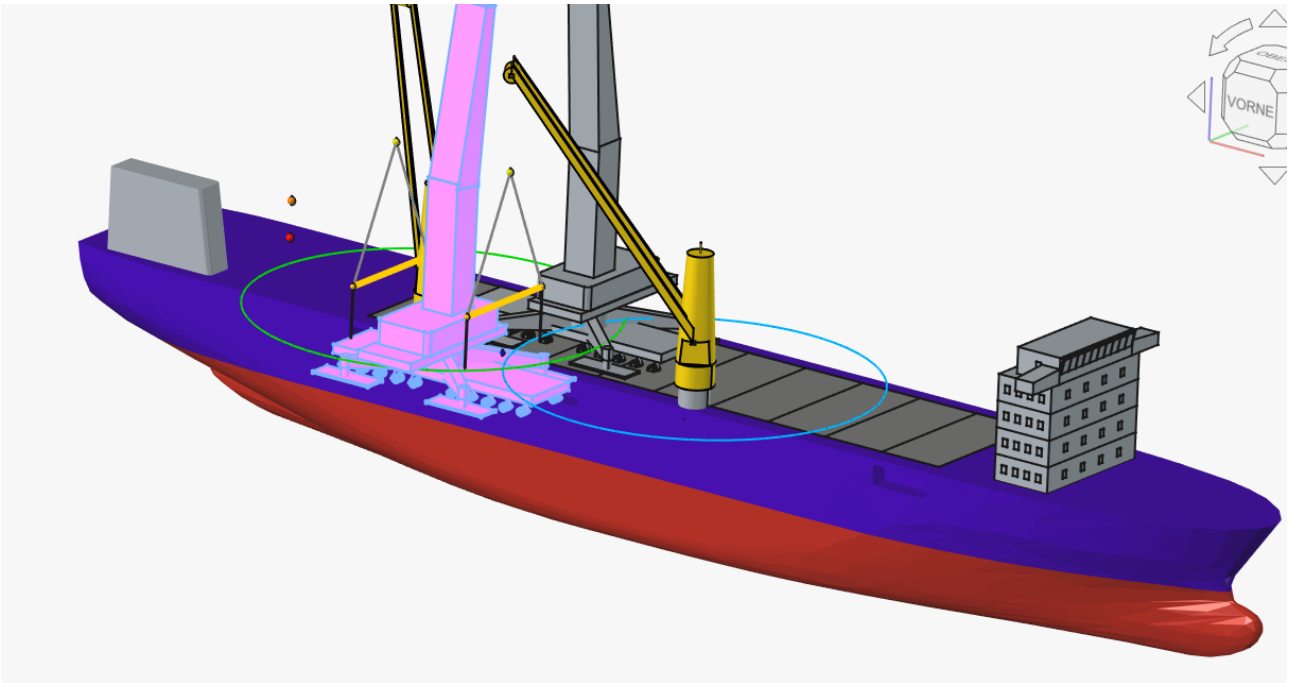

VORNE

Important information – Purpose of payment, verification and liability

Intended Use

StowMind is a software programme designed to support engineering tasks in the fields of ship loading, hydrostatics, stability, lifting operations, load distribution, cargo securing and related maritime calculations.

The software is intended solely as an aid for qualified users. It does not replace the professional judgement of a marine engineer, nor does it replace approved ship’s documents or the certification required by regulatory authorities or classification societies.

Verification of calculation results

All calculations generated using StowMind are based on input data provided or imported by the user. The user is solely responsible for ensuring that this data is accurate, complete and up to date.

Before using the calculation results for operational decisions, transport approvals, lifting operations or other safety-related applications, all results must be independently verified by the responsible engineer.

In particular, the calculation results must be compared with the valid and approved documentation for the vessel in question. This includes, in particular:

- the Approved Stability Booklet,
- the Loading Manual,
- the shipyard hydrostatics, including hydrostatics tables and pantokarens,
- the Cargo Securing Manual (CSM),
- approved loading and deck load limits,
- crane manuals, load diagrams and operating limits for all lifting equipment in use,
- manufacturer’s documentation and valid certificates for cranes, slings, lifting gear, shackles, spreaders, wire ropes, chains, round slings, lashing gear and other load-handling equipment,
- the requirements of the relevant classification society,
- the regulations of the flag state,
- as well as all other applicable national and international regulations.

Any discrepancies between the calculation results from StowMind and the approved ship’s documentation must be fully clarified before the results are used. In case of doubt, the approved

original documentation and the requirements of the competent authorities and classification society shall always take precedence.

Liability

StowMind has been developed with the utmost care and implemented and tested in accordance with recognised engineering methods and international regulations.

Nevertheless, no guarantee can be given that the software will operate error-free in every individual case or deliver suitable results for every application.

To the extent permitted by law, the author or licensor accepts no liability for direct or indirect damage, consequential damage, financial loss, business interruption or loss of profit arising from the use or non-use of the software.

Liability for wilful misconduct, gross negligence and in cases where liability is mandatory under law remains unaffected by this.

By installing or using the software, the user accepts these terms and conditions.

StowMind has been developed to support the planning, calculation, verification and documentation of ship-related tasks. The software consolidates calculations and technical information from various sources and assists the engineer in the preparation, review and traceable documentation of technical decisions. StowMind does not replace the approved ship’s documentation, nor the evidence, approvals or technical responsibility of the engineer in charge as required by the applicable regulations.

1 StowMind Capytaine Hydrodynamic Analysis

1.1 Purpose and Scope

This module is designed for the hydrodynamic analysis of ships and floating offshore structures in the frequency domain. Using the Boundary Element Method (BEM), it calculates the sea-state-related parameters for six degrees of freedom (surge, sway, heave, roll, pitch, yaw).
The analysis provides:

- Hydrodynamic coefficients (added mass, damping)
- Wave excitation forces
- Response Amplitude Operators (RAO) for all degrees of freedom
- Hydrostatic stiffnesses

Applications include the assessment of seakeeping behaviour, the preliminary design of passive roll damping systems, the design of positioning systems, and the generation of input data for time-domain-based wake simulations.

1.2 System architecture and module overview

The system consists of three closely linked Python modules, which together cover the entire workflow from geometry to report generation.

Tables

Module	Task	Runtime environment
CapytaineTools.py	Geometry export, mesh repair, script generation, solver execution, result reading and basic plots	FreeCAD Python environment
CapytaineTaskPanel.py	Graphical user interface (GUI) within FreeCAD, parameter input, control of core functions, interactive plot display	FreeCAD GUI
capytaine_analyse.py	Advanced post-processing routines: heatmaps, 3D surfaces, automatic PDF report generation	External Python subprocess

The data flow is as follows:

1. FreeCAD document containing ship geometry and load data
2. Export and cleaning of the surface mesh (STL/NPZ)
3. Generation and execution of the Capytaine Python script
4. Results saved as a NetCDF file
5. Display in the TaskPanel or advanced analysis via capytaine_analyse.py

1.3 Physical fundamentals

1.3.1 The hydrodynamic boundary value problem

Capytaine solves the linearised potential problem for a rigid body floating in harmonic waves. The total potential consists of three components:

- Froude–Krylov potential: arising from the undisturbed wave field
- Diffraction potential: disturbance of the wave field caused by the fixed body
- Radiation potentials: generated by the oscillating body in still water

The body surface is discretised into flat triangular panels. For each panel, the source strength is determined such that the boundary condition at the body surface is satisfied.

1.3.2 Hydrodynamic coefficients

Capytaine derives frequency-dependent coefficients from the calculated potentials:
Tables

Parameter	Designation	Unit	Physical meaning
Added mass	Aij(omega)	kg	Additional inertial mass of the water carried along
Radiation damping	Bij(omega)	kg/s	Energy dissipation due to forced vibrations of the body
Excitation force	Fexc,i(ω,β)	N	Total wave force acting on the restrained body

These quantities are calculated as complex numbers. As the NetCDF format does not support complex data types, the system stores the real and imaginary parts separately (e.g. added_mass_real and added_mass_imag) and recombines them during import.

Viscous additional damping

Linear potential theory systematically underestimates the roll damping of ships because it does not account for vortex shedding at sharp edges (heeling keels, rudders, fins). For medium to large roll amplitudes, it yields roll RAOs that are 2–4 times too high. At resonance, the potential peak may also diverge numerically (values between 0.5 and 0.9 rad/m depending on the frequency resolution), because the radiation damping B_{44} is very small during rolling.

The seakeeping module supplements potential theory with a **plate-based model of viscous additional damping**, which is methodologically based on PDSTRIP. Each appendage (heeling keel, rudder, fin) is modelled as a thin plate with a normal, reference area, additional mass and a quadratic transverse drag coefficient. The quadratic drag is linearly approximated as follows:

- regular wave: $b = ½ \cdot \rho \cdot S \cdot cd \cdot 8/(3\pi) \cdot |v_{rel}|$
- stochastic sea: $b = ½ \cdot \rho \cdot S \cdot cd \cdot \sqrt{(8/\pi)} \cdot \sigma_{vrel}$

As the relative velocity depends on the response, the system is solved iteratively. The BEM coefficients (added mass, radiation damping, stiffness, excitation) are **not recalculated** in the process — viscous damping is simply added to the equation of motion. The result is a second RAO curve, which is saved as `RAO_viscous` in the dataset.

1.3.3 Response Amplitude Operator

The RAO describes the transfer behaviour from the wave amplitude to the body's displacement amplitude:
RAO_j(omega, beta) = motion_amplitude_j / wave_amplitude
It is derived from the solution to the equation of motion:
(-omega^2 * (M + A(omega)) - i*omega * B(omega) + C_hydro) * RAO = F_exc(omega, beta)
Here, M is the mass matrix, A is the added-mass matrix, B is the damping matrix and C_hydro is the hydrostatic stiffness matrix.#

1.3.4 Mesh Systems and Geometry Processing

The module distinguishes between two types of geometry and applies optimised processing pipelines to each.
Solid BREP bodies (closed solid bodies):

- The solid is sectioned at the waterline (Z=0)
- The submerged volume is compared with the target displacement (mass / 1025)
- The starboard half is extracted, meshed and then mirrored
- The final mesh is deliberately left open at the waterline

Non-solid geometries (shells, imported meshes, compounds):

- Tessellation via several fallback mechanisms
- Z=0 clipping directly within the mesh using the Sutherland–Hodgman algorithm
- Removal of geometrically duplicate facets and non-manifold edges
- Enforcement of exact symmetry through halving at Y=0 and mirroring

Both approaches result in a watertight, symmetrical triangular mesh that is deliberately left open at the waterline, as Capytaine does not expect a closed surface at this point.

1.3.5 Floating position with trim

The module takes into account the ship's **actual floating attitude**, not just a flat keel. The LoadCondition provides three draught values (see 1.4.2):

- **B11**: draught aft (AP)
- **C11**: draught amidships
- **D11**: draught forward (FP)

The trim angle is calculated from these values:

$\theta = \text{atan2}(D11 - B11, LOA)$

Before the mesh is exported, the hull geometry is rotated about the Y-axis by this angle, so that the actual waterline lies on the Z=0 axis after the translation. A ship with a stern-heavy trim (B11 > D11) thus obtains a positive trim angle (bow up), which corresponds to its actual floating position.

Consequences for hydrostatics: The waterline area and its moments of inertia are calculated from the section as it is actually trimmed. C33 (heave) remains practically unchanged, whilst C44 (roll) and C55 (pitch) may vary by a few per cent depending on the trim angle. This is the **physically correct** result — the previous calculation using a flat keel was an approximation.

Consequences for the RAOs: The excitation and the hydrodynamic coefficients are also calculated for the trimmed geometry. For a heavy-lift vessel with 1–2° trim, the differences are small but systematic — and relevant when coupled with Crane Analysis and Operability, as these incorporate the roll angles and thus the hook accelerations.

1.4 Prerequisites and preparation

1.4.1 FreeCAD document

The active document must contain:

- A ship model as a solid, shell or imported mesh object
- A spreadsheet with the exact name ‘LoadCondition’

1.4.2 The LoadCondition spreadsheet

The spreadsheet must have the following cell layout. The units are critical and are interpreted by the system as follows:
Tables

Cell	Parameter	Unit	Meaning
D4	Mass	kg	Total mass of the vessel including payload
E4	Draft	mm	Average draught (converted internally to metres)
F4	KM	mm	Metacentric height above the keel (converted to metres)
G4	GM	m	Metacentric height above centre of gravity
E5	LCG	m	Longitudinal centre of gravity position
F5	TCG	m	Transverse centre of gravity position
G5	VCG	m	Vertical centre of gravity above the keel
H4	FSM	tm	Free surface moment
I7	Ixx	kg*m²	Moment of inertia about the centre of gravity
I8	Iyy	kg*m²	Pitch moment of inertia about the centre of gravity
I9	Izz	kg*m²	Yaw moment of inertia about the centre of gravity
B11	Draft aft (AP)	mm	Draught at the aft perpendicular
C11	Mid-ship draught	mm	Draft amidships (reference for trim rotation)
D11	Draft	mm	Draft at the forward lead line

Cell	Parameter	Unit	Meaning
	forward (FP)		

Note: Draft and KM must be specified in millimetres; all other values in the specified base units.

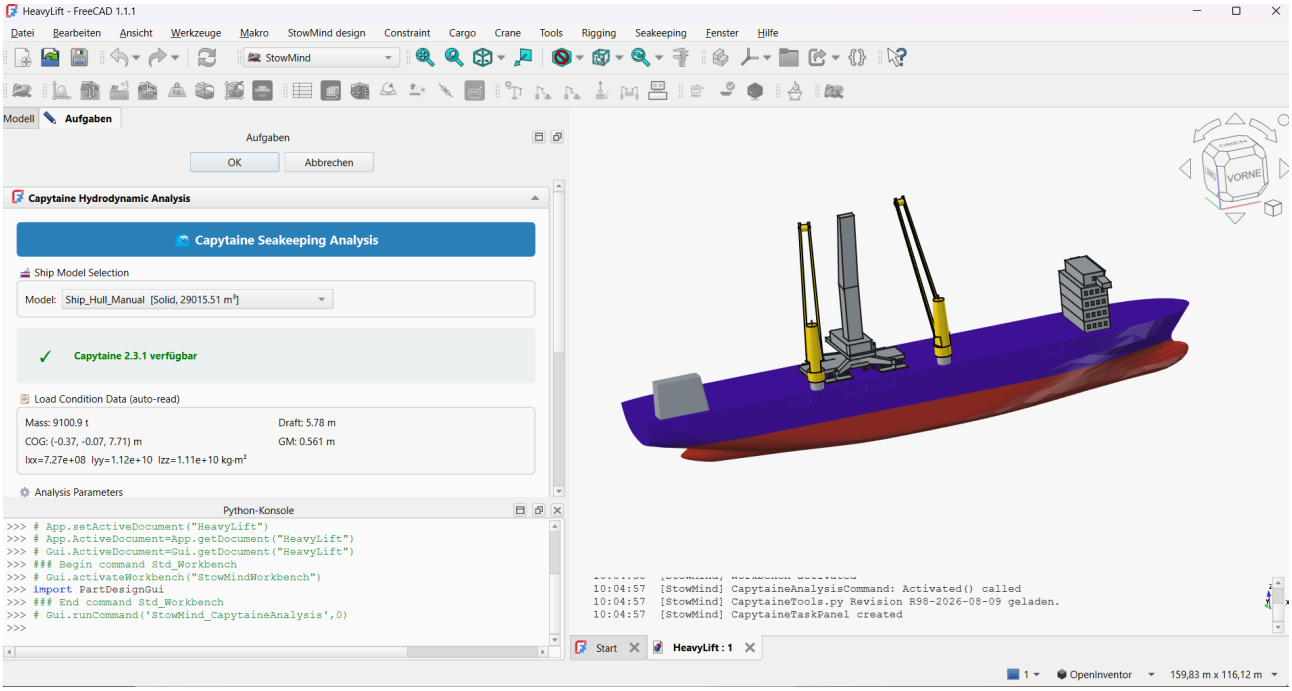
Note on draughts: B11, C11 and D11 must be specified in millimetres. The system uses these to calculate the trim angle and the midship reference for the CoG transformation. If C11 is empty or contains 0.0, the system falls back to E4 (flat keel) and issues a warning in the log.

Cells B10, C10 and D10 contain the column headings (“Aft Point [mm]”, “Mid Point [mm]”, “Fwd Point [mm]”). These are set automatically when the LoadCondition is created.

1.4.3 Geometric requirements

- The model should be modelled to a scale of 1:1 (the FreeCAD default is mm)
- The keel line should be at Z=0; the draught will be taken into account by the system later
- For symmetrical hulls, a half-geometry (Y>=0 or Y<=0) is sufficient; the system will automatically mirror it
- For monohulls, the system enforces exact symmetry through clipping and mirroring

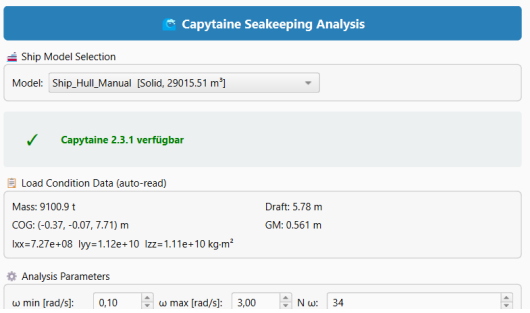
1.5 User Guide



1.5.1 Opening the TaskPanel

The analysis is controlled via the Capytaine TaskPanel. Upon launch, a window appears with several sections:

1. Ship Model Selection
2. Load Condition Data (display only)
3. Analysis Parameters
4. Run button and progress bar
5. Results section (hidden initially)



1.5.2 Selection of the ship model

The top drop-down menu lists all top-level objects in the document that have a valid shape (solids, shells, meshes). The list is sorted in descending order by volume. The largest object is usually at the top and is generally the hull.
Important: You must explicitly select the correct object. The system no longer searches automatically but strictly uses the drop-down selection.

1.5.3 Parameter Input

The parameters are set in the ‘Analysis Parameters’ group. The meaning of the individual fields:
Tables

Parameter	Default value	Setting range	Meaning
omega min	0.1 rad/s	0.01 to 10.0	Lower cut-off frequency of the analysis
omega max	3.0 rad/s	0.1 to 10.0	Upper cut-off frequency of the analysis
N omega	30	5 to 200	Number of frequency samples
Dir min	0 degrees	0 to 360	Minimum wave approach angle
Dir max	180 degrees	0 to 360	Maximum shaft approach angle
N dir	19	1 to 72	Number of directional control points
Water depth	infinite (-1)	-1 to 5000	Water depth in metres; -1 indicates deep water
Mesh thickness	5.0 mm	0.1 to 100.0	Tessellation tolerance for mesh export

Guidelines for parameter selection:

- omega min: 0.1 to 0.3 rad/s for wave action issues (corresponds to wavelengths over 60 m)
- omega max: 1.5 to 3.0 rad/s; higher values are only relevant for small structures or pressure bodies
- N omega: 30 to 60 control points produce sufficiently smooth curves
- Directions: For symmetrical hulls, 0 to 180 degrees is sufficient; the system utilises the symmetry
- Mesh tolerance: 2 to 10 mm depending on model size and desired number of panels
-

Additional parameters for viscous damping

Viscous damping is configured via a separate dialogue box (see 1.5.6). The configuration is saved in `appendages.json` alongside the `.FCStd` file. The following parameters are stored there:

Parameter	Default value	Meaning
`zeta_a`	0.5 m	Reference wave amplitude for quadratic linearisation
`model`	`regular`	Linearisation model (`regular` = regular wave, `seastate` = stochastic sea)
`bilge_keels`	1 entry	List of roll keels
`fins`	0 entries	List of rudders/fins

Guideline values for `zeta_a`:

- 0.3 m: calm sea (Hs ≈ 0.6 m)
- 0.5 m: moderate seas (Hs ≈ 1.0 m)
- 1.0 m: rough seas (Hs ≈ 2.0 m)

- 1.5 m: storm (Hs ≈ 3.0 m)

The viscous effect is strongly dependent on `zeta_a` (quadratic in damping). For operability analyses, `zeta_a ≈ Hs/4` of the dominant sea state is recommended.

