Ship Performance Simulator
Methods and Procedures

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CONTENTS

1 LIST OF SYMBOLS

Symbol	Computer Symbol	Unit	Description
A_E/A_0	AE/A0	-	Expanded blade area ratio
A_V	AV	m²	Wind main section area
A_X	AX	m²	Main section area from keel to top
B_{OA}	BOA	m	Width overall
B_{WL}	BWL	m	Max. breadth of water line
c_{AAS}	CAAS	-	Windage resistance coefficient
c_{APP}	CAPP	-	Appendage resistance coefficient
c_B	CB	-	Block coefficient at actual draft related to LOS, BOA
c_{BK}	CBK	-	Bilge keel resistance coefficient
c_P	CP	-	Prismatic coefficient at actual draft related to LOS
c_{RUDD}	CRUDD	-	Rudder resistance coefficient
D	D	m	Propeller diameter
$\boldsymbol{D_{modelled}}$	DMOD	m	Depth of ship as modelled
F_C	FC	kN	Correlation force to account for hull roughness
Fd	FD	kN	Skin friction correction
F_R	FN	-	Froude number
F_X	FX	kN	Native CFD force in x-direction, integrated over hull
J	J	-	Propeller advance ratio
k_i	KI	-	Resistance component due to appendages
$\overline{\boldsymbol{KM_T}}$	KMT	m	Transverse metacentric height above base line
K_Q	KQ	-	Torque coefficient
K_T	KT	-	Thrust coefficient
k_t	KT	-	Empirical thrust deduction correction factor
L_{CB}	XCB	m	Longitudinal center of buoyancy from aft perpendicular
L_{OA}	LOA	m	Length overall
L_{OS}	LOS	m	Length of submerged hull (transom to bulb tip)
L_{PP}	LPP	m	Length between perpendiculars
N_P	NP	1/s	Rate of revolution
P/D	P/D	-	Pitch ratio of propeller blades
P_D	PD	kW	Delivered power
P_E*	PE*	kW	Effective power derived from self-propulsion analysis
q	Q	Pa	Dynamic pressure density
R	R	kN	Resistance
R_{AAS}	RAAS	kN	Added resistance due to windage
R_{APP}	RAPP	kN	Appendage resistance
R_{CORR}	RCORR	kN	Resistance component due to roughness
R_T*	RT*	kN	Total resistance derived from self-propulsion analysis
S	S	m²	Wetted surface (dynamic)
S_0	WSA	m²	Wetted surface area (static)
S_{RUDD}	SRUDD	m²	Projected rudder area (one-sided)
T	T	m	Draft

T_A	TA	m	Draft at aft perpendicular
T_F	TF	m	Draft at forward perpendicular
T_M	TM	m	Mean draft
T_{des}	T_des	m	Moulded draft at design condition (level trim)
T_{sca}	T_sca	m	Moulded draft at scantling (level trim)
t	t	-	Thrust deduction fraction
T	TH	kN	Thrust force
T_T	THT	kN	Total thrust force
t^*	TSTAR	-	Uncorrected thrust deduct fraction
v	v	kn	Ship speed in knots
v_A	VA	m/s	Advance speed of propeller
v_S	VS	m/s	Ship speed
w	w	-	Wake fraction number
X_{CB}	XCB	m	Longitudinal center of buoyancy
Z	NPB	-	Number of propeller blades
Δ_{CF}	DCF	-	Ship correlation factor
η_D	ETAD	-	Propulsive efficiency
η_H	ETAH	-	Hull efficiency
H_O	ETAO	-	Open water efficiency of the propeller
η_R	ETAR	-	Relative rotative efficiency
λ	LAMBDA	-	Volumetric scale factor for benchmarking purposes
ρ	RHO	kg/m³	Density
∇	DISPL	t	Displacement of bare hull without shell and appendages

2 COMPUTATIONAL PROCEDURE

All CFD computations are carried out at full-scale with a State-of-the-Art RANS[1] VoF[2] CFD[3] solver. RANSE means that viscosity is directly reflected in the basic physics, i.e. boundary layer formation and flow separation can be captured by the fundamental equations. VoF means that complex wave formation including breaking waves is accurately reflected in the numerical model. And "full-scale" means that the simulation mimics sea trial, avoiding the notorious scale-effects that come with model test extrapolation to full scale. This is especially important if larger breaking waves appear, e.g. at intermediate drafts or blunt foreships, Hochkirch and Mallol (2013)[4].

2.1 Domain size and grid generation

An unstructured full-hexahedral meshing tool is used for grid generation. All calculations are carried out assuming symmetry in the y-Plane. The domain size is chosen to account for unrestricted and deep water.

A standard grid setup is used, i.e. cells are clustered around the ship hull with a cell size of ~ 0.1 % of ship length on the hull surfaces. Near areas with expected large changes in flow, the grid is refined to cell sizes of ~ 0.012 % of ship length. To accurately capture the free surface, the grid is refined to cell sizes of ~ 0.001 % of ship length in z-direction close to the expected interface location.

For accurate capturing of flow gradients in the boundary layer, extrusion cell layers normal to the ship hull surfaces are generated with a target $y+ \geq 30$ (cell height normal to wall of ~ 0.008 % of ship length).

The resulting size of the computational grid ranges from about 3 to 5 Mio cells. Figure 1 shows an example of the resulting mesh.

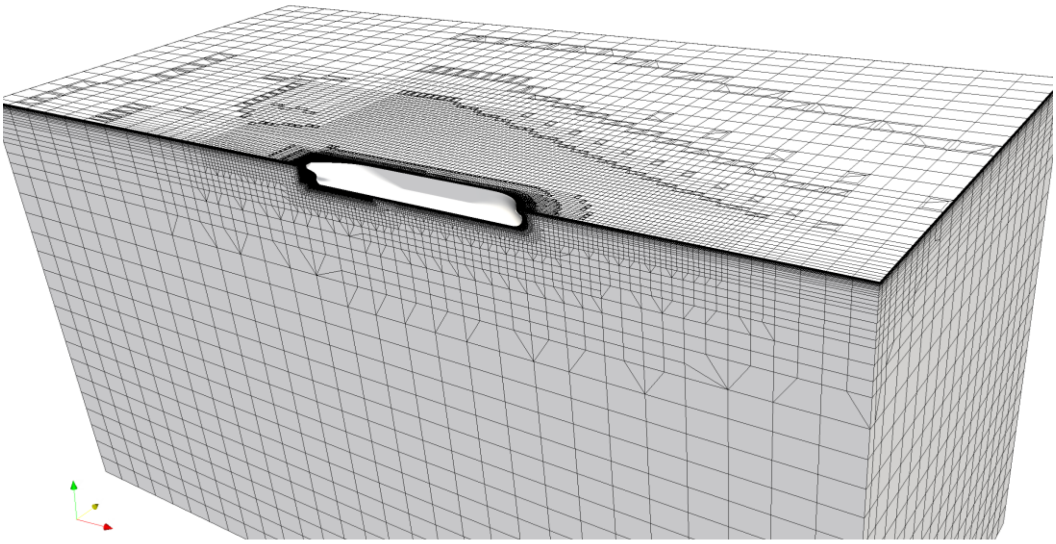

Figure 1: Typical Computational grid with refinements towards the hull surfaces and the free surface

2.2 Ship motions

For all Ship Performance Simulator computations, the ship model is free to heave and trim, i.e. the heave and pitch motions are solved for. Heel, yaw and sway motion are fixed and the forward translation is imposed by the computational setup. To deal with start-up problems as sloshing, spray and wave reflections a sinusoidal start-up ramp is used.

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[1] RANS – Reynolds Averaged Navier Stokes

[2] VoF – Volume of Fluids

[3] CFD – Computational Fluid Dynamics

[4] HOCHKIRCH, K.; MALLOL, B. (2013), On the importance of full-scale CFD simulations for ships, 12th COMPIT Conf., Cortona, pp.85-95

2.3 Free surface effects

The free surface is captured by a Volume of Fluid (VoF) approach. This requires solving of an additional transport equation for the fraction of fluid in each cell. A value of one means that the cell is filled completely by the higher density fluid (e.g. water in a water and air mixture).