1.5.4 Starting and monitoring the analysis

After clicking ‘Run Capytaine Analysis’, the system goes through the following phases:

- Mesh export (progress approx. 10 per cent): The ship model is meshed, cleaned and saved as an STL/NPZ file in the Temp directory.
- Script generation (approx. 25 per cent): The Python script for Capytaine is written.
- Solver run (approx. 35 to 80 per cent): Capytaine calculates the hydrodynamic coefficients for all combinations of frequency, direction and degree of freedom. This is the most time-consuming step.
- Result import (approx. 90 per cent): The NetCDF file is read and complex variables are reconstructed.
- Completion (100 per cent): The results are available.

During the run, messages are displayed in the log window at the bottom of the panel. Errors appear in red, warnings in yellow and success messages in green.

1.5.5 Automatic saving

If the FreeCAD document has already been saved (file name known), the NetCDF result is automatically copied to the project folder. The file name contains a timestamp and parameters for identification. If the document has not yet been saved, the file is not saved automatically; however, you can save the file manually using the ‘Save NetCDF’ button.

1.5.6 Configuring viscous damping

The additional viscous damping is controlled via two buttons at the bottom of the TaskPanel (group ‘🌊 Viscous Damping’):

1. ‘Configure appendages...’

Opens a dialogue box with two tables:

- **Bilge Keels**: | Column | Meaning | Typical value | |---|---|---| | x from [m] | Start of keel (Midship = 0) | −0.35·LOA | | x to [m] | End of keel | +0.20·LOA | | y [m] | Bilge position | 0.85·(B/2) | | z [m] | Bilge height | 0.65·Draft | | height [m] | Keel width (radial) | 0.3–0.6 m | | cd [-] | Transverse drag coefficient | 4–6 | | n seg | Number of segments per side | 6–10 |
- **Rudders / Fins**: | Column | Meaning | Typical value | |---|---|---| | Name | Designation | ‘Rudder’ | | x [m] | Force application point | −0.48·LOA | | z [m] | Position | −0.5·Draft | | axis | `vertical` (rudder) or `horizontal` (fin) | vertical | | length [m] | span | 3–6 m | | chord [m] | chord | 2–4 m | | cl_alpha [-] | lift gradient | 0 (at rest) or 2π (in motion) | | cd [-] | drag coefficient | 1.0 |

In addition, the linearisation parameters:

- `ζ_a`: reference wave amplitude (see 1.5.3)
- `model`: `regular` or `seastate`
- For `'seastate'`: `Hs` and `Tp` of the target sea state

Once the dialogue box is closed, the configuration is saved in `appendages.json`.

2. "Apply viscous damping"

Calculates the viscous RAO and saves it to the current dataset (`RAO_viscous`) as well as persistently in the `.nc` file. The button is only active once a BEM run has been successfully completed.

After clicking, the following lines should appear in the log:

```
Viscous damping: N plate(s), VCG_mesh = X.XXX m
RAO_viscous stored in dataset (in memory).
Dataset re-saved with RAO_viscous: ...
Project RAO file updated: ...
```

If a line begins with `WARNING:`, persistence has failed — the calculation is then only present in memory, not in the file.

What the system calculates:

1. Generate plates from the configuration (segments per bilge-keel side + fins)
2. For each frequency and direction: fixed-point iteration of viscous damping
3. Calculate RAO with viscous damping
4. Write the result as `RAO_viscous` to the dataset
5. When persisting: `_real/_imag` split for NetCDF
6. Set the flag `prefer_viscous_rao = 1`

When to expect which values:

Configuration	**Roll-Peak viscous (relative to potential)**
1 Bilge-Keel, h=0.4 m, cd=5, ζ_a=0.5	approx. 0.85–0.95
1 bilge keel, h=0.6 m, cd=5, ζ_a=1.0	approx. 0.55–0.70
1 bilge keel + rudder, h=0.6 m, cd=5, ζ_a=1.0	approx. 0.45–0.60
Without appendages	no change (warning in the log)

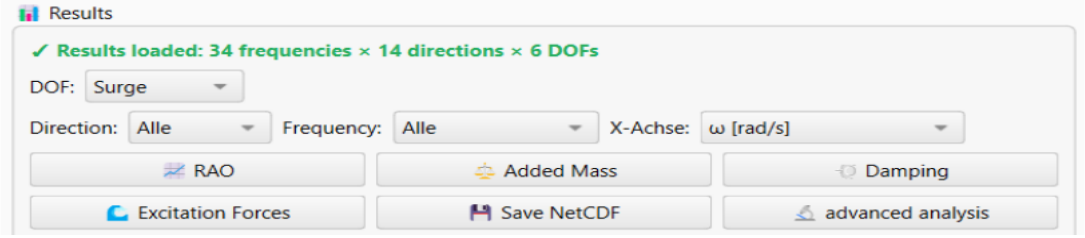
Viscous damping has no effect on surge and heave — the RAO remains virtually unchanged in these cases. Only roll and (to a lesser extent) yaw are affected.

1.6 Results in the TaskPanel

1.6.1 Overview

Once the analysis has been successfully completed, the Results section appears. It displays a summary:

- Number of frequencies
- Number of wave directions
- Number of degrees of freedom (always 6)



1.6.2 Filters and plot controls

Before generating graphs, you can apply filters:
Tables

Control	Options	Effect
DOF	Surge, Sway, Heave, Roll, Pitch, Yaw	Selects the degree of freedom for the plot
Direction	All or individual degrees	Displays all directions or just one as a curve
Frequency	All or individual values	Plots a red marker on the graph
X-axis	omega, period T, wavelength lambda	Changes the horizontal axis

Note: If a single direction is selected, the values are displayed as a line plot against frequency. If ‘All’ is selected, an overlaid display of all directions is generated.

1.6.3 Available plots in the panel

Tables

Button	Output	File name in the temp folder
RAO	Value of the response amplitude operator along the selected X-axis	rao_[DOF].png
Added mass	Diagonal element of the added mass matrix A_ii	added_mass_[DOF].png
Damping	Diagonal element of the damping matrix B_ii	damping_[DOF].png
Excitation Forces	Force amplitudes for all 6 DOFs in the selected direction	forces_[direction]deg.png

The graphs are saved in the Temp directory and displayed simultaneously in the panel. The display scales automatically to fit the available area.

RAO plot with viscous damping

If the dataset contains an RAO_viscous variable, the RAO plot displays **two curves per wave direction**:

- **dashed** (thin, semi-transparent): potential theory without viscous damping
- **solid** (thick, coloured): with viscous damping

For surge and heave, both curves practically coincide. For roll (and, with strong roll excitation, also sway/yaw), the viscous curve is significantly lower in the resonance range. The difference is a direct measure of the contribution of the anti-sway keels and rudders.

The legend shows the wave direction (`pot β=90°` vs. `visc β=90°`). If a single direction is selected (the ‘Direction’ drop-down menu), only one pair is plotted; if ‘All’ is selected, all 19 pairs are superimposed.

1.6.4 Manual saving

The ‘Save NetCDF’ button can be used to save the results file to any location. The format is NetCDF 4, which can be opened using Python (xarray), MATLAB or Ocean Data View.

1.7 Advanced Calculation

1.7.1 Launching

The advanced analysis is launched via the ‘Advanced Analysis’ button in the TaskPanel. Alternatively, the script can be run manually:
python capytaine_analyse.py [NetCDF file] [optional: omega_min]

The script runs as a separate process and does not open a FreeCAD window. It is intended for detailed offline analysis.

1.7.2 Automatically Generated Graphs

The script automatically generates five plots for each of the six degrees of freedom. These are saved as individual PNG files in the same directory as the NetCDF file.

Tables

Graph	File name	Content	Display type
RAO heatmap	rao_[DOF]_heatmap.png	RAO amplitude versus frequency (Y) and wave direction (X)	2D colour plot with colour bar
RAO 3D	rao_[DOF]_3d.png	The same data as a three-dimensional surface	3D surface plot with viewing angle
Added mass	added_mass_[DOF]_heatmap.png	Added mass diagonal element by frequency and direction	2D heatmap or line plot
Damping	damping_[DOF]_heatmap.png	Damping diagonal element versus frequency and direction	2D heatmap or line plot
Excitation forces	excitation_[DOF]_heatmap.png	Excitation force amplitude versus frequency and direction	2D heatmap

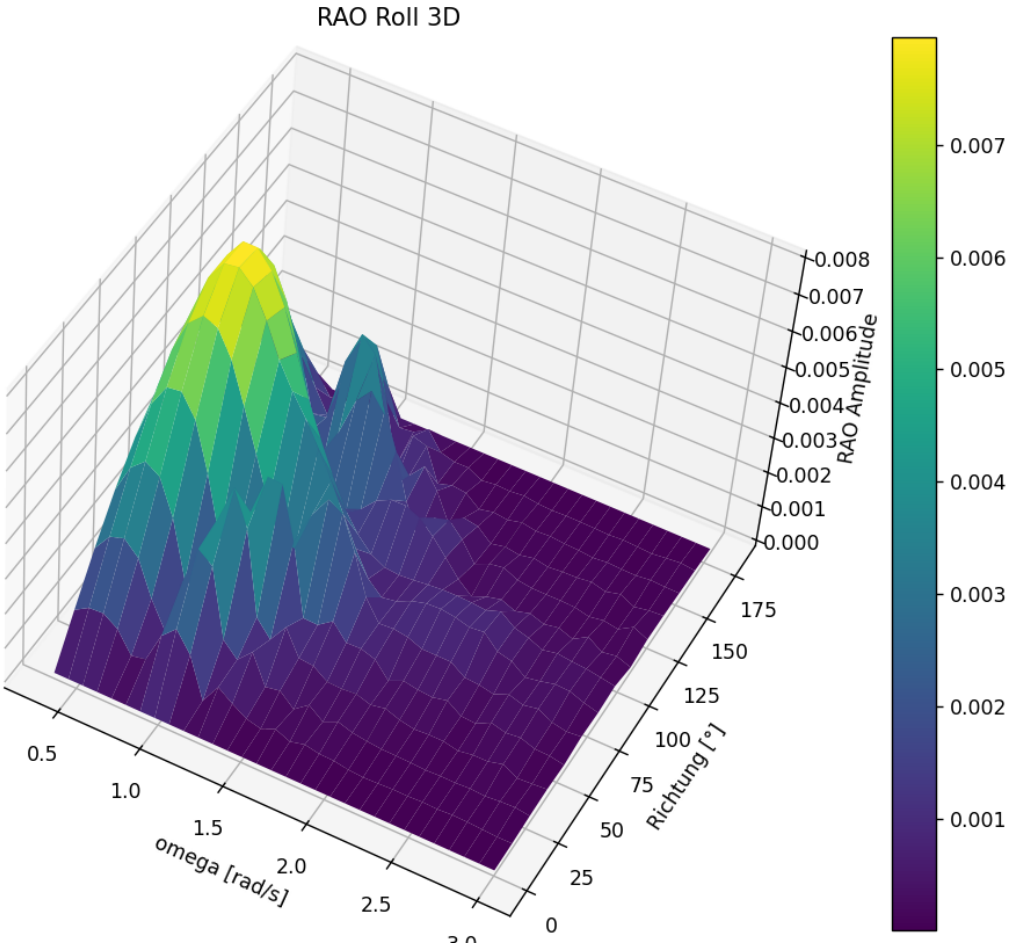
Note on heatmaps vs. line plots: If the results contain multiple wave directions, a heatmap is generated automatically. If only one direction is present, a one-dimensional line plot against frequency is created.

Report with viscous damping

If the `.nc` file contains an RAO_viscous variable, the PDF report displays both curves on the RAO pages (potential as a dashed line, viscous as a solid line). The title page also includes a note on the viscous configuration:

```
Viscous damping: ACTIVE (bilge keels: 2×8 segments, zeta_a = 1.0 m)
```

For datasets without `RAO_viscous,` the report remains unchanged (potential curve only).



1.7.3 The PDF report

In addition to the individual graphs, the script generates a summary report named report.pdf in the results directory.
Structure of the report:

- Page 1: Title page with project parameters
  - Ship’s mass in kg and tonnes
  - Centre of gravity coordinates (LCG, TCG, VCG)
  - Moments of inertia Ixx, Iyy, Izz
  - Frequency range and number of support points
  - Wave direction range and number of support points
  - Water depth (numerical value or infinite)
  - Omega cutoff applied (suppressed low frequencies)
- Pages 2 to 31: five pages per degree of freedom
  1. RAO heatmap
  - RAO 3D surface
  - Added mass plot
  - Damping plot

- Excitation Forces Heatmap

The report is generated in A4 landscape format and can be used directly for documentation and expert reports without any further processing.

1.7.4 Omega Cutoff

By default, the script filters out frequencies below 0.3 rad/s. These are discarded as unrealistic, as they correspond to extremely long waves (at 0.3 rad/s, the wavelength is approximately 685 m in deep water). The cutoff value can be adjusted using a second command-line argument.

1.7.5 File storage

All output files are saved in the same directory as the input NetCDF file:
[Directory of the .nc file]/ report.pdf rao_Surge_heatmap.png rao_Surge_3d.png added_mass_Surge_heatmap.png damping_Surge_heatmap.png excitation_Surge_heatmap.png rao_Sway_heatmap.png ... (similarly for all 6 DOFs)

1.8 Troubleshooting and Quality Assurance

1.8.1 Geometric errors and their handling

Tables

Symptom in the log	Cause	System response
Boundary is not closed	Open edges in the mesh (holes, unsealed areas)	Automatic trimming of small holes, zipping of seam gaps
Overlapping panels	Geometrically overlapping facets	Removal of geometrically duplicate facets
Non-manifold edges	Edges with more than 2 adjacent facets	Healing by removing the smallest facets on the affected edges
Many separate islands	Several unconnected areas in the model	Component analysis, removal of tiny islands, debug STL export

1.8.2 Plausibility checks

The system performs the following checks during export:

- Volume comparison: Submerged volume is compared with the target displacement (mass / 1025)
- Deviation of 20 to 100 per cent: warning in the log
- Deviation over 100 per cent: Export is aborted with an error message
- Asymmetry check: For full hulls, exact symmetry is enforced

1.8.3 Notes on mesh quality

- The number of panels should be between 500 and 5000. Fewer than 500 panels will result in inaccurate results, whilst more than 5000 will increase the computation time excessively.
- The ratio of the longest to the shortest edge within a panel (aspect ratio) should be less than 50. Extremely narrow triangles (slivers) at the waterline can lead to numerical singularities.
- The waterline must result in a clean, closed contour within the mesh. The system automatically removes flat cap facets that may form at the waterline.

1.9 Viscous damping – physical principles and practice

1.9.1 Why potential theory fails for rolling bodies

Linear potential theory assumes a frictionless, vortex-free flow. It is therefore unable to account for energy dissipation due to vortex shedding at sharp edges (rudder blade, fin). However, for rolling motions with a significant amplitude, this loss is the dominant damping mechanism.

Consequence: The roll RAO derived purely from potential theory is often by a factor of 2–4 too high at resonance. For a heavy-lift vessel with GM = 0.94 m and a natural roll period of ≈ 17 s, the potential peak can reach values of 0.5–0.9 rad/m (corresponding to a roll angle of 30–50° for a 1 m wave), which never occurs in reality.

Furthermore, the potential peak is often **not convergent** — the value depends on the frequency resolution because the radiation damping B_{44} during rolling is extremely small (~3×10^4 kg·m²/s for your ship) and the RAO formula $1/(2\zeta)$ becomes numerically unstable there.

1.9.2 Methodology

The module uses a **plate-based model** that is methodologically based on PDSTRIP (the established standard in naval architecture for viscous rolling damping):

- Each appendage (bilge-keel segment, rudder, fin) is modelled as a thin plate
- The quadratic transverse resistance is linearly approximated ($8/(3\pi)$ for regular waves, $\sqrt{(8/\pi)}$ for stochastic seas)
- The relative velocity at the plate depends on the response → fixed-point iteration
- The BEM coefficients are **not** recalculated; the plate terms are simply added to the equation of motion

The model has been validated against the limiting case of infinite damping (RAO → 0) and against the potential case (no plates → `rao_potential()` reproduces `ds['RAO']` bit-for-bit).

1.9.3 Configuration – typical values

Bilge-keel position:

- `x0/x1`: along the bilge, where it runs parallel to the waterline (typically 40–60 per cent of LOA)
- `y`: on the hull surface, approx. 0.85–0.90 × B/2
- `z`: where the bilge has the bend between the side and the bottom (typically 0.6–0.7 × Draft)
- `height`: 0.3–0.6 m (400–600 mm for heavy-lift vessels)

Rudder/fins:

- `x`: 0.48 × LOA aft of AP (rudder position)

- `z`: 0.5 × draught below SWL
- `length × chord`: as per manufacturer's specifications
- `cd`: 1.0 for slender profiles, 2.0 for blunt ones
- `cl_alpha`: 0 when stationary, 2π when moving (but then only effective when travelling forwards)

Transverse drag coefficients `cd` for bilge keels:

- 2.0: very conservative (underestimates damping)
- 4.0–5.0: realistic for medium roll amplitudes (5–10°)
- 6.0–8.0: for large roll amplitudes or Ikeda-calibrated models
    - 8.0: unrealistically high, usually an indication of incorrect plate position

1.9.4 Validating results

Always check after the 'Apply' run:

1. **Roll peak reduction:** expected factor of 1.5–3.0 depending on configuration
2. **Surge/heave unchanged:** no reduction (warning if there is)
3. **Persistence:** `RAO_viscous_real` in the `.nc` file, `prefer_viscous_rao = 1`
4. **Crane/Mooring:** the viscous RAO is used automatically (flag in the Attrs)

Common errors:

- Roll peak is not reduced: plates lie outside the wetted area (`y` or `z` incorrect) → check `damping_matrix` in the console
- Reduction too high (factor > 5): `height` or `cd` too large → check typical values
- The difference between `zeta_a = 0.5` and `zeta_a = 1.0` is very large: this is normal, as it is quadratic in `zeta_a`

1.9.5 Limitations of the methodology

- The model is **linearised**. It applies only to moderate roll amplitudes (up to approx. 15–20°).
- It **does not** take into account the effects of forward motion on the plates (this is usually not a critical factor in heavy-lift operations, as the ships travel slowly).
- It **does not** take into account sloshing effects in tanks.
- It **does not** account for interactions between the bilge keel and the hull boundary layer (the plate is modelled as a free plate in undisturbed flow; this is conservative in the sense that damping is underestimated).

For most operability issues, the model accuracy is sufficient. For classification verifications with stringent requirements (e.g. the DNV standard for dynamic positioning), the result should be compared with Ikeda equations or measurement data.

Chapter 2: Crane Load Analysis

2.1 Purpose and Scope

The Crane Load Analysis module is used for the dynamic assessment of ship's cranes under the influence of sea state. Based on the hydrodynamic analysis (RAOs), it calculates the resulting accelerations at the hook point and derives the dynamic load capacity reduction from these. The analysis provides:

- **Acceleration spectra** at the hook point for all three spatial directions
- **Significant accelerations** (vertical and resultant) for defined sea state parameters
- **Dynamic load-carrying capacity** of the cranes, taking vertical acceleration into account
- **Graphical representations** of acceleration curves and response spectra

Applications include the safety assessment of lifting operations, the design of load-limiting systems, the optimisation of crane positions on board, and the creation of operating limit diagrams for various sea state conditions.

2.2 System architecture and module overview

The system consists of two closely linked Python modules which, together, cover the entire workflow from data retrieval to the presentation of results.