Fluid properties such as density and viscosity are calculated as a weighted average based on the volume fraction of each fluid in each cell. If not otherwise specified all calculations are carried out as 2-phase-calculations considering free surface effects.

2.4 Effects of the working propeller

The effect of a working propeller is captured by a so-called Body Force or Actuator Disk method. Hereby the thrust of the propeller is modelled by volume forces which are applied in the propeller disk or rather a cylinder with the diameter and approximate thickness of the propeller. As a result, effects such as the stream contraction and flow acceleration are captured, while effects such as hub or tip vortices are neglected. Parameters such as the propeller torque and the relative rotative efficiency (η_R) need to be assumed from empirical relations.

The Body Force method (without considering rotational flow components) is the standard method. Symmetry about the x-z-plane is maintained and self-propulsion is achieved by balancing the integrated forces. The integrated forces may be corrected, e.g. for Reynolds effects in model scale (friction deduction Fd) if appropriate.

2.5 Fluid properties

According to ITTC Procedures Rev.2 the standard properties are applied as follows:

- For full scale calculations and predictions in case of inland vessels:
  15°C, fresh water ($\rho_{water} = 999.1026\ kg/m^3$, $\nu = 1.1386e^{-6}\ m^2/s$)
- For full scale calculations and predictions in case of sea going vessels:
  15°C, fresh water ($\rho_{water} = 1026.0210\ kg/m^3$, $\nu = 1.1892e^{-6}\ m^2/s$)

Other properties may be applied if special treatment is required in a certain project or if required by the customer.

2.6 Turbulence closure

The Navier–Stokes equations govern the velocity and pressure of a fluid flow. In a turbulent flow, each of these quantities may be decomposed into a mean part and a fluctuating part. Averaging the equations gives the Reynolds-averaged Navier–Stokes (RANS) equations, which govern the mean flow. However, the nonlinearity of the Navier–Stokes equations means that the velocity fluctuations still appear in the RANS equations, in the nonlinear term $-\overline{pv'_\iota v'_\jmath}$ from the convective acceleration. This term is known as the Reynolds stress, R_{ij}. To obtain equations containing only the mean velocity and pressure, the RANS equations need to be closed by modelling the Reynolds stress term R_{ij} as a function of the mean flow, removing any reference to the fluctuating part of the velocity. (WikiPedia: https://en.wikipedia.org/wiki/Turbulence_modeling)

Methods to achieve this closure are usually referred to as Turbulence Models. Several turbulence models of varying complexity exist and are available in the different CFD codes.

DNV's Ship Performance Simulator uses a k-ω-SST turbulence model with wall functions as standard turbulence model. Depending on the respective implementation, this requires the dimensionless wall distance to be $30 < y+ < 300$.

Other turbulence models with (high Re) or without (low Re) wall functions can be applied if required by the project.

3 CFD RESULTS

This chapter describes how thrust, wake and thrust deduction fraction are obtained from the raw CFD results in order to perform the final power prediction.

3.1 Thrust (T)

The Thrust is derived as result from the VoF computation. This considers:

- full scale (sea water 15°C)
- no appendages (even w/o rudder)
- fully turbulent flow
- hydraulic smooth surface
- unrestricted water
- self-propulsion condition with a body force propeller model, no rotative components
- symmetry about center-plane

The thrust reads:

$$T = Fx(T) \tag{1}$$

Whereas Fx is the native total force integrated over the body in the propulsion simulation.

3.2 Thrust deduction fraction (t)

The interaction of hull and propeller causes an increase of required propeller load which is commonly described by the thrust deduction fraction. In Ship Performance Simulator load variation computations are carried out for self-propulsion condition and the thrust deduction fraction t^* is computed based on the linearized load variation results. Resistance is derived by extrapolating the derived linear load variation relation to zero thrust.

3.3 Wake fraction (w)

The wake fraction is determined by velocity integration of the propeller disk area and correcting for the momentum introduced due to the propeller effect.

4 POWERING PREDICTION

4.1 Corrections:

4.1.1 CFD-Ship correlation factor (c_{CFD})

The CFD-ship correlation factor c_{CFD} is an empirical factor based on comparison of full-scale CFD and full-scale trials. Thus, it is a correction for any systematic errors in CFD resistance and powering prediction procedures.

Note: Correlations for welding seams and plate buckling are currently not accounted for.

With the wetted surface area at rest S_0 and:

$$q = \frac{\rho}{2} \cdot v_S^2 \tag{2}$$

the additional resistance component calculates to:

$$R_{CORR} = c_{CFD} \cdot q \cdot S_0 \tag{3}$$

4.1.2 Windage

The added resistance due to windage is calculated as:

$$R_{AAS} = c_{AAS} \cdot q \cdot S_0 \tag{4}$$

with:

$$c_{AAS} = c_{DA} \cdot \frac{\rho_{Air}}{\rho} \cdot \frac{(v_S + v_{Air})^2}{v_S^2} \cdot \frac{A_V}{S_0} \tag{5}$$

c_{DA} is the windage coefficient which will be assumed to be 0.9 by default. v_{Air} is the wind speed according to the chosen trial condition. I.e. set to zero for 0 Bft. A_V is the projected area of the ship above the modelled depth of the hull in the transverse plane. It is determined by:

$$A_V = A_X - B_{OA} \cdot D_{modelled} \tag{6}$$

A_X is a required input and is used as given by the client.

4.1.3 Thruster openings, bilge keels and other appendages

The additional resistance due to bow and stern thruster openings, bilge keels and other appendages is considered according to Holltrop and Mennen (1982):

$$R_{APP} = \sum q \cdot (1+k)_{APP} \cdot c_F \cdot S_{APP} \tag{7}$$

Whereas:

$$(1+k)_{APP} = \begin{cases} [1.5 \,..\, 2.0] \; for\ single\ screw\ rudder \\ 2.80 \; for\ twin\ screw\ rudder \end{cases} \tag{8}$$

$$(1+k)_{APP} = [1.0 \,..\, 1.4] \; for\ bilge\ keels \tag{9}$$

$$(1+k)_{APP} = [4.0 \,..\, 7.0] \; for\ external\ shafting\ (struts,\ bossings,\ brackets) \tag{10}$$

$$(1+k)_{APP} = 2.8 \; for\ stabilizer\ fins \tag{11}$$

With c_F according to ITTC 57 correlation line.

$$R_{THRUSTER} = 2 \cdot q \cdot \pi \cdot d^2 \cdot C_{BTO} \tag{12}$$

With:

$$CBTO = [0.003 \,..\, 0.012] \tag{13}$$

4.2 Total resistance and total thrust

The total resistance is calculated as:

$$R_T = T \cdot (1-t) + R_{CORR} + R_{AAS} + R_{APP} + R_{THRUSTER} \tag{14}$$

And total thrust simply becomes:

$$T_T = \frac{R_T}{1-t} \tag{15}$$

Whereas:

$$t = (1+k_t) \cdot t^* \tag{16}$$

k_t is an empirical value based on DNV's experience for the specific ship under consideration and t^* the uncorrected thrust deduction fraction.

4.3 Efficiencies

4.3.1 Hull efficiency

Hull efficiency η_H is calculated from:

$$\eta_H = \frac{1-t}{1-w} \tag{17}$$

4.3.2 Relative rotative efficiency

The relative rotative efficiency η_R is determined from the formulations of Holltrop and Mennen (1982),

for single screw vessels:

$$\eta_R = 0.9922 - 0.05908 \cdot \frac{A_E}{A_0} + 0.07424 \cdot (C_P - 0.0225 \cdot X_{CB}) \tag{18}$$

and twin screw vessels:

$$\eta_R = 0.9737 + 0.111 \cdot (C_P - 0.225 \cdot X_{CB}) - 0.06325 \cdot \frac{P}{D} \tag{19}$$

Whereas $\frac{A_E}{A_0}$ is the expanded blade area reatio and X_{CB} the longitudinal center of buoyancy.