Module	Task	Runtime environment
CraneAnalysis.py	Core calculations: RAO extraction, accelerations at the hook point, spectral response, dynamic load reduction, plotting functions	FreeCAD Python environment, can be used independently
CraneTaskPanel.py	Graphical user interface (GUI) within FreeCAD, crane selection, parameter input, interactive display of results	FreeCAD GUI

The data flow is as follows:

- **FreeCAD document** containing crane objects and the LoadCondition spreadsheet
- **Extraction of crane parameters** from LoadCondition (positions in metres, masses)
- **Identification of crane objects** in the document (StowMindCrane, ShipCrane)
- **Selection of RAO dataset** from the project storage (Capytaine results)
- **Calculation of hook accelerations** using rigid-body kinematics
- **Spectral response analysis** using JONSWAP or Pierson-Moskowitz spectra
- **Calculation of the dynamic SWL reduction** based on significant vertical acceleration

- **Display in the TaskPanel** as a table and interactive plots

---

2.3 Physical principles

2.3.1 Kinematics at the hook point

The motion of any point on board a floating vessel results from the superposition of the six rigid-body degrees of freedom. For a point with coordinates r=(x,y,z)r=(x,y,z) relative to the reference point (usually the centre of gravity), the following applies:

Complex displacement (phase-correct superposition):

δx = Surge + Pitch · z − Yaw · y; δy = Sway + Yaw · x − Roll · z; δz = Heave + Roll · y − Pitch · x; δx, δy, δz = Surge + Pitch · z − Yaw · y = Sway + Yaw · x − Roll · z= Heave + Roll · y − Pitch · x

The **acceleration** in each direction is obtained by taking the second derivative with respect to time, which in the frequency domain corresponds to multiplication by −ω²:

a_i(ω) = ω² · |δ_i(ω)| a_i(ω) = ω² · |δ_i(ω)|

The **resulting acceleration** (magnitude) is calculated from the Euclidean norm of the complex displacement components:

|a(ω)| = ω² · |δx|² + |δy|² + |δz|² |a(ω)| = ω² · |δx|² + |δy|² + |δz|²

Important note: The RAOs for the individual degrees of freedom are complex numbers and have different phase positions. Taking the absolute value of the individual components directly before superposition would result in the loss of phase information. Therefore, the superposition must be carried out **in the complex domain**, and only then is the absolute value calculated.

2.3.2 Spectral response

The significant acceleration is obtained by integrating the response spectrum over frequency:

σai2=∫0∞Sζζ(ω) · |Hi(ω)|2 dωσai2=∫0∞Sζζ(ω) · |Hi(ω)|2dω

Where:

- Sζζ(ω)Sζζ(ω) is the sea state spectrum (JONSWAP or Pierson-Moskowitz)
- Hi(ω) is the transfer function from wave amplitude to acceleration in the ii direction

The **significant acceleration** is defined as:

ai,sig = 4 · σai² ai,sig = 4 · σai²

The module calculates the significant acceleration for:

- Vertical direction (azaz)
- Resultant acceleration (|a||a|)

- All three spatial directions separately (ax, ay, az; ax, ay, az)

2.3.3 Dynamic load capacity reduction

The dynamic load on a crane in rough seas is determined by the static load and the vertical acceleration at the hook point. The **reduction factor** is:

fred = gg + az,sigfred = g + az,sigg

The **dynamic working load limit** (dynamic SWL) is calculated as:

SWLdyn = SWLstat · fred SWLdyn = SWLstat · fred

The **dynamic factor** (load increase compared to static):

fdyn = 1 + az,sig; fdyn = 1 + gaz,sig

2.3.4 Sea state spectra used

JONSWAP spectrum (Joint North Sea Wave Project):

SJONSWAP(ω) = α · g² · ω^(−5) · exp(−1.25 · (ω_p / ω)⁴) · γ exp(−(ω − ω_p)² / (2σ²ω_p²)
SJONSWAP(ω) = α · g² · ω − 5 · exp(−1.25 · (ω / ω_p)⁴) · γ exp(−2σ²ω_p² (ω − ω_p)²)

where:

- $\alpha = 0.076 \cdot (Hs \cdot \omega p^2/g)^{0.75}$ $\alpha = 0.076 \cdot (Hs \cdot \omega p^2/g)^{0.75}$
- σ = 0.07 σ = 0.07 for ω ≤ ω_p ω ≤ ω_p, σ = 0.09 σ = 0.09 for ω > ω_p ω > ω_p
- γ = 3.3 γ = 3.3 (peak enhancement factor, adjustable from 1.0 to 10.0)

Pierson–Moskowitz spectrum (fully developed lake):

SPM(ω) = 516 · Hs² · ω_p⁴ · ω⁻⁵ · exp(−1.25 · (ω_pω)⁴)SPM(ω) = 165 · Hs² · ω_p⁴
· ω⁻⁵ · exp(−1.25 · (ωω_p)⁴)

2.4 Prerequisites and Preparation

2.4.1 FreeCAD document

The active document must contain:

1. **Crane objects** of type `StowMindCrane` or `ShipCrane` (optional)
2. **LoadCondition spreadsheet** with crane positions and masses
3. **RAO dataset** from a previous Capytaine analysis

2.4.2 The LoadCondition spreadsheet – Crane section

The table must contain a section headed **‘CRANES**’. The expected structure:

Column	Content	Unit	Meaning
A	Crane name (e.g. ‘Crane 1’)	—	Identification
B	Component (“crane boom” or “load on hook”)	—	Distinguishing between components
C	Mass	kg	Mass of the crane boom or the load
D	LCG (x)	m	Longitudinal position of the centre of gravity
E	TCG (y)	m	Transverse position of the centre of gravity
F	VCG (z)	m	Vertical position of the centre of gravity

Important notes:

- All position specifications are **in metres** (not mm!)
- For each crane, **both** entries must be provided: ‘Crane boom’ and ‘Load on hook’
- The position of the “load on the hook” defines the **hook point** for the acceleration calculation
- The crane name in column A must be identical for both entries

Example of a complete crane section:

A	B	C	D	E	F
CRANES					
Crane 1	Jib	4500	2.5	-1.2	8.0
Crane 1	Load on hook	12,000	4.8	-1.5	12.5
Crane 2	Jib	3800	-3.2	0.8	8.2
Crane 2	Load on hook	8,500	-5.5	1.0	13.0

2.4.3 Crane objects in the document (optional)

The system automatically searches for crane objects with the proxy types `StowMindCrane` or `ShipCrane`. These objects may contain additional properties:

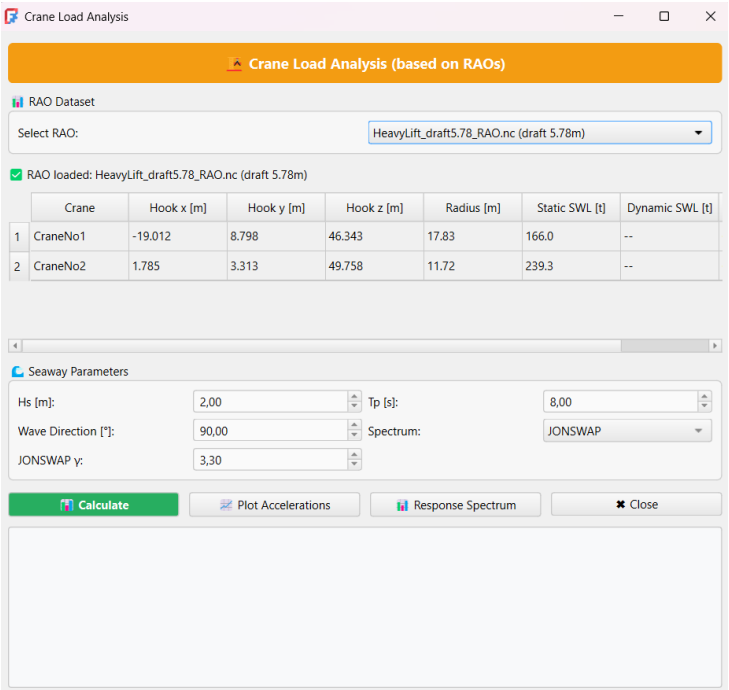
- `CurrentRadius` / `CurrentMaxLoad`: Direct specification of radius and SWL
- `UseLoadStages`: Enables the use of load stages
- `Stage1_Weight`, `Stage1_MinRadius`, `Stage1_MaxRadius`: Load stage definition
- `Auto_MinRadius`, `Auto_MaxRadius`, `Auto_MinWeight`, `Auto_MaxWeight`: Automatic SWL curve

Fallback mechanism: If no crane object is found, the system uses the data from the LoadCondition.

2.4.4 RAO dataset

The RAO dataset must originate from the Capytaine analysis and be available in the project storage. It must contain:

- **Complex RAOs** for all 6 degrees of freedom (or real/imaginary parts)
- **Frequency array** (ωω)
- **Wave directions** (in degrees)
- **Coordinate system** (the reference point is the centre of mass)



2.4.5 Use of the viscous RAO

When loading the RAO dataset, the Crane module automatically checks whether a viscous RAO is present:

- If `RAO_viscous` exists in the `.nc` file **and** `prefer_viscous_rao = 1` is set, the viscous RAO is used.
- If only `RAO` (Potential) is available, this is used (fallback with a warning in the log).

The selection is controlled by a **‘Use viscous RAO (if available)’** tick box in the TaskPanel:

- When a file is loaded, the checkbox is automatically synchronised with the flag in the file.
- Manually toggling the checkbox changes the behaviour for the current session, **not** the file.
- If the file does not contain a viscous RAO, the checkbox is greyed out.

The effect of viscous RAO:

- **Roll-related accelerations** (a_y for cross-seas, a_x/az for roll excitation) decrease by a factor of 1.5–3.0 in the resonance range.
- **Heave-related accelerations** (a_z for bow/stern waves) remain practically unchanged.
- **Dynamic SWL reduction:** becomes more realistic, as the significance of a_z is now physically sound.

2.4.6 Which file is the correct one?

There may be several `.nc` files in the project folder (various drafts, various BEM runs). The combo box in the TaskPanel lists them all. **Important:**

- Select the file with the draft that matches the current load condition.
- If there are several files with the same draft (old and new versions): select the one with the more recent ‘saved_at’ timestamp and the most ω points.
- The file with `RAO_viscous` should always be preferred if viscous damping is to be active.
- If in doubt: check using the console — `PS.load_rao(draft_m=...)` and `'RAO_viscous' in ds`.

2.4.7 Unit conventions

Critical units – The system explicitly expects:

Quantity	Unit	Source
Positions (x, y, z)	**Metres**	LoadCondition, crane objects (Placement.Base is converted from mm to m)
Masses	kg	LoadCondition, crane objects
SWL	Tonnen	From crane objects or calculated
Accelerations	m/s^2	Calculated from RAOs
Frequencies ωω	rad/s	RAO dataset
Sea state parameters Hs, TpHs, Tp	m, s	User input

Note: FreeCAD's Placement.Base is set to millimetres by default. The system **automatically** converts these values to metres before each calculation.

2.5 User Guide

2.5.1 Opening the TaskPanel

The Crane TaskPanel is launched via the corresponding button in the FreeCAD interface or via the project storage. Once launched, a window appears with several sections:

- **RAO Dataset** – Selection of the hydrodynamic dataset
- **Crane Table** – List of all cranes found, with positions and SWL
- **Seaway Parameters** – Input of sea state parameters
- **Control buttons** – Calculation, plots, close
- **Results output** – Text field displaying calculation results

2.5.2 Selection of the RAO dataset

The top drop-down menu lists all RAO datasets available in the project storage. The entries contain information on:

- **Draft** (draught) of the analysis
- **Date/time stamp** of creation
- NetCDF **file name**

Important: The selected RAO dataset must correspond to the current ship condition (load condition, draught). The mooring positions are interpreted relative to the ship's centre of gravity.

2.5.3 Crane table

The table shows all cranes read from the LoadCondition, with the following information:

Column	Content	Meaning
Crane	Crane name	Identification
Hook x [m]	x-position	Longitudinal position of the hook
Hook y [m]	y-position	Transverse position of the hook
Hook z [m]	z-position	Vertical position of the hook (above the keel)
Radius [m]	Horizontal radius	Distance from the crane base to the hook
Static SWL [t]	Static working load limit	From crane specifications or calculated
Dynamic SWL [t]	Dynamic working load limit	Updated following calculation
Source	Data source	"LoadCondition", "Crane object" or "LoadCondition (fallback)"

The table is **not editable**; all values are automatically read from the document.

Tooltip: For the static SWL, detailed information on the calculation is displayed when the mouse hovers over the field (e.g. load level used or interpolation parameters).

2.5.4 Seaway parameters

The parameters are set in the **‘Seaway Parameters’** group:

Parameter	Default value	Range	Meaning
Hs [m]	2.0	0.1 – 20.0	Significant wave height
Tp [s]	8.0	2.0 – 30.0	Peak period of the sea state spectrum
Wave direction [°]	90	0 – 360	Wave direction (relative to the ship)
Spectrum	JONSWAP	JONSWAP / Pierson-Moskowitz	Spectrum type
JONSWAP γ	3.3	1.0 – 10.0	Peak enhancement factor (JONSWAP only)

Guidelines for parameter selection:

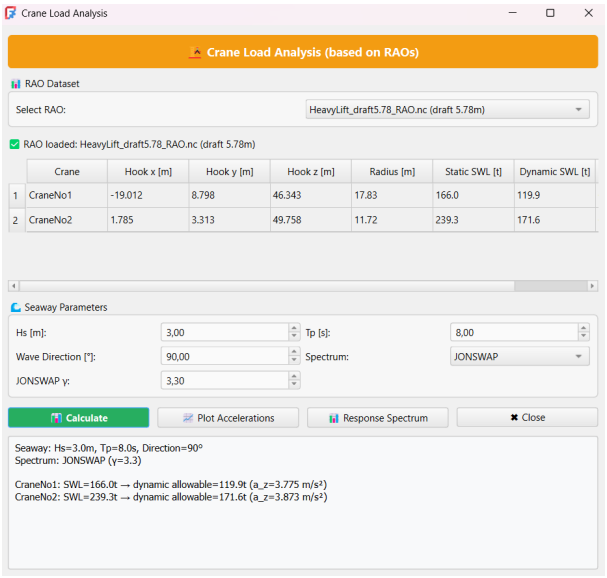
- **Hs:** Typical values for the North Sea: 2–4 m; for coastal waters: 1–2 m
- **Tp:** Depends on Hs; typically 5–12 s; short periods in wind-driven seas, long periods in swell
- **Wave Direction:** 0° = from astern, 90° = from starboard, 180° = from ahead
- **JONSWAP γ:** 3.3 for the North Sea; 1.0 for fully developed seas (PM equivalent); higher values for sharper peaks

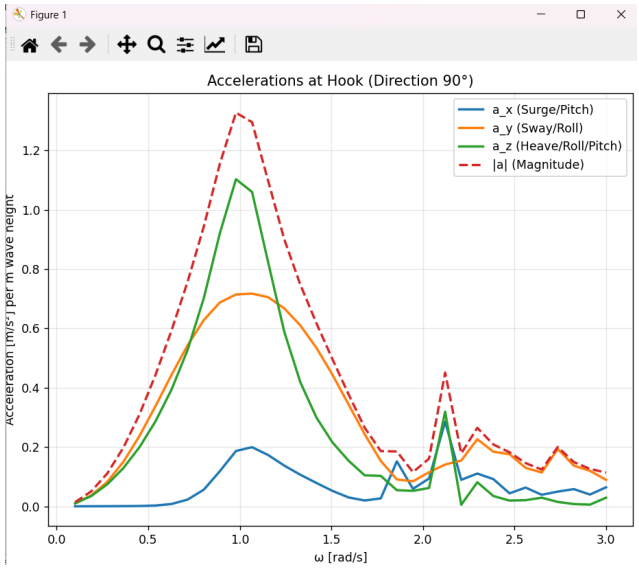
2.5.5 Start calculation

After clicking on 📊 **Calculate,** the system goes through the following steps:

1. **Check:** RAO dataset loaded? No errors?
2. **For each crane in the table:**
    - Extraction of the hook position
    - Calculation of accelerations using `compute_hook_accelerations()`
    - Spectral response using `compute_spectral_response()`
    - Dynamic SWL reduction using `` `crane_load_reduction()` ``
3. **Updating the table:** the ‘Dynamic SWL’ column is populated
4. **Output:** Text box displays a summary of all calculations

The calculation uses the **significant vertical acceleration** az,sigaz,sig to determine the dynamic load-bearing capacity. The resulting acceleration ∣a∣sig∣a∣sig is also calculated and displayed in the text field.





2.5.6 Plot functions

The panel offers three plot functions:

📈 Plot Accelerations

- Displays the acceleration amplitudes ax, ay, az, ∣a∣ax, ay, az, ∣a∣ as a function of frequency
- Displayed as a line plot
- Useful for identifying resonance frequencies

📊 Response Spectrum

- Shows the response spectrum SazSaz (vertical acceleration)
- Superimposed on the sea state spectrum (scaled)
- Shows the significant accelerations as text on the plot
- Enables visual assessment of the spectral energy distribution

Both plots are displayed in separate windows and can be interactively manipulated via the Matplotlib interface (zoom, pan, save).

2.5.7 Evaluation of results

After the calculation, the text box at the bottom of the panel is populated with a summary:

text

```
Seaway: Hs=2.0m, Tp=8.0s, Direction=90°
Spectrum: JONSWAP (γ=3.3)

Crane 1: SWL=12.0t → dynamic allowable=9.8t (a_z=2.45 m/s²)
Crane 2: SWL=8.5t → dynamic allowable=6.9t (a_z=2.51 m/s²)
```

The values can be used to produce operating limit diagrams or load limitation plans.

2.6 Results and Interpretation

2.6.1 Acceleration amplitudes

The function `compute_hook_accelerations()` returns the following for each frequency and wave direction:

Quantity	Unit	Meaning
axax	m/s² per metre of wave height	Acceleration in the x-direction (surge/pitch/yaw)
ayay	m/s² per metre of wave height	Acceleration in the y-direction (sway/roll/yaw)
azaz	m/s² per metre of wave height	Acceleration in the z-direction (heave/roll/pitch)
(| \mathbf{a} |)	m/s² per metre of wave height	Resulting acceleration amplitude

The amplitudes are **linear** with respect to wave height; that is, when Hs = 2 m, the accelerations double compared with Hs = 1 m.

2.6.2 Significant accelerations

The significant accelerations are **directly** comparable with the acceleration due to gravity g = 9.81 m/s²g = 9.81 m/s²:

Value	Interpretation
asig < 0.5 m/s²asig < 0.5 m/s²	Low dynamic load (< 5 per cent of g)
0.5 < asig < 2.0 m/s²0.5 < asig < 2.0 m/s²	Moderate load (5–20 per cent of g)
2.0 < asig < 5.0 m/s²2.0 < asig < 5.0 m/s²	High load (20–50 per cent of g)
asig > 5.0 m/s²asig > 5.0 m/s²	Very high load (> 50 per cent of g) – restrictions required

Practical recommendation: Lifting operations should generally be carried out when az,sig < 2.0 m/s² az,sig < 2.0 m/s². At higher values, a dynamic analysis of the load-bearing equipment and slings is required.

2.6.3 Dynamic load-bearing capacity

The dynamic working load limit depends on the static SWL and the vertical acceleration:

SWLdyn = SWLstat · gg + az,sig SWLdyn = SWLstat · g + az,sig g

Examples of typical reductions:

az, sigaz, sig [m/s²]	Reduction factor	Reduction at 10 t SWL
1.0	0.907	9.07 t (–9.3 %)
2.0	0.831	8.31 t (–16.9 %)
3.0	0.766	7.66 t (–23.4 %)
5.0	0.662	6.62 t (–33.8 %)

2.6.4 Influence of the hook position

The accelerations at the hook point depend heavily on its position relative to the centre of gravity:

- **Lever arm effects:** Large horizontal distances (x, y) result in higher accelerations due to roll and pitch movements
- **Vertical position:** A high hook point (large z) amplifies the accelerations caused by pitch and roll
- **Crane positioning:** Cranes positioned close to the centre of gravity (small x, y) experience lower accelerations

Optimisation recommendation: When planning lifting operations, cranes should, where possible, be positioned close to the centre of gravity.