4.3.3 Open water efficiency

The open water efficiency η_O is directly determined from the full-scale propeller open water curve using:

$$\frac{K_T}{J^2} = \frac{T_T}{N_P \cdot \rho \cdot D^2 \cdot v_A^{*2}} \tag{20}$$

If no individual open water curve is provided, a Wageningen B-Series propeller based on the provided propeller diameter D, number of blades z, pitch ratio P/D and effective blade area ratio A_E/A_0 is used including the respective Reynolds number corrections. If a custom open water curve is specified, this is used to determine η_O.

4.4 Power demand:

The necessary delivered power is calculated from:

$$P_D = \frac{T_T \cdot (1-t) \cdot v_S}{\eta_H \cdot \eta_R \cdot \eta_0} \tag{21}$$

5 BENCHMARKING

Besides the powering prognosis for the vessel under consideration a benchmarking functionality is offered upon request (extra costs apply). Taking advantage of the large number of vessels in the Ship Performance Simulator data base, a direct comparison to reasonable alternative designs is possible in an anonymous way. While DNV ensures that the process of determining the performance in a systematic way the geometries and further details of the vessels in the database are treated fully anonymous to ensure no disclosure of design information.

To allow a fair comparison similar designs are selected from the data base. Typical similarity criteria are:

- Slenderness ratio $L/V^{1/3}$
- Length-beam ratio L/B
- Beam-draft ratio B/T
- Block coefficient c_B
- Ship type
- Number of propellers

The applied boundaries are displayed in the report. To ensure a sensible comparison, a minimum number of designs need to be available. In case this threshold cannot be met the benchmark will not be available.

Since the data base designs are ‘only’ similar their results will be processed further to perform the benchmark. A scale factor is determined to create ‘displacement identity’:

$$\lambda = \frac{V_{vessel}^{1/3}}{V_{data\ base}^{1/3}} \quad (22)$$

The comparison will be performed based on delivered power P_D as described in (21).

Note: Each power curve considers the project specific input, i.e. that identical designs will show a different power level if e.g. the propeller data differs.

6 GEOMETRY GENERATION

A digital 3D geometry is required to perform the requested CFD simulations. For a reliable outcome, the used hull geometry shall be as close as possible to the real geometry. In case a digital 3D geometry is not available to the customer, the 3D hull surface needs to be carefully reengineered from drawings. This service is optionally offered by DNV. The complex process of geometry generation is based on selected construction frames and water lines (sections of the ideal hull surface). For each vessel, typically 25-30 frames are required to represent the original hull with adequate accuracy.

The process of geometry generation consists of 6 basic steps:

1. Frame selection:
   The relevant frames used to rebuild the vessel are selected with the help of the General Arrangement (GA) plan. The “density” of the selected frames is a function of the ships region. Due to the complex shape of aft and fore body a higher frame-density is required here, whereas, at midship area a lower density of selected frames may be sufficient.

2. Support grid:
   Using all available information a support grid is generated containing all relevant information about the location of frames, waterlines, decks, buttocks and the propeller.

3. Arrangement of frames and waterlines:
   The picture of each selected frame or waterline is imported into a CAD software, where it is individually arranged, scaled, rotated, rectified and straightened, if necessary.

4. Digitizing of frames and waterlines:
   If all frames and waterlines are aligned with the support grid, each of them is retraced to digitize the relevant curve information.

5. Surface generation:
   Based on the digitized frames a smooth, digital 3D hull surface is generated, which approximates all available frames and geometric information within a given tolerance. This step requires extensive experience.