2.7 Troubleshooting and quality assurance

2.7.1 Common errors and solutions

Symptom	Cause	Solution
"No LoadCondition spreadsheet found"	Spreadsheet does not exist or has the wrong name	Create a spreadsheet named "LoadCondition"
"No CRANES section found"	Section missing or misspelt	Insert a section with **CRANES** in column A
"No crane hook positions found"	Missing entries for “Load on hook”	Enter both components for each crane
SWL = 0.0	No crane object, no load stages	Create a crane object in the document or enter the SWL directly in LoadCondition
"No RAO dataset loaded"	No RAO in the project memory	Perform Capytaine analysis first
Negative or implausible accelerations	Incorrect units (mm instead of m)	Check positions are in metres
Plots are not appearing	Matplotlib backend issue	Backend switched automatically; set tkagg manually if necessary

2.7.2 Plausibility checks

The system carries out the following checks during the calculation:

- **Unit conversion:** Placement.Base is converted from mm to m
- **RAO integrity:** Check for the presence of ‘RAO’ or ‘RAO_real’/‘RAO_imag’
- **Frequency range:** Filtering of unrealistically low frequencies (< 0.1 rad/s)
- **SWL plausibility:** No negative or extremely high values

2.7.3 Debug mode

The module includes a debug mode, which is activated by setting `DEBUG_CRANE = True` in `CraneAnalysis.py`:

python

```
DEBUG_CRANE = True  # Enables debug output
```

In debug mode, the following information is output:

1. **Jib positions** in metres
2. **Intermediate results** of the acceleration calculation

3. **Load levels used** in determining the SWL

The debug output appears in the FreeCAD Report View.

2.7.4 Notes on the quality of results

- The accuracy of the accelerations depends on the quality of the RAOs (mesh resolution, frequency and directional discretisation)
- Spectral integration requires sufficient frequency resolution (at least 30 nodes in the relevant range)
- The assumption of linear waves (small amplitudes) is no longer valid without restriction for Hs > 5 mHs>5m
- The calculation does not take into account non-linear effects such as list or dynamic trim conditions

---

2.8 Appendix: Technical Reference

2.8.1 Important functions in CraneAnalysis.py

Function	Parameter	Return value	Description
`read_crane_data_from_loadcondition(doc)`	FreeCAD document	List of crane data or error message	Reads crane positions and masses from LoadCondition
`find_crane_objects(doc)`	FreeCAD document	List of crane objects	Finds StowMindCrane/ShipCrane in the document
`get_crane_static_swl(crane_obj, hook_pos_m)`	Crane object, hook position in m	SWL in tonnes, description	Calculates static SWL from load stages or auto-curve
`compute_hook_accelerations(dataset, hook_pos_m, wave_direction_deg)`	RAO dataset, position, direction	Dictionary containing accelerations	Calculates the complex superposition of the RAOs
`compute_spectral_response(dataset, hook_pos_m, Hs, Tp, ...)`	RAO, position, sea state parameters	Dictionary containing spectral results	Performs spectral response analysis
`crane_load_reduction(stat_load_tonnes, accel_z_significant)`	Static load, acceleration	Dictionary with reduction factors	Calculates dynamic load-carrying capacity

2.8.2 Data structures

Crane data (from LoadCondition):

python

```
{
    'name': 'Crane 1',           # Crane name
    'hook_pos_m': (4.8, -1.5, 12.5),  # Hook position in metres
```

```
    'boom_pos_m': (2.5, -1.2, 8.0),   # Boom position in metres
    'hook_mass_kg': 12000.0,     # Mass of the load in kg
    'boom_mass_kg': 4500.0       # Mass of the crane boom in kg
}
```

Acceleration results:

python

```
{
    'omega': array([...]),       # Frequency array in rad/s
    'a_x': array([...]),         # Acceleration x in m/s² per m
    'a_y': array([...]),         # Acceleration in the y-direction in m/s² per
metre
    'a_z': array([...]),         # Acceleration z in m/s² per metre
    'a_abs': array([...]),       # Resultant acceleration
    'wave_direction_deg': 90.0,  # Wave direction in degrees
    'hook_pos': (4.8, -1.5, 12.5) # Hook position in metres
}
```

Spectral response:

python

```
{
    'a_z_significant': 2.45,     # Significant vertical acceleration in m/s²
    'a_abs_significant': 3.12,   # Significant resultant acceleration in m/s²
    'omega': array([...]),       # Frequency array
    'S': array([...]),           # Sea state spectrum
    'S_a_z': array([...]),       # Response spectrum (vertical)
    'S_a_abs': array([...]),     # Response spectrum (resultant)
    'a_z': array([...]),         # Vertical transfer function
    'a_abs': array([...]),       # Resulting transfer function
    'wave_direction_deg': 90.0,
    'Hs': 2.0,
    'Tp': 8.0,
    'spectrum': 'JONSWAP (γ=3.3)',
    'gamma': 3.3
}
```

2.8.3 Dependencies

Module/Library	Usage	Note
FreeCAD	CAD data access	Placement, document objects
numpy	Numerical calculations	Arrays, trigonometric functions
matplotlib	Plots	Optional; if omitted, no graphical output
xarray	RAO data access	From Capytaine results
PySide2/PySide6	GUI	Qt bindings for FreeCAD

Chapter 3: Mooring Analysis

3.1 Purpose and Scope

The Mooring Analysis module is used for the static and dynamic assessment of mooring systems for floating structures. Based on hydrodynamic analysis (RAOs), it calculates the resulting line forces and anchor forces under the influence of wind, current and sea state. The analysis provides:

- **Static equilibrium calculation** with 3 degrees of freedom (surge, sway, yaw) for mooring lines and anchor chains
- **Spectral response analysis** of line forces under the influence of sea state
- **Time-domain simulation** of transient mooring line tension and drift movements
- **Systematic variation in direction** to identify critical load cases
- **Failure simulation** (damaged condition) for the loss of individual lines
- **Partial safety factor assessments** in accordance with DNV/ISO for strength verification
- **Interactive mooring editor** for the visual placement of fairleads and bollards
- **PDF report export** with tables and graphs

Applications include the design of mooring systems for ships and offshore structures, the assessment of operational limits, the preparation of load plans, and the certification of mooring designs in accordance with classification rules.

3.2 System architecture and module overview

The system consists of three main modules covering the entire workflow from geometry creation to the documentation of results:

Module	Task	Runtime environment
MooringAnalysis.py	Core calculations: catenary model, 3-DOF equilibrium, spectral analysis, time domain, PDF export	FreeCAD Python environment, can be used independently
MooringTaskPanel.py	Graphical user interface (GUI) for analysis parameters, result display, plotting functions	FreeCAD GUI
MooringEditor.py	Interactive editor for the visual placement of fairleads and bollards, automatic line generation with material parameters	FreeCAD GUI

The data flow is as follows:

- **FreeCAD document** containing ship geometry and load data
- **MooringEditor** – visual placement of fairleads (on the vessel) and bollards (on the quay)

- **Export of mooring data** to the MooringData spreadsheet
- **Selection of RAO dataset** from the project repository (Capytaine results)
- **Reading of environmental data** from LoadCondition (projected areas for wind and current)
- **Static equilibrium calculation** (Newton-Raphson with 3 DOF)
- **Spectral response analysis** or time-domain simulation
- **Display in the TaskPanel** as a table, text output and interactive plots
- **PDF report export** for documentation purposes

3.3 Physical principles

3.3.1 Static equilibrium with 3 degrees of freedom

The system treats the vessel as a rigid body with the following degrees of freedom:

- **Surge** (XX): Longitudinal translation
- **Sway** (YY): Translation in the transverse direction
- **Yaw** (ψψ): Rotation about the vertical axis

The equilibrium condition is:

Fmooring(q)+Fenv=0Fmooring(q)+Fenv=0

where the state vector is q=(X,Y,ψ)Tq=(X,Y,ψ)T.

The mooring forces consist of:

1. **line forces** (elastic springs with pre-tension)
2. **Anchor forces** (catenary model with ground contact)

The solution is obtained using a **Newton–Raphson method** that employs scaling and damping to avoid numerical instabilities.

3.3.2 Line force model

Each mooring line is modelled as a linear spring with pre-tension:

$T = \max(0,\ T_0 + k \cdot (L - L_0))$ $T = \max(0, T_0 + k \cdot (L - L_0))$

where:

- T_0: Pre-tension [kN]

- kk: line stiffness [kN/m]
- L_0: Initial length [m]
- LL: Current length [m]

The cable stiffness is calculated from the modulus of elasticity, the diameter and the length:

k = E · AL0 k = L0E · A

where:

- EE: modulus of elasticity [Pa]
- A = π · (d/2)²A = π · (d/2)²: cross-sectional area [m²]

The force components at the fairlead are calculated from the direction of the line and the tensile force. The moment about the reference point is given by:

Mz = x · Fy − y · Fx Mz = x · Fy − y · Fx

3.3.3 Catenary model for anchor chains

The catenary model describes the shape of a heavy chain under its own weight. The **horizontal distance** XX as a function of the horizontal tension THTH is:

X = a · a sinh(Sa) X = a · a sinh(aS)

where:

- a = TH/w; a = TH/w: catenary parameters
- ww: weight of the chain per metre underwater [kN/m]
- SS: Free-hanging chain length (scope)

The **scope factor** is defined as:

Scope=LChainedScope=dLChain

where dd is the water depth. Typical values:

- **3.0**: Offshore (standard)
- **4.0–5.0**: Shallow water
- **1.5–2.0**: Harbour (limited space)

Ground contact (grounding): If the horizontal distance XX is less than the maximum range, part of the chain rests on the seabed:

L_bottom = L_chain − S_free L_bottom = L_chain − S_free S_free = d² + 2 · a · d S_free = d² + 2 · a · d

When the chain is fully extended ($X \leq L_bottom$ $X \leq L_bottom$), the horizontal tension $TH = 0$ $TH = 0$ (slack).

Holding Capacity: The maximum horizontal force that the anchor can absorb in the ground (depending on ground type, anchor size and embedment). If the chain force exceeds the holding capacity, it is limited.

3.3.4 Environmental forces

Environmental forces consist of wind and current. Both are calculated from the **projected areas** (from ProjectedAreas.py) and the velocities:

Wind force:

$FWind = 12 \cdot \rho Air \cdot vWind^2 \cdot cf \cdot Aproj$ $FWind = 21 \cdot \rho Air \cdot vWind^2 \cdot cf \cdot Aproj$

Current force:

$FCurrent = 12 \cdot \rho Water \cdot vCurrent^2 \cdot cd \cdot AprojFCurrent = 21 \cdot \rho Water \cdot vCurrent^2 \cdot cd \cdot Aproj$

The **projected area** as a function of the angle of attack β:

$Aproj(\beta) = Alongitudinal \cdot |\cos \beta| + Alateral \cdot |\sin \beta|$ $Aproj(\beta) = Alongitudinal \cdot |\cos \beta| + Alateral \cdot |\sin \beta|$

Conventions (FROM/TO):

- **FROM**: The direction specification indicates the direction from which the wind/flow is coming (industry standard)
- **TO**: The direction indicates the direction in which the wind/current is pointing/flowing (mathematical convention)

Heuristic wave drift: The module provides a simplified estimate of the mean wave drift force:

$FDrift=12 \cdot \rho \cdot g \cdot B \cdot \int(|RAOSurge|^2+|RAOSway|^2) \cdot S(\omega)\, d\omega FDrift=21 \cdot \rho \cdot g \cdot B \cdot \int(|RAOSurge|^2+|RAOSway|^2) \cdot S(\omega) d\omega$

This is a **heuristic** (not a QTF-based calculation) and is intended only for initial estimates.

3.3.5 Spectral response

The spectral response of the line forces is described by the transfer function $HT(\omega)HT(\omega)$:

$ST(\omega)=S\zeta\zeta(\omega) \cdot |HT(\omega)|2ST(\omega)=S\zeta\zeta(\omega) \cdot |HT(\omega)|2$

The significant line force is given by:

$Tsig = 4 \cdot \int 0\infty\ ST(\omega)\, d\omega$ $Tsig = 4 \cdot \int 0\infty\ ST(\omega)\, d\omega$

The maximum line force (4σ value) is:

$T_4\sigma = \bar{T} + Tsig$ $T_4\sigma = T + Tsig$

3.3.6 Safety factors according to DNV/ISO

The **design-relevant line force** is calculated from the mean force and the dynamic component using partial safety factors:

TDesign = Tmean · γpret + T4σ · γenv TDesign = Tmean · γpret + T4σ · γenv

The utilisation **factor** is given by:

Utilisation = TDesign / MBL/SC Utilisation = MBL/SC / TDesign

where:

- MBL: Minimum Breaking Load
- SC: Safety factor

Typical values:

1. γpret=1.0 γpret=1.0 (for prestressing)
2. γenv = 1.3 (for ambient loads)
3. SC=1.67SC=1.67 (for dynamic analysis)

3.4 Prerequisites and Preparation

3.4.1 FreeCAD document

The active document must contain:

- **Ship model** as a solid, shell or imported mesh object
- **LoadCondition spreadsheet** with ship data and projected areas (optional, but recommended)
- **MooringData spreadsheet** with mooring line parameters (generated automatically or populated by the editor)
- **RAO dataset** from a previous Capytaine analysis

3.4.2 The MooringData spreadsheet – LINES section

The spreadsheet must contain a section headed **‘LINES**’. The expected structure:

Column	Content	Unit	Meaning
A	Name	—	Identification of the line
B	Fairlead x	m	Position of the fairlead (on the vessel)

Column	Content	Unit	Meaning
C	Fairlead y	m	Position of the fairlead
D	Fairlead z	m	Position of the fairlead
E	Bollard x	m	Position of the bollard (at the quay)
F	Bollard y	m	Position of the bollard
G	Bollard z	m	Position of the bollard
H	Stiffness	kN/m	Cable stiffness (calculated automatically)
I	Pretension	kN	Pre-tension
J	Breaking load	kN	Breaking load

Optional – WIND/CURRENT/SHIP sections for environmental data:

Section	Columns	Content
WIND	B: area_SB, C: area_PS, D: area_FWD, E: area_AFT, F: form_factor, G: height_above_wl	Projected wind areas
CURRENT	B: area_SB, C: area_PS, D: area_FWD, E: area_AFT, F: drag_coeff, G: depth_below_wl	Projected current areas
SHIP	B: beam, C: draught, D: lpp	Ship dimensions

3.4.3 LoadCondition spreadsheet (for environmental data)

The module uses the projected areas from the LoadCondition (generated by ProjectedAreas.py). The relevant cells:

Cell	Parameter	Unit	Meaning
B7	Lateral wind area	m²	Projected lateral area for wind
E7	Wind centre of gravity x	m	Longitudinal position of the wind attack point
G7	Wind CoG z	m	Vertical position of the wind action point
B8	Wind frontal area	m²	Projected bow/stern area for wind
B9	Current lateral area	m²	Projected lateral area for current
E9	Current CoG x	m	Longitudinal position of the current point of application
G9	Current CoG z	m	Vertical position of the current point of application
B10	Current frontal area	m²	Projected bow/stern area for current
C4	Beam	m	Ship’s beam
D4	LPP	m	Length between perpendiculars
E4	Draft	mm	Draught (in mm!)

3.4.4 Unit conventions

Size	Unit	Note
Positions (x, y, z)	**Metres**	All position data in MooringData

Size	Unit	Note
Forces	**kN**	Line forces, environmental forces
Stiffnesses	**kN/m**	Cable stiffness
Speeds	**m/s**	Wind and current
Water depth	**m**	For the Katenarm model
Frequencies	**rad/s**	From RAO dataset

Important: The LoadCondition contains the draft in **mm** – the system converts this automatically.

3.4.5 Use of viscous RAO

As in the Crane Analysis, the Mooring module automatically checks whether a viscous RAO is available. The **‘Use viscous RAO (if available)’** tick box synchronises with the flag in the file when it is loaded.

Effect on mooring results:

- The mooring line forces are calculated based on the movements of the fairlead, which are derived from the 6-DOF RAOs. As viscous damping reduces the roll amplitude, the **roll-induced mooring line forces** (typically with cross-seas at 90°/270°) decrease by 10–30 per cent.
- The **surge/sway/yaw-dominated line forces** remain virtually unchanged.
- The **static equilibrium position** is not affected by the RAO (it depends on environmental forces and line stiffness).
- The **spectral response** (`T_sig`) becomes more realistic because the roll motion is no longer overestimated.

For operability and design analyses, the viscous RAO is the correct basis. The potential RAO can be used for comparative calculations, but is too conservative for design purposes.

3.5 User Guide

3.5.1 The MooringEditor – Visual creation of the mooring configuration

The MooringEditor is an interactive tool for the visual placement of fairleads and bollards, as well as for creating mooring lines.

Opening the Editor:

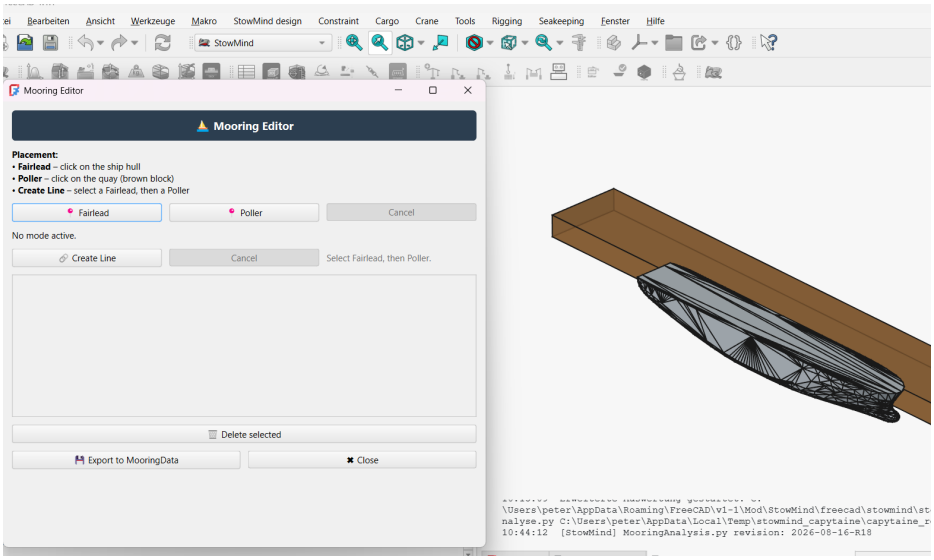
The Editor is launched via the relevant menu item or command:

python

```
from StowMind import MooringEditor as ME
ME.start_mooring_editor()
```

Workflow in the editor:

1. **Automatic creation of a working document:**



   1. The current ship model is copied into a new document
   2. A quay block (brown cuboid) is generated automatically
   3. The position of the quay is calculated based on the vessel's beam and draught

2. **Placing fairleads (on the vessel):**

1. Click on 📍 **Fairlead**
2. Click on a point on the ship's hull (3D view)
3. Enter the breaking load in kN

3. **Placing bollards (on the quay):**
    1. Click on 📍 **Bollard**
    2. Click on a point on the quay block
    3. Enter the breaking load in kN
4. **Creating mooring lines:**
    1. Click on 🔗 **Create Line**
    2. First, select a fairlead (red dot)
    3. Then select a bollard (orange dot)
    4. In the dialogue box: Select the material, diameter, pre-tension and breaking load
5. **Managing objects:**
    1. The list shows all points and lines with their parameters
    2. Use 🗑️ **Delete selected** to delete objects
    3. Select 💾 **Export to MooringData** to export the data to a spreadsheet

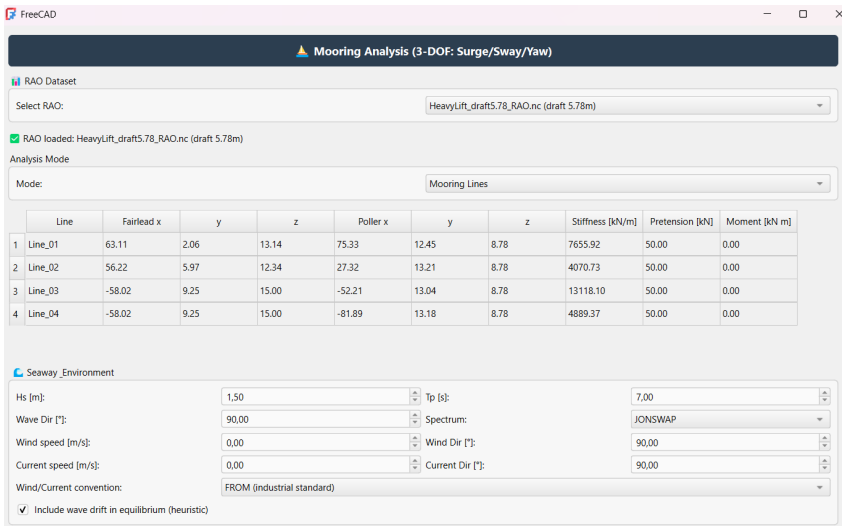
Material library:

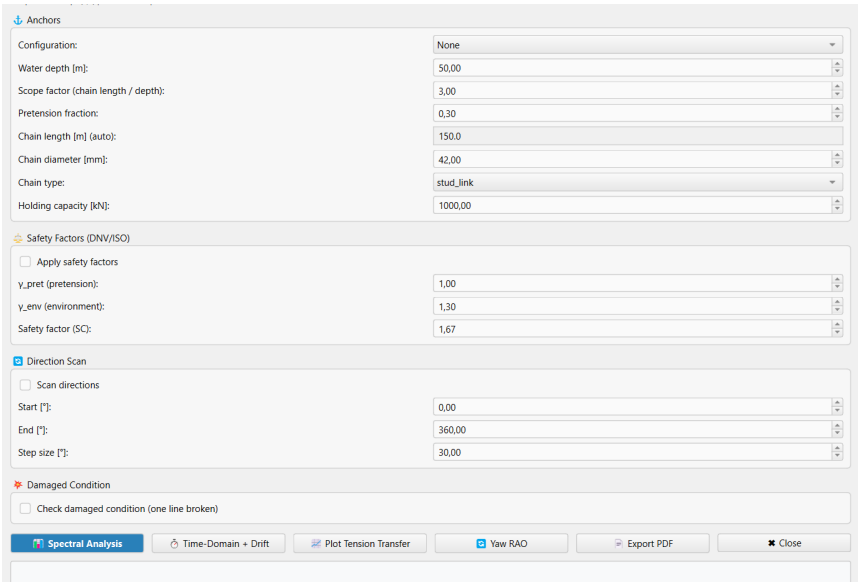
Material	Modulus of elasticity [GPa]	Density [kg/m³]	Standard diameter [mm]
Wire rope	120	7850	36
Chain	200	7850	42
Synthetic (HMPE)	45	970	60

Tip: The stiffness $k = E \cdot A/L$ is calculated automatically from the modulus of elasticity, diameter and line length.

3.5.2 Opening the MooringTaskPanel

The Mooring Task Panel is launched via the corresponding button in the FreeCAD interface or via the project storage.





python

```
from StowMind import MooringTaskPanel as MTP
MTP.createTask(dataset, output_dir)
```

Once launched, a window appears containing the following sections:

- **RAO Dataset** – Selection of the hydrodynamic dataset
- **Analysis Mode** – Choose between mooring lines, anchors or both
- **Mooring Lines Table** – Overview of the lines loaded
- **Seaway & Environment** – Sea state parameters, wind, current
- **Anchors** – Configuration of anchor chains
- **Safety Factors** – DNV/ISO partial safety factors
- **Direction Scan** – Systematic variation in direction
- **Damaged Condition** – Failure simulation
- **Buttons** – Calculation, Plots, PDF Export
- **Output** – Text box displaying calculation results

3.5.3 Selection of the RAO dataset

The top drop-down menu lists all RAO datasets available in the project storage. The entries contain information on:

- **Draft** (draught) of the analysis
- **Date/time stamp** of creation
- NetCDF **file name**

Important: The selected RAO dataset must correspond to the current ship condition.

3.5.4 Selecting the analysis mode

Mode	Description	Application
Mooring Lines	Conventional lines only	Mooring systems with bollards on the quay
Anchors only	Anchor chains only	Anchoring at sea
Both	Combined mooring lines and anchors	Port facilities with additional mooring

3.5.5 Sea state parameters and environment

Parameter	Default value	Range	Meaning
Hs [m]	1.5	0.1 – 20.0	Significant wave height
Tp [s]	7.0	2.0 – 30.0	Peak period
Wave direction [°]	90	0 – 360	Wave direction
Spectrum	JONSWAP	JONSWAP / PM	Spectrum type
Wind speed [m/s]	0	0 – 60	Wind speed
Wind direction [°]	90	0 – 360	Wind direction
Current speed [m/s]	0	0 – 10	Flow velocity
Current direction [°]	90	0 – 360	Flow direction
Convention	FROM	FROM / TO	Direction convention

Wind and current conventions:

- **FROM** (industry standard): 90° = wind/current coming from starboard
- **TO** (mathematical): 90° = wind/current points to starboard

Heuristic drift:
The **‘Include wave drift in equilibrium’** option activates the simplified estimation of the mean wave drift force. This is added to the static equilibrium calculation.

> ⚠ **Note:** This is a heuristic, not a QTF-based calculation. A detailed drift analysis is required for final design work!

3.5.6 Configuring Anchor Chains

The anchor configuration offers the following options:

Parameters	Default value	Significance
Configuration	None / 1 Anchor / 4 Anchors	Anchor arrangement
Water depth [m]	50	Water depth
Scope factor	3.0	Chain length / water depth
Pretension fraction	0.3	Preload factor (0.3 = 30% of maximum reach)
Chain diameter [mm]	42	Chain Diameter
Chain type	stud_link	Chain Type (stud_link / open_link)
Holding capacity [kN]	1000	Maximum holding force of the anchor

Anchor Positioning:

The anchors are positioned in such a way that there is a defined preload (slack) at zero deflection. The horizontal distance from the fairlead to the anchor results from:

$$XAnker = Xmax \cdot fpret XAnker = Xmax \cdot fpret$$

with:

- XmaxXmax: Maximum horizontal reach of the chain
- fpretfpret: bias factor (typically 0.2–0.5)

At fpret=1.0fpret=1.0, the chain is at the limit (no slack) – this state is faulty and should be avoided.

3.5.7 Safety Factors (DNV/ISO)

The safety factors can optionally be applied to the spectral results:

Factor	Default value	Significance
γ_pret	1.0	Partial safety coefficient for preload
γ_env	1.3	Partial safety coefficient for ambient loads
Safety factor (SC)	1.67	Safety factor on breaking load (for dynamic analysis)

The design-relevant utilization rate is calculated and shown in the results.

3.5.8 Directional Scan

The directional scan systematically searches different wave, wind and current directions:

Parameters	Default value	Significance
Start [°]	0	Starting angle
End [°]	360	End Angle
Step size [°]	30	Step size

The analysis is carried out for each combination of wave, wind and current direction. The result is the **most critical load case** (maximum line force).

Note: The compute time scales with (End−StartStep)3(StepEnd−Start)3.

3.5.9 Damaged Condition

If this option is activated, the system simulates the **failure of each individual line** one by one:

- Line ii is removed
- The static equilibrium is recalculated
- The maximum force in the remaining lines is determined

The result shows the **maximum line force** when damaged and the **line that has failed**.

3.5.10 Start Calculation

📊 **Spectral Analysis:**

6. Calculates the spectral response of the line forces
7. Displays TmeanTmean, TsigTsig, T4σT4σ and Usage Level
8. Faster calculation as no time domain simulation is required

⏱️ **Time-Domain + Drift:**

- Performs a time domain simulation
- Shows the evolution of line forces over time
- Takes into account the heuristic drift force

After the calculation, the results are displayed in the table and in the text box.

3.5.11 Plot Functions

📈 **Plot Tension Transfer:**

- Shows the transfer functions HT(ω)HT(ω) for all lines
- Display as a line plot over the frequency
- Useful for identifying resonant frequencies

🔁 **Yaw RAO:**

- Displays the Yaw-RAO for the currently set wave direction
- Representation as a line plot

3.5.12 PDF Report Export

Export 📄 **PDF** creates a comprehensive report that includes:

- **Title page** with analysis parameters
- **Ambient** Forces and Static Line/Anchor Forces (Table)
- **Spectral results** (table with TmeanTmean, TsigTsig, etc.)
- **Time series** (if time domain simulation is performed)
- **Tension Transfer Functions** (Graphics)

The report is created in A4 landscape format and can be used directly for documentation and expert opinions.

3.6 Results and interpretation

3.6.1 Static equilibrium results

The static equilibrium calculation provides:

Size	Unit	Significance
Offset dx	mm	Longitudinal displacement of the ship
Offset dy	mm	Transversal displacement of the ship
Yaw	°	Rotation of the ship around the vertical axis
T_stat	kN	Static line force (after equilibrium)
Wait	kN·m	Moment of the line around the reference point

Interpretation of the offset values:

- dx<100 mmdx<100mm: Low displacement (good)
- dx>500 mmdx>500mm: Significant displacement (check)
- dy<100mmdy<100mm: Low displacement (good)
- dy>500 mmdy>500mm: Significant displacement (check)
- Yaw<2◦Yaw<2◦: Low Turn (Good)
- Yaw>5◦Yaw>5◦: Significant rotation (check)

3.6.2 Spectral Results

The spectral response provides for each line:

Size	Unit	Significance
TmeanTmean	kN	Medium line force (preload + static component)
TsigTsig	kN	Significant dynamic line force
T4σT4σ	kN	Maximum Value (Tmean+TsigTmean+Tsig)
TminTmin	kN	Minimum value (max(0,Tmean−Tsig)max(0,Tmean−Tsig))
Utilization	%	Degree of Utilization Related to Breaking Load

Interpretation of the utilization rates:

- <50%<50%: Low utilization (unproblematic)
- 50-80%50-80%: Moderate utilization (acceptable)
- >80%>80%: High utilization (critical – optimization required)
- >100%>100%: Overload (not allowed)

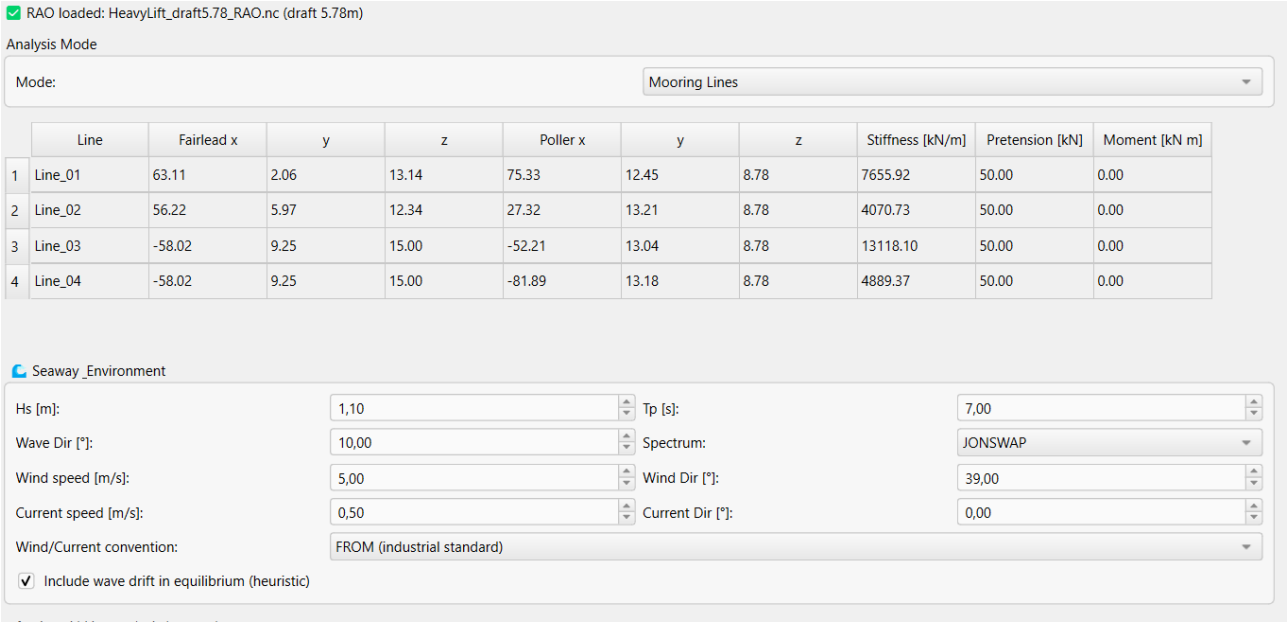
3.6.3 Typical results in comparison

Condition	TmeanTmean	TsigTsig	T4σT4σ	Usage
Calm (no swell)	50 kN	0 kN	50 kN	5%
Light Swell (Hs=1.0m)	55 kN	15 kN	70 kN	7%
Mean Swell (Hs=2.0m)	65 kN	35 kN	100 kN	10%
Strong swell (Hs=4.0m)	90 kN	80 kN	170 kN	17%

3.6.4 Influence of wave direction

The most critical wave direction depends on the arrangement of the lines:

- **Lines longitudinal:** Critical for longitudinal waves (0°/180°)
- **Lines transverse:** Critical for waves from the transverse direction (90°/270°)
- **Combination:** Worst-case is often in sloping seas (45°/135°)



3.6.5 Influence of Anchor Configuration

Configuration	Pros	Cons
1 anchor (central)	Simple, cost-effective	Low stability against yaw
4 anchors (corners)	High Yaw Stability	Multiple anchors, higher costs
No anchors	Simple, for port	No additional security

3.7 Troubleshooting and Quality Assurance

3.7.1 Common Errors and Solutions

Symptom	Cause	Solution
"No MooringData spreadsheet found"	Spreadsheet not present	Use the editor or create it manually
"No LINES section found"	Section Missing	**Insert LINES** in column A
"No valid mooring lines found"	Missing or invalid entries	Check Fairlead and Bollard Positions
"Equilibrium: NOT CONVERGED"	Numerical instability	Increase damping, reduce preload, decrease step size
"RAO not found in dataset"	Outdated NetCDF file	Re-perform Capytaine analysis with updated version
Implausible Line Forces (>MBL)	Wrong units (mm instead of m)	Check Locations in MooringData for Meters
"No wind/current areas found"	ProjectedAreas not executed	Check or run ProjectedAreas.py LoadCondition
Drift force NaN	RAO Interpolation Error	Check the direction of the waves; if necessary, use the next available direction

3.7.2 Plausibility checks

The system performs the following checks during the calculation:

6. **Line lengths:** L>0L>0 and not extremely short (L>0.5L>0.5 m)
7. **Line stiffness:** k>0k>0 and not extremely high (k<1e6k<1e6 kN/m)
8. **Preload:** T0≥0T0≥0 and T0<MBLT0<MBL
9. **Catenar parameters:** a>0a>0, d>0d>0, S>dS>d
10. **Environmental forces:** No NaN values; limitation to physically sensible values

3.7.3 Debug Mode

The module contains debug outputs that appear in the FreeCAD report view. Important debug information:

- **Anchor Positioning:** Fairlead Position, Anchor Position, Chain Length, Scope
- **Equilibrium:** Residual Norm, Iterations, Convergence Status
- **Line forces:** TT, FxFx, FyFy, FzFz for each line
- **Environmental forces:** wind and electricity components with projected surfaces

3.7.4 Notes on the quality of results

- The **spectral response** depends on the quality of the RAOs (mesh resolution, frequency and directional discretization)
- The **Katenar calculation** assumes idealized chain behavior (no friction, no elongation)
- The **wave drift heuristic** is not a QTF calculation – a QTF-based approach is required for final designs
- The **time domain simulation** is a linear approach (no nonlinear effects such as slack/punch)
- The **directional scan** can be computationally intensive with a fine step size – use wisely

---

3.8 Appendix: Technical Reference

3.8.1 Important features in MooringAnalysis.py

Function	Parameters	Returns	Description
`read_mooring_data_from_spreadsheet()`	doc (optional)	Leash List or Error	Reads Mooring Lines from Spreadsheet
`read_wind_current_data()`	doc (optional)	Wind/Power Data	Reads environmental data
`compute_env_forces()`	Wind/current data, speeds, directions	Forces and Moments	Calculates wind and current forces
`solve_static_equilibrium_general()`	Lines, Anchors, Environmental Forces, Reference Point	Displacement, Yaw, Convergence Status	3-DOF Newton-Raphson
`catenary_horizontal_tension()`	Distance, water depth, scope, chain weight	Horizontal tension	Katenar calculation
`compute_spectral_mooring_response()`	Dataset, Lines, Hs, Tp, Direction	Spectral results	Spectral Response Analysis
`full_mooring_analysis()`	Dataset, Lines, Anchors, Sea Parameters	Full results	Main function for analysis
`export_pdf_report()`	Results, file name, title	—	PDF Report Export

3.8.2 Data Structures

Mooring Leash (from Spreadsheet):

python

```
{
    'name': 'Line_01',
    'fairlead': (2.5, -1.2, 0.0), # (x, y, z) in meters
    'bollard': (15.0, 8.0, 2.0), # (x, y, z) in meters
    'stiffness': 150.0, #kN/m
    'pretension': 50.0, #kN
    'breaking_load': 2000.0, #kN
    'length_initial': 13.5#m (automatically calculated)
}
```

Anchor Configuration:

python

```
{
    'name': 'anchor_1',
    'fairlead_pos': (2.5, -1.2, 0.0), #(x, y, z) in meters
    'anchor_pos': (15.0, -8.0, -50.0), # (x, y, z) in meters
    'water_depth': 50.0, #m
    'chain_length': 150.0, #m
    'weight_per_m': 0.85, # kN/m (underwater)
    'holding_capacity': 1000.0 # kN
}
```

Results of the spectral response:

python

```
{
    'name': 'Line_01',
    'T_mean': 52.3, #kN
    'T_sig': 12.5, #kN
    'T_4sigma': 64.8, #kN
    'T_min': 39.8, #kN
    'utilization': 0.032, # 3.2%
```

```
    'omega': array([...]), # rad/s
    'tension_transfer': array([...]), # kN/m
    'S_T': array([...]) # kN²·s
}
```

3.8.3 Dependencies

Module/Library	Usage	Note
FreeCAD	CAD data access	Placement, Document Objects
Numpy	Numerical calculations	Arrays, linear algebra
matplotlib	Plots and PDF export	Optional; no graphical output if missing
xarray	RAO Data Access	From Capytaine results
PySide2/PySide6	GUI	Qt bindings for FreeCAD
matplotlib.backends.backend_pdf	PDF Creation	For report export

3.8.4 Constants and Defaults

Constant	Value	Significance
`rho_air`	1,225 kg/m³	Airtightness
`rho_water`	1025 kg/m³	Seawater
`g`	9.81 m/s²	Acceleration due to gravity
`POINT_RADIUS_MM`	500 mm	Radius of Fairlead/Bollard Points in the Editor
`QUAY_WIDTH_M`	30 m	Width of the Kai Block in the Editor
`QUAY_CLEARANCE_M`	1 m	Distance ship–quay in the editor

Chain Weight Coefficient:

Chain type	Coefficient	Formula
Stud Link	0.0219	wAir=0.0219 · d2wAir=0.0219 · d2 [kg/m]
Open Link	0.0186	wAir=0.0186 · d2wAir=0.0186 · d2 [kg/m]

The underwater weight factor is 0.869 (buoyancy).

3.9 Practical application notes

3.9.1 Workflow for a Mooring Analysis

- **Preparation:**
    - Create or load ship model in FreeCAD

    - LoadCondition spreadsheet with ship data and projected areas
    - Perform Capytaine Analysis (Create RAO Dataset)
- **To create a mooring configuration:**
    - Open MooringEditor
    - Placing Fairleads on the Ship
    - Place bollards on the quay
    - Create lines between fairleads and bollards
    - Setting Material and Parameters
    - Export to MooringData Spreadsheet
- **Perform analysis:**
    - Open MooringTaskPanel
    - Select RAO dataset
    - Set swell parameters
    - Set wind and current parameters
    - Optional: Configure anchors
    - Optional: Enable Safety Factors, Directional Scan, Damaged Condition
    - Start "Spectral Analysis" or "Time-Domain + Drift"
- **Interpreting results:**
    - Check Static Displacement and Yaw
    - Evaluate line forces and utilization rates
    - Identify critical lines
    - Use plots for visual analysis
- **Documentation:**
    - Export PDF Report
    - Copy Results to Calculation Report

3.9.2 Recommendations for practice

- **Prestress:** Typically 5–10% of the breaking load, but not less than 50 kN for steel wire ropes
- **Scope factor:** At least 3.0 for anchor chains, better 4.0–5.0 in shallow water
- **Leash Arrangement:** Distribute the lines symmetrically to minimize yaw moments

- **Directional scan:** Use increments of 30-45° for an initial estimate, 15° for detailed analysis
- **Damaged condition:** Check whether the system is still stable even if a line fails
- **Safety Factors:** Apply DNV/ISO factors for design-relevant verifications

Source of error	Avoidance
Wrong units (mm instead of m)	Specify all locations in MooringData in meters
Low preload (slack)	Preload at least 5% of the breaking load
Too high preload	Can lead to overload with small deflection
Unrealistic wave direction	Adjust wave direction to actual site conditions
Missing Projected Areas	Run ProjectedAreas.py before analysis
Insufficient frequency resolution	Capytaine analysis with at least 30 frequency support points

Chapter 4: Points of Interest – Acceleration Analysis for Arbitrary Points

4.1 Purpose and scope

The Points of Interest (POI) module is used to evaluate accelerations at any point on board a vessel under the influence of sea conditions. It extends the kinematics used in crane analysis to **any point** – from cargo corners to lashing points to sensitive equipment. The analysis provides:

- **Significant accelerations** in all three spatial directions (axax, ayay, azaz) as well as the resulting acceleration (|a||a|)
- **Comparison with user-defined limits** for each axis separately
- **Spectral responses** for each point (frequency spectra of the accelerations)
- **Graphical representations** of the acceleration curves and response spectra
- **Interactive creation of points of interest** via manual entry or selection of 3D objects

Applications include the safety-related assessment of load securing systems, the design of lashings, the verification of acceleration limits for sensitive cargo (e.g. electronics, medical technology) and the creation of operating limit diagrams for specific load positions.

4.2 System Architecture and Module Overview

The system consists of three closely linked Python modules that cover the entire workflow from point creation to result presentation:

Module	Task	Running environment
PointOfInterest.py	Definition of POI objects (App::FeaturePython), properties (position, acceleration limits, results), view provider with 3D marker	FreeCAD Python environment, FreeCAD GUI
PointOfInterestAnalysis.py	Core calculations: Reuse of CraneAnalysis kinematics for arbitrary points, limit check, plot functions	FreeCAD Python Environment
PointOfInterestTaskPanel.py	Graphical user interface (GUI) for point creation, limit value definition, calculation and result display	FreeCAD GUI

The data flow is as follows:

7. **FreeCAD document** with ship geometry and load data
8. **Creation of POI objects** – manually via X/Y/Z input or by selecting a 3D object
9. **Definition of acceleration limits** for each point (optional)

10. **RAO Dataset Selection** from Project Storage (Capytaine Results)
11. **Calculation of accelerations** at the POI using rigid body kinematics
12. **Spectral response analysis** using JONSWAP or Pierson-Moskowitz spectra
13. **Limit value check** and color status display (PASS/FAIL)
14. **Presentation in the TaskPanel** as table, text output and interactive plots

---

4.3 Physical basics

4.3.1 Kinematics at any point

The module uses the **same kinematics** as the crane analysis (see chapter 2.3.1). For a point with the coordinates r=(x,y,z)r=(x,y,z) relative to the reference point (center of gravity), the complex superposition of the six rigid-body degrees of freedom applies:

δx=Surge+Pitch · z−Yaw · yδy=Sway+Yaw · x−Roll · zδz=Heave+Roll · y−Pitch · xδxδyδz=Surge+Pitch · z−Yaw · y=Sway+Yaw · x−Roll · z=Heave+Roll · y−Pitch · x

The **acceleration** in each direction is obtained by multiplying by −ω2−ω2:

ai(ω)=ω2 · |δi(ω)|ai(ω)=ω2 · |δi(ω)|

The **resulting acceleration** (magnitude) is calculated from the Euclidean norm of complex displacement components:

|a(ω)|=ω2 · |δx|2+|δy|2+|δz|2|a(ω)|=ω2 · |δx|2+|δy|2+|δz|2

Important note: The RAOs for the individual degrees of freedom are available as complex numbers and have different phase positions. The superposition must be complex, and only then is the amount formed.

4.3.2 Spectral Response

The significant acceleration results from the integration of the response spectrum via frequency:

σai2=∫0∞Sζζ(ω) · |Hi(ω)|2 dωσai2=∫0∞Sζζ(ω) · |Hi(ω)|2dω

Significant acceleration is defined as:

ai,sig=4 · σai2ai,sig=4 · σai2

The module calculates the significant acceleration for:

- All three spatial directions separately (ax,ay,azax,ay,az)
- The resulting acceleration (|a|||)

4.3.3 Limit value test

For each POI **, separate limit values** can be defined for each axis:

Feature	Unit	Significance
`AccelLimitX`	m/s²	Permissible significant longitudinal acceleration (0 = not tested)
`AccelLimitY`	m/s²	Permissible significant lateral acceleration (0 = not tested)
`AccelLimitZ`	m/s²	Allowable significant vertical acceleration (0 = not tested)
`AccelLimitAbs`	m/s²	Allowable Significant Resulting Acceleration (0 = Unchecked)

The examination is carried out by simple comparison:

PASS ⟺ ai,sig≤Limitifu¨all tested axes iPASS⟺ai,sig≤Limitifu¨all tested axes i

A threshold of **0.0** means "not checked" – this axis is ignored in the status assessment.

Typical limit values for different types of loads:

Load type	Azaz [m/s²]	⎪a⎪⎪a⎪ [m/s²]	Justification
Bulk material (steel)	5.0	8.0	High intrinsic stability
Container (Standard)	3.0	5.0	Container Stack Stable
Paper Rolls	2.0	3.5	Sensitive to falling over
Electronics / Medical	1.5	2.5	Shock-sensitive components
Liquid Cargo (Tanks)	2.0	3.0	Consider Sloshing Effects
Vehicles (cars)	2.5	4.0	Limit safety systems

4.4 Prerequisites and preparation

4.4.1 FreeCAD Document

The active document must contain:

- **RAO dataset** from previous Capytaine analysis (for acceleration calculation)
- **Ship model** (for selecting objects for POI creation, optional)

No further requirements – Points of interest can be created without an existing ship model.

4.4.2 Coordinate System

The POI positions are indicated in the **ship coordinate system** :

Axis	Direction	Unit
xx	Longitudinal (Bug Positive)	Meters
yy	Transversal (starboard positive)	Meters
zz	Vertical (positive upwards, keel at z=0)	Meters

The reference point for all movements is the center of gravity of the ship (as in the RAO analysis).

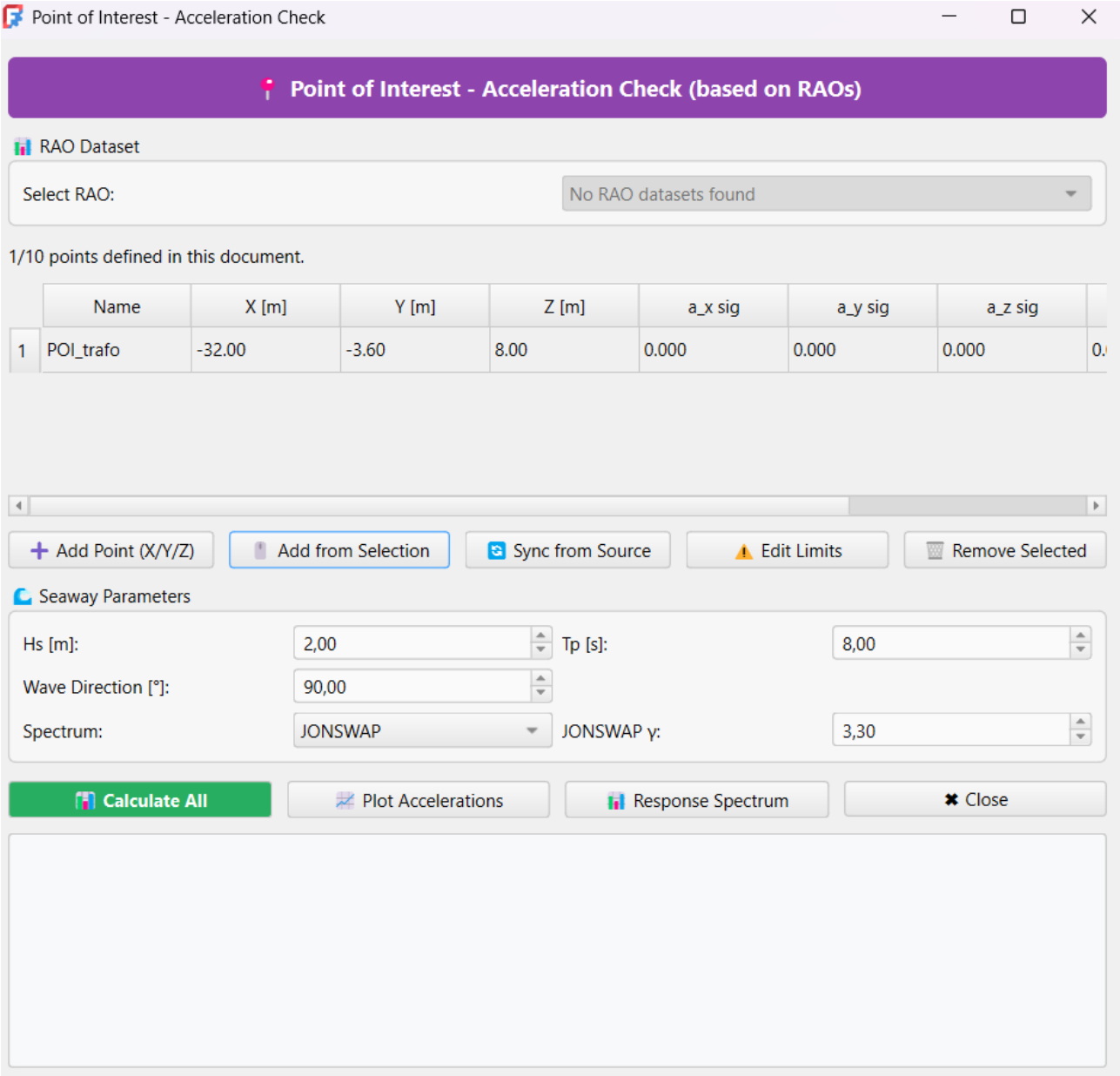
4.4.3 Limiting the number of points

The number of points of interest is limited to **a maximum of 10 points** (constant `MAX_POI`). This is for performance and clarity.

4.5 Instruction manual

4.5.1 Opening the TaskPanel

The POI TaskPanel is started via the corresponding button in the FreeCAD interface:



python

```
from StowMind import PointOfInterestTaskPanel as POITP
POITP.createTask(dataset)
```

After starting, a window will appear with the following sections:

- **RAO Dataset** – Hydrodynamic Dataset Selection
- **Point Table** – Overview of all defined POIs with positions and results
- **Point Management** – Buttons to create, sync and delete
- **Seaway Parameters** – Sea State Parameters for the Calculation
- **Buttons** – Calculation, Plots, Close
- **Results Output** – Calculation Results Text Box

4.5.2 Creating Points of Interest

The module offers two methods for creating POIs:

Method 1: Manual Input (📷 Add Point (X/Y/Z))

- Click Add 📷 **Point (X/Y/Z)**
- In the dialog, enter:
  - **Name:** Descriptive name (e.g., "Container_Stapel_1")
  - **X, Y, Z:** Position in meters in the ship coordinate system
  - **Description:** Free text (e.g. "Lower corner stack 1")
- Confirm with **OK**

Method 2: Selecting a 3D Object (🖱️ Add from Selection)

- In the 3D view, select an object (e.g., a container, a tab, a piece of equipment)
- Click Add 🖱️ **from Selection**
- The name is automatically derived from the object name (editable)
- The position is taken from the **object's Placement.Base** (automatic conversion of mm → m)

Note: When selecting an object, the link is saved as a `SourceObject`. The **position can be updated later** via 🔄 Sync from Source.

4.5.3 Definition of Acceleration Limits

Separate limit values can be defined for each POI:

- Select the desired POI in the table
- Click Edit ⚠ **Limits**
- Enter a limit in m/s² for each axis
    - **0.0** means "not checked" (this axis is ignored)
- Confirm with **OK**

The limit values are stored as properties of the POI object and are retained even after the panel is closed.

4.5.4 Selecting the RAO Dataset

The top drop-down menu lists all RAO records available in the project store. The entries contain information about:

- **Draft** of the analysis
- **Date/timestamp** of creation
- **File name** of the NetCDF

Important: The selected RAO dataset must match the current ship condition.

4.5.5 Sea state parameters

The parameters are set in the **Seaway Parameters** group :

Parameters	Default value	Area	Significance
Hs [m]	2.0	0.1 – 20.0	Significant wave height
Tp [s]	8.0	2.0 – 30.0	Peak period
Wave Direction [°]	90	0 – 360	Wave direction (relative to the ship)
Spectrum	JONSWAP	JONSWAP / Pierson-Moskowitz	Spectrum Type
JONSWAP γ	3.3	1.0 – 10.0	Peak enhancement factor

4.5.6 Start Calculation

Click Calculate 📊 **All** to perform the calculation for all defined POIs.

Calculation process:

- For each POI in the table:
    - Extraction of the position from the POI object
    - Calculation of accelerations with `compute_hook_accelerations()` (identical to crane analysis)
    - Spectral response with `compute_spectral_response_xyz()`
    - Limit value check with `check_limits()`
    - Storage of results on the POI object (`LastAccelX`, `LastAccelY`, `LastAccelZ`, `LastAccelAbs`)
- Updated the table with:
    - Significant accelerations (4 columns)
    - Status indicator: **PASS** (green), **FAIL** (red) or **no limit set** (grey)

4.5.7 Plot Functions

📈 **Plot Accelerations**

- Shows the acceleration amplitudes ax,ay,az,|a|ax,ay,az,|a| over the frequency
- **Limit lines** are entered as dashed lines in the corresponding color
- Useful for identifying resonant frequencies and visually verifying limits

📊 **Response Spectrum**

- Displays the response spectra Sax,Say,Saz,S|a|Sax,Say,Saz,S|a|
- Display as a line plot over the frequency
- Display of significant accelerations as text in the plot

4.5.8 Synchronization of Position Changes

If the `SourceObject` (the original 3D object) has been moved, the position of the POI can be updated:

5. Select the POI in the table
6. Click Sync 🔁 **from Source**
7. The position is re-read from the `Placement.Base` of the source object

Note: The link is **not live** —changes to the source object are not automatically applied.

4.5.9 Deleting Points of Interest

- Select the desired POI in the table
- Click Remove 🗑 **Selected**
- Confirm the deletion

4.6 Results and interpretation

4.6.1 Overview of results in the table

Column	Contents	Significance		
Name	POI designation	Identification		
X, Y, Z [m]	Position	In the ship coordinate system		
a_x sig	Significant longitudinal acceleration	m/s²		
a_y sig	Significant lateral acceleration	m/s²		
a_z sig	Significant vertical acceleration	m/s²		
	a	SIG	Significant resulting acceleration	m/s²
Status	PASS / FAIL / no limit set	Color Rating		

Color coding of the status indicator:

Status	Color	Significance
PASSPORT	Green (#d5f5e3)	All tested axles are within the limit values
FAIL	Red (#fadbd8)	At least one axle exceeds the limit value
No Limit Set	Grey (#dddddd)	No limit values defined – no assessment possible

4.6.2 Significant Accelerations

The significant accelerations are **directly** comparable to the acceleration due to gravity g=9.81 m/s2g=9.81m/s2:

Value	Interpretation
ASIG<0.5 m/s2ASIG<0.5m/s2	Low dynamic load (< 5% of g)
0.5<asig<2.0 m/s20.5<asig<2.0m/s2	Moderate Strain (5–20% of g)
2.0<asig<5.0 m/s22.0<asig<5.0m/s2	High load (20-50% of g)

Value	Interpretation
ASIG>5.0 m/s2ASIG>5.0M/S2	Very high load (> 50% of g) – check fuse

4.6.3 Typical results for different positions

Position	axax	ayay	azaz	|a||a|	Characteristics
Center of gravity (0,0,0)	0.5–1.5	0.5–1.5	1.0–2.5	1.5–3.0	Low lever arms
Bug (+,0,0)	2.0–4.0	1.0–2.0	2.0–4.0	3.0–5.5	Strong through pitch and heave
Heck (-,0,0)	1.5–3.5	1.0–2.0	2.0–4.0	3.0–5.0	Strong by pitch
Starboard (0,+,0)	1.0–2.0	2.0–4.0	2.0–4.0	3.5–5.5	Strong by Roll
High Position (0,0,+)	2.0–4.0	2.0–4.0	1.0–2.0	3.5–5.0	Strong through Pitch and Roll

4.6.4 Influence of wave direction

The accelerations at a POI are strongly dependent on the direction of the wave:

Wave direction	Dominant movement	Critical POI Position
0° (from aft)	Pitch, Heave	Bow and stern positions
90° (from starboard)	Roll, Sway	Starboard and port positions
180° (from the front)	Pitch, Heave	Bow and stern positions
45° / 135°	Combination	Corners and high positions

Recommendation: Perform the analysis for multiple wave directions to identify the worst-case scenario.

4.7 Troubleshooting and Quality Assurance

4.7.1 Common Errors and Solutions

Symptom	Cause	Solution
"No RAO dataset loaded"	No RAO in Project Storage	Perform Capytaine Analysis First
"Maximum of 10 points reached"	Points limit reached	Delete unnecessary POIs
POI shows wrong position	Wrong units (mm instead of m)	enter position in meters; converted from mm in sync
SourceObject found, but position incorrect	Object movement after creation	**Run Sync from Source**
Status remains "no limit set"	No limit values defined	**Edit Running Limits** for the POI
Plot does not appear	Matplotlib backend problem	Backend automatically switched; if necessary, set TKAGG manually
Accelerations negative/implausible	Incorrect units in RAO	Check the RAO dataset for consistency

4.7.2 Plausibility checks

The system performs the following checks during the calculation:

- **Position range:** x,y,zx,y,z within the ship dimensions?
- **Limits:** Non-negative values (0 = not tested)
- **RAO integrity:** presence of 'RAO' or 'RAO_real'/'RAO_imag'
- **Frequency range:** Filtering of unrealistically low frequencies (< 0.1 rad/s)

4.7.3 Debug Mode

The module uses the same debug flag as the crane analysis (`DEBUG_CRANE` in `CraneAnalysis.py`). When debug mode is activated, the following information is output:

- **POI positions** in meters
- **Interim Results** of the Acceleration Calculation
- **Limit check** with detailed PASS/FAIL information

4.7.4 Notes on the quality of the results

- The accuracy of the accelerations depends on the quality of the RAOs (mesh resolution, frequency and directional discretization)
- Spectral integration requires sufficient frequency resolution (at least 30 support points in the relevant area)
- The assumption of linear waves (small amplitudes) is no longer fully valid at Hs>5 mHs>5m
- The calculation does not **take into account** nonlinear effects such as striking side or dynamic trim positions
- **Limit values must be defined by the user** – the system only checks whether they are complied with

---

4.8 Appendix: Technical Reference

4.8.1 Key Features

Function	Parameters	Returns	Description
`create_poi(doc, label, position_m, description)`	Document, Name, Position	POI object	Creates a new POI

Function	Parameters	Returns	Description
	(m), Description		
`create_poi_from_object(doc, label, source_obj, description)`	Document, Name, Source Object, Description	POI object	Creates POI from 3D object
`sync_poi_from_source(poi_obj)`	POI object	(Success, Message)	Updated position from SourceObject
`find_poi_objects(doc)`	Document	List of POIs	Searches for all POIs in the document
`get_poi_position_m(obj)`	POI object	(x, y, z) to m	Reads position in meters
`compute_poi_spectral_response()`	Dataset, POI, Hs, Tp, ...	Spectral results	Calculates spectral response
`check_limits(poi_obj, spec)`	POI, Spectrum	{checks, ok, any_checked}	Checks limit values
`run_poi_calculation()`	Dataset, POI, Hs, Tp, ...	(spec, limits)	Full calculation + limit value check

4.8.2 Data Structures

POI object (App::FeaturePython):

python

```
{
    'Placement': App.Placement, # Position (in mm)
    'Label': 'Container_1', # Name
    'description': 'bottom corner stack 1', # free text
    'SourceObject': <Object>, # Linked 3D object (optional)
    'AccelLimitX': 2.0, # limit in m/s² (0 = not checked)
    'AccelLimitY': 2.0, # limit in m/s² (0 = not checked)
    'AccelLimitZ': 3.0, # limit in m/s² (0 = not checked)
    'AccelLimitAbs': 4.0, # limit in m/s² (0 = not checked)
    'LastAccelX': 0.0, # Last result in m/s²
    'LastAccelY': 0.0, # Last result in m/s²
    'LastAccelZ': 0.0, # Last result in m/s²
    'LastAccelAbs': 0.0, # Last result in m/s²
}
```

Results of the spectral response:

python

```
{
    'a_x_significant': 2.45, # Significant longitudinal acceleration in m/s²
    'a_y_significant': 1.87, # Significant lateral acceleration in m/s²
    'a_z_significant': 3.12, # Significant vertical acceleration in m/s²
    'a_abs_significant': 4.56, # Significant Resulting Acceleration in m/s²
    'omega': array([...]), # frequency array in rad/s
    'S': array([...]), # Swell spectrum
    'S_a_x': array([...]), # response spectrum (x)
    'S_a_y': array([...]), # response spectrum (y)
    'S_a_z': array([...]), # response spectrum (z)
    'S_a_abs': array([...]), # response spectrum (resulting)
    'a_x': array([...]), # transfer function (x)
    'a_y': array([...]), # transfer function (y)
    'a_z': array([...]), # transfer function (z)
    'a_abs': array([...]), # transfer function (resulting)
    'pos': (4.8, -1.5, 12.5), # POI position in meters
    'wave_direction_deg': 90.0,
    'Hs': 2.0,
    'Tp': 8.0,
    'spectrum': 'JONSWAP (γ=3.3)',
    'gamma': 3.3
}
```

Limit value test:

python

```
{
    'checks': {
        'x': True, # PASS (a_x ≤ LimitX)
        'y': True, # PASS (a_y ≤ LimitY)
        'z': False, # FAIL (a_z > LimitZ)
        'abs': None # not checked (limit = 0)
    },
    'ok': False, # Overall rating: FAIL (because 'z' is False)
    'any_checked': True # At least one axis has been checked
}
```

4.8.3 Dependencies

Module/Library	Usage	Note
FreeCAD	CAD data access	Placement, Document Objects
FreeCADGui	3D interaction	Selection of objects, markers
Numpy	Numerical calculations	Arrays, trigonometric functions
matplotlib	Plots	Optional; no graphical output if missing
xarray	RAO Data Access	From Capytaine results
PySide2/PySide6	GUI	Qt bindings for FreeCAD
CraneAnalysis	Core calculations	Reuse of kinematics
PointOfInterest	POI definition	Object Model and View Provider

4.8.4 Constants and Defaults

Constant	Value	Significance
`MAX_POI`	10	Maximum number of points of interest
`PROXY_TYPE`	"StowMindPOI"	Identifier for POI proxy objects
`DEFAULT_COLOR`	(1.0, 0.55, 0.0)	Marker color (orange)
`DEFAULT_SIZE`	150.0 mm	Marker diameter in mm

4.9 Practical application instructions

4.9.1 Workflow for a POI Analysis

- **Preparation:**
    - Create or load ship model in FreeCAD
    - LoadCondition Spreadsheet with Ship Data
    - Perform Capytaine Analysis (Create RAO Dataset)
- **Define points of interest:**
    - Open POI TaskPanel
    - Select RAO dataset
    - Create POIs manually or from 3D objects
    - Define limit values for each POI
- **Perform analysis:**
    - Set swell parameters (Hs, Tp, direction, spectrum)
    - 📊 **Run Calculate All**

    - Check Table for PASS/FAIL
- **Interpreting results:**
    - Identify exceedances
    - Use plots for visual analysis
    - If necessary, adjust limit values or strengthen safety measures
- **Documentation:**
    - Table as screenshot or export
    - Use plots for reports

4.9.2 Recommendations for practice

- **Place POIs at the relevant points:**
    - Corners of containers or cargo pieces
    - Attachment points of lashings
    - Sensitive equipment (machinery, electronics)
    - High points (superstructure, masts)
- **Define realistic limits:**
    - Follow the manufacturer's instructions
    - Consider the type of load securing
    - Use the guideline values given in section 4.3.3 as a starting point
- **Perform several scenarios:**
    - Different wave directions (0°, 45°, 90°, 135°, 180°)
    - Different sea states (light, medium, heavy seas)
    - Variation of spectrum parameters (JONSWAP vs. PM, various γ)
- **Document the results:**
    - Which POIs have FAIL?
    - What accelerations have been exceeded?
    - What measures have been taken?

4.9.3 Typical sources of error and avoidance

Source of error	Avoidance
Wrong units (mm instead of m)	Enter POI positions in meters; converted from mm in sync
No limit values defined	⚠ **Edit Running Limits** for Each POI
Unrealistic limits	Use manufacturer specifications or guideline values
Wrong wave direction	Align direction with actual site conditions
RAO dataset doesn't match	Check Draft and Load Condition
POI in the wrong position	Verify position with 3D view; if necessary, execute sync

4.9.4 Integration with other modules

The POI module is **closely linked to the crane analysis** and uses its entire calculation infrastructure. The consistency of the results is therefore guaranteed.

Advantages of this architecture:

- No duplication of physics code
- Same RAO interpretation as in crane analysis
- Unified Plot Functions
- Reuse of spectral analysis

Limitations:

4. POI analysis uses the same coordinate system convention (center of gravity for reference)
5. The same RAO constraints apply (linear theory, small amplitudes)

4.10 Conclusion

The Points of Interest module is a **lean but powerful extension** of the StowMind suite. It allows the evaluation of accelerations at any point on board without the need to perform a separate crane analysis for each point.

The **tight integration with the CraneAnalysis** ensures consistent physical fundamentals, while the **simple point management** and **clear limit value check** facilitate practical application in ship operation and cargo securing.

With the ability to create POIs both **manually** and **from 3D objects** , and the **automatic synchronization** of position changes, the module offers a high degree of flexibility for various application scenarios – from load securing planning to the inspection of sensitive equipment.

Chapter 5: Operational Planning (Operability Analysis)

5.1 Purpose and scope

The Operability Analysis is used to evaluate the **operability of cranes under varying sea conditions**. It links the results of the hydrodynamic analysis (RAOs) with statistical swell distributions (scatter diagrams) to quantify the **percentage of usability** of a crane for a given load. The analysis provides:

- **Response matrix** of significant hook acceleration azaz over an HsHs and TpTp lattice
- **Dynamic carrying capacity** for any sea state
- **Percentage of operability** taking into account the statistical distribution of sea states
- **Identification of limiting sea states** (which conditions actually limit operational capability)
- **Comparison of different load cases and ships** with regard to their operational readiness
- **Persistence of response matrices** for rapid re-evaluation without recalculation of BEM

Use cases include the planning of lifting operations, the evaluation of operating limits for different load weights, the selection of suitable cranes for specific areas of operation, and the creation of operating boundary diagrams for on-board documentation.

5.2 System Architecture and Module Overview

The system consists of three closely linked modules that implement a **cost-separated architecture** – expensive calculations are performed once and stored persistently, while the actual operability assessment **can be** repeated immediately and as often as desired:

Module	Task	Costs	Running environment
operability_matrix.py	Core calculations: response matrix az(Hs,Tp)az(Hs,Tp) from RAOs, operability assessment, scatter interpolation, vessel comparison	High (BEM + Spectral Integration)	FreeCAD Python environment, can be used independently
operability_storage.py	Persistence of response matrices (NetCDF + JSON index) with metadata (depth, GM, fingerprint)	Low (File I/O)	FreeCAD Python Environment
OperationTaskPanel.py	Graphical user interface (GUI) for calculation, storage, loading, evaluation and comparison	Low (UI)	FreeCAD GUI

The data flow is as follows:

- **FreeCAD Document** with Ship Model, LoadCondition and Crane Objects
- **RAO Dataset Selection** from Project Storage (Capytaine Results)
- **Crane selection** – extraction of hook position and static SWL
- **Load Scatter Chart** – Statistical Swell Distribution (CSV)
- **Calculate response matrix** (expensive, one-off) – az(Hs,Tp)az(Hs,Tp) for all sea states
- **Storage** of the response matrix with metadata (depth, GM, fingerprint)
- **Operability Assessment** (Favorable, Arbitrarily Repeatable) – Application of Static SWL and Load Weight
- **Statistical Evaluation** – Link to Scatter Chart → Operability Percentage
- **Comparison of different load cases** – ranking according to operational readiness

---

5.3 Physical basics

5.3.1 The Response Matrix – az(Hs,Tp)az(Hs,Tp)

The response matrix is the central intermediate result of the operability analysis. It contains the significant vertical hook acceleration azaz for each pair of values of significant wave height HsHs and peak period TpTp:

az(Hs,Tp)=4 · ∫0∞Sζζ(ω; Hs,Tp) · |Hz(ω)|2 dωaz(Hs,Tp)=4 · ∫0∞Sζζ(ω; Hs,Tp) · |Hz(ω)|2dω

Where:

- Sζζ(ω; Hs,Tp)Sζζ(ω; Hs,Tp): Swell spectrum (JONSWAP or Pierson-Moskowitz)
- Hz(ω)Hz(ω): Transfer function from the wave amplitude to the vertical acceleration on the hook
- ωω: Circular frequency [rad/s]

The transfer function Hz(ω)Hz(ω) is calculated from the complex superposition of the RAOs at the hook point (see Chapter 2.3.1).

Special feature: The response matrix does not depend on the crane SWL or the weight to be lifted. It is a purely sea-specific property of the ship and the hook position. This is the key to differentiated architecture.

5.3.2 Directional averaging

The response matrix can be formed in two ways:

Worst-Case (Standard): For each (Hs,Tp)(Hs,Tp) pair, the highest acceleration across all wave directions is chosen. This is the conservative approach for the planning phase when the wave direction is not yet determined.

az(Hs,Tp)=maxθaz(Hs,Tp,θ)az(Hs,Tp)=θmaxaz(Hs,Tp,θ)

Mean: The mean value is formed over all directions. This makes sense if the wave direction is statistically evenly distributed.

az(Hs,Tp)=1Nθ∑θaz(Hs,Tp,θ)az(Hs,Tp)=Nθ1θ∑az(Hs,Tp,θ)

5.3.3 Dynamic Load Capacity and Operability

The dynamic carrying capacity for a sea state results from the static SWL and the significant vertical acceleration:

SWLdyn(Hs,Tp)=SWLstat · gg+az(Hs,Tp)SWLdyn(Hs,Tp)=SWLstat · g+az(Hs,Tp)g

A sea state is considered **operable** if the dynamic carrying capacity is greater than or equal to the required load:

operable(Hs,Tp) ⟺ SWLdyn(Hs,Tp)≥Lerfoperabel(Hs,Tp)⟺SWLdyn(Hs,Tp)≥Lerf

5.3.4 Statistical operability (scatter chart)

The **total operability** results from the weighted sum of all operable sea states, weighted by their probability of occurrence from the scatter diagram:

Operabilita¨t[%]=100 · ∑operabelP(Hs,Tp)∑alleP(Hs,Tp)Operabilita
¨t[%]=100 · ∑alleP(Hs,Tp)∑operabelP(Hs,Tp)

The scatter chart contains the **relative frequency** of swell conditions at a given location. Typical sources include:

- **North Sea:** GONO (German Oceanographic Datacentre) or DNV statistics
- **Global:** Global sea state catalogue (e.g. ERA5, ESA CCI)
- **Site-specific measurements:** From buoys or ship measurements

Format of the scatter chart:

Hs\Tp	3.0s	4.0s	5.0s	6.0s	...
0.5m	0.12	0.18	0.25	0.20	...
1.0m	0.08	0.15	0.22	0.18	...
1.5m	0.05	0.10	0.18	0.15	...

Hs\Tp	3.0s	4.0s	5.0s	6.0s	...
2.0m	0.02	0.05	0.12	0.10	...

The values can be available as a percentage (sum = 100%), per mille (sum = 1000 ‰) or absolute frequencies (sum variable) – the system normalizes automatically.

5.3.5 Differentiated architecture – justification

The calculation of the response matrix az(Hs,Tp)az(Hs,Tp) is computationally intensive because:

- For each wave direction the RAOs need to be calculated at the hook point
- For each (Hs,Tp)(Hs,Tp) pair, a spectral integration is performed
- A typical grid with 12×13=15612×13=156 cells and 1212 directions ≈1,872≈1,872 individual calculations requires

The **operability assessment** , on the other hand, is very fast:

- Elementary arithmetic only (g/(g+az)g/(g+az), comparison with load)
- No BEM, no spectral integration
- Can respond to user input in real-time

Architectural consequence:

- The response matrix is **calculated and** stored **once**
- The operability assessment can be performed **as many times as you want** with different SWLs, loads, and scatter graphs
- A **comparison of different load cases** is possible without recalculation

---

5.4 Prerequisites and preparation

5.4.1 FreeCAD Document

The active document must contain:

- **Ship model** as solid (for fingerprint and load condition)
- **LoadCondition spreadsheet** with ship data (draft, GM, mass)
- **Crane objects** of the type `StowMindCrane` or `ShipCrane` (for hook position and SWL)
- **RAO dataset** from previous Capytaine analysis

5.4.2 Scatter Chart (CSV)

The scatter chart must be in **CSV format** :

Columns: Tp-Bin Centers in Seconds (First Cell Empty)
Lines: Hs-Bin centers in meters (first cell, then probabilities)

Example:

Text

```
,Tp=3.0,Tp=4.0,Tp=5.0,Tp=6.0,Tp=7.0,Tp=8.0,Tp=9.0,Tp=10.0,Tp=11.0,Tp=12.0,Tp=13.0,Tp=14.0,Tp=15.0,Tp=16.0
Hs=0.5,0.12,0.18,0.25,0.20,0.12,0.06,0.03,0.02,0.01,0.01,0.00,0.00,0.00,0.00,0.00
Hs=1.0,0.08,0.15,0.22,0.18,0.12,0.08,0.05,0.03,0.02,0.01,0.01,0.01,0.00,0.00
...
```

The values are **automatically normalized** – you can use absolute frequencies, per mille or percentage.

5.4.3 Location of the Response Matrices

The response matrices are stored in the `~/StowMind/operability/` directory :

File	Contents
`index.json`	Metadata (ship name, load case, draught, GM, fingerprint, time stamp)
`<vessel>__<load_case>.nc`	NetCDF file with the response matrix (azaz, directional angles if necessary)

The **fingerprint** (hash of hull volume, dimensions, draft and GM) is used to detect changes – if the model or load condition changes, the stored matrix is marked as stale.

5.4.4 Use of viscous RAO

The response matrix is calculated from the RAO of the selected dataset. If the `.nc` file contains `RAO_viscous` and `prefer_viscous_rao = 1` is set, the viscous RAO flows into the matrix. Otherwise, the potential RAO.

Important consequence:

The response matrix and `the prefer_viscous_rao` flag are **not** linked. If you change the viscous RAO (e.g. different cd values) after creating a response matrix, the response matrix must **be recalculated**. The system does not automatically detect this.

Recommendation: When switching between potential and viscous, always go through the entire chain again:

- Capytaine: `Apply viscous damping` (if you haven't already)
- Operability: `Compute Response Matrix` (new, with viscous RAO)
- Operability: `Evaluate` (on the new matrix)

Impact on Operability Results:

- The viscous RAO reduces roll accelerations → lower `a_z(Hs,Tp)` in the response matrix → higher dynamic SWL → **higher operability**.
- For a heavy-lift vessel with a sway keel, operability can increase by 5-15 percentage points.
- The effect is greatest in middle periods (Tp = 6–10 s) because the roll resonance is most strongly stimulated there.

5.5 Instruction Manual

5.5.1 Opening the TaskPanel

The Operation-TaskPanel is started via the corresponding button in the FreeCAD interface:

python

```
from StowMind import OperationTaskPanel as OTP
OTP.createTask(dataset, hull_shape)
```

Once launched, a window with three tabs will appear:

5. **1. Compute / Save** – Calculation and storage of the response matrix
6. **2. Evaluate** – Load and evaluate operability
7. **3. Compare Vessels** – Comparison of different ships/load cases

5.5.2 Selecting a RAO Dataset

At the top of the panel is the Combobox **RAO Dataset**. This lists all RAO datasets available in the project storage. The entries include:

- **Depth** of the analysis
- **Date/timestamp** of creation
- **File name** of the NetCDF

Important: The selected RAO dataset must match the current ship condition.

5.5.3 Tab 1: Compute/Save – Compute and Storage

Load Condition:

- Automatically read from the LoadCondition spreadsheet
- Display of **Draft [m]** and **GM [m]**

Crane selection:

- Selecting the crane from the drop-down list
- Display of **hook position [m]** and **static SWL [t]**

Scatter Grid:

Parameters	Default value	Significance
Hs max [m]	6.0	Maximum significant wave height
Hs step [m]	0.5	Step size of wave height
Tp max [s]	16.0	Maximum peak period
Tp step [s]	1.0	Period step size
Direction step [deg]	30	Step size of wave direction (for worst-case sweep)

Note: If a scatter chart is already loaded (tab 2), its bins will be automatically applied – the manual settings will then be ignored.

Start calculation:

Click Compute 📊 **& Save Response Matrix**. The calculation can take several minutes, depending on the grid size and the number of directions .

After successful calculation:

- The response matrix is stored in the `~/StowMind/operability/` directory
- The entry appears in the list of saved matrices
- The status is displayed in the text box

5.5.4 Tab 2: Evaluate - Operability Assessment

1. Load Saved Matrix:

4. Select an entry from the drop-down list
5. Click Load
6. The metadata (draft, GM, save time, SWL) is displayed

2. Load Scatter Chart:

- Click Load 📁 **Scatter CSV**
- Select a CSV file in the format described
- The status shows the dimensions of the loaded scatter chart

3. Evaluate operability:

- Enter the **required load [t]** (80 t by default)
- Click Evaluate ⚙️ **Operability**

Results:

The text box shows:

Text

```
Operability: 78.3%
Static SWL: 120.0t
Dynamic SWL at these conditions: 95.2t (worst-case reduction)
Required: 80.0t

Top limiting sea states (non-operable, by probability):
  Hs=2.5m Tp=6.0s (p=1.85%)
  Hs=3.0m Tp=7.0s (p=1.23%)
  Hs=3.5m Tp=8.0s (p=0.67%)
  ...
```

The **limiting swell states** are those states that actually limit operability – not the absolute worst state, but those with the highest probability of occurrence that are not operable.

Interpretation of operability:

Operability	Rating	Significance
> 95%	Amazing	Crane can be used almost without restriction
85–95 %	Good	Minor restrictions in extreme seas
70–85 %	Satisfactory	Noticeable restrictions – operational planning required
50–70 %	Sufficient	Significant restrictions – only in case of favorable weather forecast
< 50%	Insufficient	Crane is not suitable for this location

5.5.5 Tab 3: Compare Vessels – Comparison of Different Load Cases

This tab allows you to **compare multiple stored response matrices** for their operability under the same scatter graph and the same required load.

Procedure:

- **Select entries:** Select the entries to be compared in the list (multiple selection with Ctrl+click)
- **Refresh:** Click ↻ **Refresh List** to refresh the list
- **Start a comparison:** Click Compare 🏆 **Selected**

Result:

The table shows:

Vessel / Load Case	Operability %
MV Nordwind / Draft 8.5m GM 1.8m	82.3 %
MV Nordwind / Draft 8.5m GM 2.4m	87.1 %
MV Ostwind / Draft 9.2m GM 2.0m	79.5 %

Application examples:

- Comparison of different **ballast states** (different GM)
- Comparison of different **cranes** on the same ship
- Comparison of different **ships** for a given operation

5.6 Results and interpretation

5.6.1 The Response Matrix – az(Hs,Tp)az(Hs,Tp)

The response matrix can be visualized as **a heat map** (not included in the panel, but possible with your own script):

Text

```
Tp [s] → 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Hs [m] ↓
0.5       0.5 0.6 0.7 0.8 0.9 0.9 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2
1.0       0.9 1.1 1.3 1.5 1.6 1.7 1.6 1.5 1.3 1.1 0.9 0.7 0.5 0.4
1.5       1.3 1.6 1.9 2.2 2.4 2.5 2.4 2.2 1.9 1.6 1.3 1.0 0.8 0.6
2.0       1.8 2.1 2.5 2.9 3.2 3.3 3.2 2.9 2.5 2.1 1.8 1.4 1.0 0.8
2.5       2.2 2.6 3.1 3.6 4.0 4.1 4.0 3.6 3.1 2.6 2.2 1.7 1.3 1.0
3.0       2.6 3.1 3.7 4.3 4.8 4.9 4.8 4.3 3.7 3.1 2.6 2.0 1.5 1.2
3.5       3.0 3.6 4.3 5.0 5.6 5.7 5.6 5.0 4.3 3.6 3.0 2.3 1.8 1.4
...
```

Observations:

3. The highest accelerations occur during **middle periods** (5–9 s) – this is the typical resonance region
4. During very long periods (> 12 s), the accelerations decrease (the ship follows the waves)
5. Acceleration scales linearly with HsHs

5.6.2 Dynamic SWL and Operability Map

The response matrix and the static SWL result in the **dynamic SWL**:

SWLdyn(Hs,Tp)=SWLstat⋅gg+az(Hs,Tp)SWLdyn(Hs,Tp)=SWLstat⋅g+az(Hs,Tp)g

The **operability map** shows for each sea state whether the required load can be lifted:

Text

```
Tp [s] → 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Hs [m] ↓
```



5.6.3 Limiting Sea States

The output of the limiting sea states is particularly valuable for **operational planning**:

Text

```
Top limiting sea states (non-operable, by probability):
  Hs=2.5m Tp=6.0s (p=1.85%)
  Hs=3.0m Tp=7.0s (p=1.23%)
  Hs=3.5m Tp=8.0s (p=0.67%)
```

Interpretation:

- The state Hs=2.5 m,Tp=6.0 sHs=2.5m,Tp=6.0s occurs with 1.85 % probability and is **not operable**
- This state is the **single largest contributor** to non-operability
- Improvement measures should target this condition (e.g. reduction of the load, different crane position)

Important difference to the worst-case scenario:

- The **worst-case** scenario (Hs=6.0 m,Tp=8.0 sHs=6.0m,Tp=8.0s) may only occur with 0.01%
- The **limiting state** is the one with the **highest probability**, which is inoperable – it has the greatest impact on overall operability

5.6.4 Influence of ship and load condition

The **dynamic influence of GM and depth** on operability:

Condition	Draft [m]	GM [m]	azaz at Hs=3 m,Tp=8 sHs=3m,Tp=8s	Operability
Ballast	5.0	2.5	3.2 m/s²	82 %
Half full	7.5	1.8	3.8 m/s²	74 %
Full	9.5	1.2	4.5 m/s²	61 %

Interpretation:

- **Ballast condition:** Higher GM → lower rolling movements → lower accelerations → higher operability
- **Full state:** Lower GM → stronger rolling motions → higher accelerations → lower operability
- The **load condition** has a significant influence on the operational capability

---

5.7 Troubleshooting and Quality Assurance

5.7.1 Common Errors and Solutions

Symptom	Cause	Solution
"No RAO dataset – run Capytaine first"	No RAO in Project Storage	Perform Capytaine Analysis
"No hook position – select a crane"	No crane in the document or no hook position	Create Crane Object or Check LoadCondition
"Scatter interpolation failed"	Scatter grid deviates from response matrix	Create Scatters with Equal Bins or Allow Interpolation
"No valid entries loaded"	Selected matrices are missing or damaged	Recalculate Matrix
Fingerprint does not match	Hull/Load Condition Changed	Recalculate Response Matrix
Calculation very slow	Grids that are too large or too many directions	Increase Hs/Tp Step or Reduce Directional Resolution
Operability = 0%	SWL too low or load too high	Choose a larger crane or lower load

5.7.2 Plausibility checks

The system performs the following checks during the calculation:

- **RAO integrity:** presence of 'RAO' or 'RAO_real'/'RAO_imag'
- **Hook position:** Within the ship's dimensions?
- **Scatter normalization:** Sum of probabilities = 1 (after normalization)
- **Dynamic SWL:** Non-negative and plausible (SWL_reduziert ≤ SWL_statisch)
- **Fingerprint:** Detection of changes to hull or load condition

5.7.3 Fingerprint – Change Detection

The fingerprint is made up of the following quantities:

- Hull Volume
- Hull dimensions (X, Y, Z length)
- Draft [m]
- GM [m]

In case of changes (e.g. model changed, load condition updated), the saved matrix is marked as **stale** .

The fingerprint also contains a hash of the appendages.json since version X. If the viscous configuration is changed (different `cd`, different `height`, different `zeta_a`), the fingerprint changes and the stored response matrix is marked as stale.

When loading a stale matrix, the warning appears:

WARNING: stored matrix fingerprint does not match current appendages config.
Please re-run compute_response_matrix() before trusting this entry. The system warns when loading:

Text

```
⚠ WARNING: stored matrix fingerprint does not match current hull/draft/GM.
   Please re-run compute_response_matrix() before trusting this entry.
```

5.7.4 Notes on the quality of results

- The **response matrix** is valid only for the **specific load condition** (Draft, GM, Trim)
- The **scatter statistic** must be representative **of the** location
- **Worst-case directional averaging** is conservative – for location-specific directional statistics, the mean is more appropriate
- The **drift forces** are not taken into account in the operability analysis (vertical acceleration only)

5.8 Appendix: Technical Reference

5.8.1 Key Features

Function	Parameters	Returns
`compute_response_matrix()`	Dataset, Hook-Pos, Hs/Tp-Bins, Directions, Mode	Response Matrix Dict

Function	Parameters	Returns
`evaluate_operability()`	Response Matrix, SWL, Load	Operability dict
`apply_wave_scatter()`	Evaluate-Result, Scatter-P	Operability Percent
`interpolate_scatter_to_response_grid()`	Scatter Grid, Response Grid	Interpolated P
`compare_vessel_operability()`	List of entries, scatter, load	Ranking List
`save_response_matrix()`	Response matrix, metadata	Key
`load_response_matrix()`	Vessel-Name, Load-Case	(Matrix, Metadata)
`list_entries()`	optional: vessel name	Index Entries
`check_stale()`	Vessel-Name, Load-Case, Hull, Draft, GM	Bool

5.8.2 Data Structures

Response Matrix (response_matrix):

python

```
{
    'Hs_bins': array([0.5, 1.0, 1.5, ...]), # m
    'Tp_bins': array([3.0, 4.0, 5.0, ...]), #s
    'directions_deg': array([0, 30, 60, ...]), # °
    'a_z_sig': ndarray(n_Hs, n_Tp), # m/s²
    'governing_direction_deg': ndarray(n_Hs, n_Tp), #° (at worst_case)
    'direction_mode': 'worst_case' | 'mean',
    'spectrum': 'jonswap' | 'pm',
    'gamma': 3.3,
}
```

Operability result (evaluate_operability):

python

```
{
```

```
    'Hs_bins': array([...]),
    'Tp_bins': array([...]),
    'dyn_swl_t': ndarray(n_Hs, n_Tp), #t
    'reduction_factor': ndarray(n_Hs, n_Tp), # g/(g+a_z)
    'operable': ndarray(n_Hs, n_Tp, dtype=bool),
    'swl_static': 120.0, #t
    'required_load_t': 80.0, #t
}
```

Scatter Evaluation (apply_wave_scatter):

python

```
{
    'operability_pct': 78.3, # %
    'covered_prob': 0.783, # normal probability
    'total_prob': 1.0, # Sum after normalization
    'excluded_cells': [ # Top 10 limiting states
        (2.5, 6.0, 0.0185),
        (3.0, 7.0, 0.0123),
        ...
    ]
}
```

Index entry (index.json):

json

```
{
  "MV_Nordwind__Draft_8.50m_GM_1.80m": {
    "vessel_name": "MV Nordwind",
    "load_case_label": "Draft_8.50m_GM_1.80m",
    "nc_path":
"/home/user/StowMind/operability/MV_Nordwind__Draft_8.50m_GM_1.80m.nc",
    "source_nc_path": "/home/user/StowMind/project/2026-08-14_RAO.nc",
    "hook_pos_m": [4.8, -1.5, 12.5],
    "swl_static_t": 120.0,
    "draft_m": 8.5,
    "gm_m": 1.8,
    "hull_fingerprint": "a3f4e7b2c1d9",
    "notes": "worst-case direction sweep, 30 deg steps",
```

```
    "saved_at": "2026-08-14 15:30:22"
  }
}
```

5.8.3 Dependencies

Module/Library	Usage	Note
FreeCAD	CAD data access	LoadCondition, Crane Objects, Hull Shape
Numpy	Numerical calculations	Arrays, vectorization
xarray	NetCDF I/O	Saving and loading the response matrices
scipy	Interpolation	RegularGridInterpolator for Scatter Interpolation
matplotlib	Optional plots	Response matrix heatmaps (not in the panel)
CSV	Input	Scatter Chart Import
JSON	Metadata	Index file for stored matrices
hashlib	Fingerprint	SHA1 hash for change detection
CraneAnalysis	Core calculations	RAO Extraction, Spectral Analysis
CapytaineTools	LoadCondition	Read Draft, GM, Mass
project_storage	RAO Access	Loading RAO datasets

5.8.4 Memory Path and Configuration

Constant	Value	Significance
`STORAGE_DIR`	`~/StowMind/operability/`	Home directory for stored matrices
`INDEX_PATH`	`~/StowMind/operability/index.json`	Metadata Index
NetCDF file	`<vessel>__<load_case>.nc`	Response Matrix
Scatter CSV	Custom	Input for Scatter Chart

5.9 Practical application instructions

5.9.1 Workflow for an Operability Analysis

4. **Preparation:**
    - Create or load ship model in FreeCAD
    - LoadCondition spreadsheet with ship data (draft, GM, mass)
    - Perform Capytaine Analysis (Create RAO Dataset)
    - Create a crane object in the document or use an existing crane
5. **Get Scatter Chart:**

- Obtain site-specific statistics (e.g. GONO, DNV, measurements)
- Prepare in CSV format (see Section 5.4.2)

6. **Calculate Response Matrix (One-Time):**
    - Open Operation TaskPanel
    - Select RAO dataset
    - Select crane (hook position and SWL are adopted)
    - Set Grid Parameters (or Load Scatter Graph)
    - 📊 **Run Compute & Save Response Matrix**
    - Wait – calculation can take several minutes
7. **Evaluate operability (as often as you like):**
    - Tab 2 **. Evaluate**
    - Load Saved Matrix
    - Load scatter graph (if not already used in compute)
    - Enter the required load
    - ⚙️ **Run Evaluate Operability**
    - Check operability percentage and limiting conditions
8. **Comparison and optimization:**
    - Tab 3 **. Compare Vessels**
    - Compare different load cases (ballast, full)
    - Compare different crane or hook positions
    - Use operability results to make decisions

5.9.2 Recommendations for practice

- **Grid Resolution:**
    - HsHs increment: 0.5 m for rough overview, 0.25 m for detailed analysis
    - TpTp increment: 1.0 s for rough overview, 0.5 s for detailed analysis
    - Directional step size: 30° for overview, 15° for detailed analysis
- **Scatter Chart:**
    - Use representative location statistics
    - Update statistics in case of changes in the area of operation

    - Consider seasonal fluctuations
- **Worst-case vs. mean:**
    - Use **worst-case** for conservative planning (if the wave direction is not fixed)
    - Use **Mean** for Location-Specific Analysis with Directional Statistics
- **Operability goals:**
    - For scheduled operations: > 85% target
    - For critical operations: > 95% targeted
    - For emergency operations: > 70% acceptable

5.9.3 Typical sources of error and avoidance

Source of error	Avoidance
Wrong RAO Draft	Select the RAO dataset with the appropriate depth
Wrong hook position	Check Hook Position from Crane Object or LoadCondition
Wrong SWL	Check SWL from Crane Object or Load Stages
Scatter grid mismatch	Create Scatters with Equal Bins or Allow Interpolation
Outdated response matrix	Recalculate on changes to hull or load condition
Unrealistic operability	Compare results with empirical values and operating limits

5.9.4 Integration with other modules

The operability analysis is the **parenthesis** between:

- **Capytaine (Chapter 1):** Provides the RAOs as input
- **CraneAnalysis (Chapter 2):** Provides the acceleration transmission on the hook
- **MooringAnalysis (Chapter 3):** Returns the static displacement (not directly used, but relevant for completeness)
- **POI (Chapter 4):** Analogy – Accelerations at Arbitrary Points

The **response matrix** is the link between **hydrodynamic analysis** (expensive) and **operational decision-making** (cheap).

5.10 Conclusion

The Operability Analysis is a **strategic extension** of the StowMind suite. It translates the results of the hydrodynamic analysis into a **practical, decision-relevant metric**: the percentage of operational capability of a crane under real sea conditions.

The **cost-separated architecture** (expensive calculation once, favorable valuation as often as desired) enables:

6. **Fast "what-if" analyses** – different loads, cranes or scatter diagrams without recalculation
7. **Comparison of different load cases** – ballast vs. full, different GM
8. **Comparison of different ships** – for tenders or fleet management
9. **Identification of the actual limitations** – not the most extreme swell, but the most likely non-operable conditions

The **persistence of the response matrices** ensures that computational time is not lost once invested – the results are available for different scenarios and users.

With the ability to import scatter diagrams and calculate operability for any load, the Operational Readiness Analysis provides a **powerful tool** for **operational planning, crane selection, and operational limit assessment**.

Appendix A: Appendages Configuration (appendages.json)

A.1 File Format

```
{
  "bilge_keels": [
    {
      "x0": -45.0,
      "x1": 25.0,
      "y": 8.5,
      "z": -4.0,
      "height": 0.6,
      "cd": 5.0,
      "cm": 1.0,
      "n_seg": 8,
      "mirror": true
    }
  ],
  "fins": [
    {
      "name": "rudder",
      "x": -50.0,
      "z": -3.0,
      "axis": "vertical",
      "length": 5.0,
      "chord": 3.0,
      "clalpha": 0.0,
      "cd": 1.0,
      "cm": 1.0,
      "r": 1.0
    }
  ],
  "zeta_a": 1.0,
  "model": "regular",
  "seastate_Hs": 2.0,
  "seastate_Tp": 8.0
}
```

A.2 Parameter description

Bilge Keels:

Field	Unit	Significance	Recommended range
x0, x1	m	Start/End Position in Longitudinal Direction (Midship = 0)	−0.35· LOA to +0.20· LOA
y	m	Transverse position (on hull surface)	0.85· (B/2)
z	m	Vertical Position (Bilge-Buckling)	0.65· Draft
height	m	Keel width (radially protruding)	0.3–0.6
cd	–	Lateral drag coefficient	4.0–6.0
cm	–	Additional mass	1.0

Field	Unit	Significance	Recommended range
		coefficient	
n_seg	–	Number of segments per page	6–10
mirror	bool	Both sides (true) or only one (false)	true

Fins/Rudders:

Field	Unit	Significance	Recommended range
Name	–	Description	"Rudder", "Fin_Port" etc.
x	m	Force Attack Point (1/4 Tendon)	−0.48· LOA (Rudder)
z	m	Vertical Position	−0.5· Draft
AXIS	–	`vertical` (rudder) or `horizontal` (fin)	vertical
length	m	Wingspan	3–6
Chord	m	Tendon	2–4
clalpha	1/wheel	Buoyancy gradient	0 (without drive) or 2π (with drive)
cd	–	Lateral drag coefficient	1.0

A.3 Where the file is located

The `appendages.json` is saved **in the project folder** (next to the `. FCStd` file). If no file exists, the default configuration is used when the dialog is opened for the first time and the file is created when the file is saved.

Not in the module folder — this is a common mistake. The module folder contains only the Python files. The `appendages.json` belongs to the respective project.

A.4 Check configuration via console

```
import FreeCAD as App
from freecad.stowmind.stowmindSeakeeping import appendages as APP
cfg = APP.load(doc=App.ActiveDocument)
print(cfg)
```

If there are different values than expected, either the wrong file is loaded (module folder instead of project folder) or the change was not saved.

Summary of changes

#	Section	Art	Contents
1	1.3.2	Enlargement	Viscous damping as a supplement to potential theory
2	1.3.5	**New**	Trim calculation from B11/C11/D11
3	1.4.2	Enlargement	B11/C11/D11 in the LoadCondition table
4	1.5.3	Enlargement	Appendages Parameters and `zeta_a` Guidelines
5	1.5.6	**New**	Dialog "Configure appendages" and "Apply viscous damping"
6	1.6.3	Enlargement	RAO plot with two curves (potential + viscous)
7	1.7.2	Enlargement	PDF report with viscous configuration
8	1.9	**New**	Physical Principles and Practice of Viscous Damping
9	2.4.5	**New**	Crane: Use of viscous RAO
10	3.4.5	**New**	Mooring: Use of viscous RAO
11	5.4.4	**New**	Operability: Use of viscous RAO
12	5.7.3	Enlargement	Appendages hash in the fingerprint
13	Appendix A	**New**	Appendages JSON Format

Sections 2.4.5, 3.4.5 and 5.4.4 are the **most important innovations** — they document that the viscous RAO can be used as the basis for all downstream modules (crane, mooring, operability). This was not possible before and is now the central added value of the module.