6. Quality checks

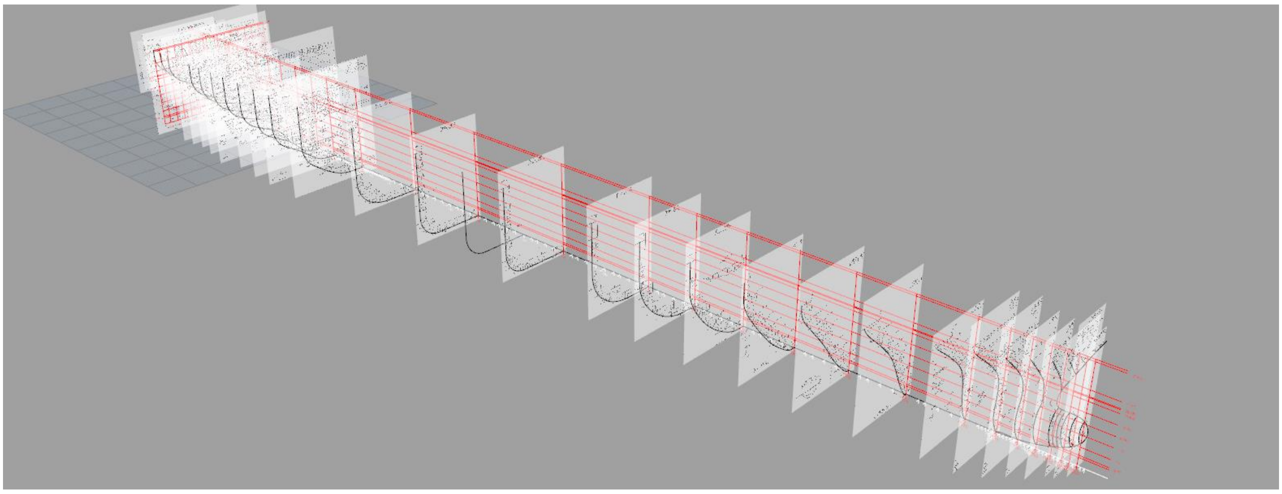

Figure 2: Support grid example (red) visualizing the changing frame densities over ship length by the varying distance between selected frames (white)

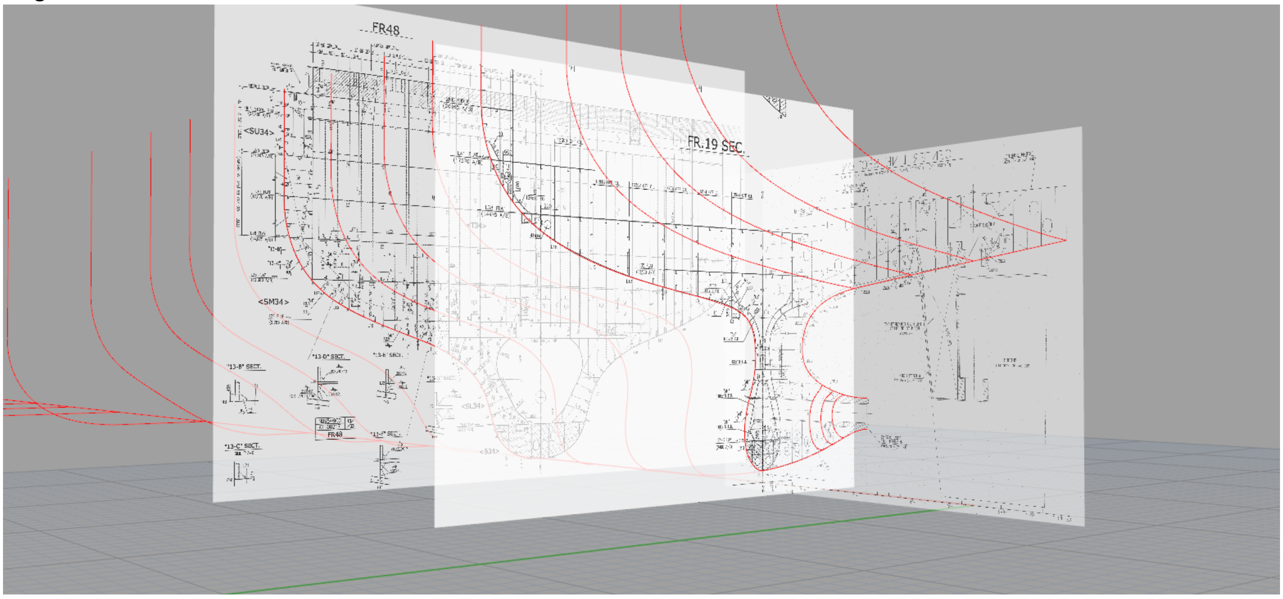

Figure 3: Example of arranged pictures and digitized frames at their correct positions

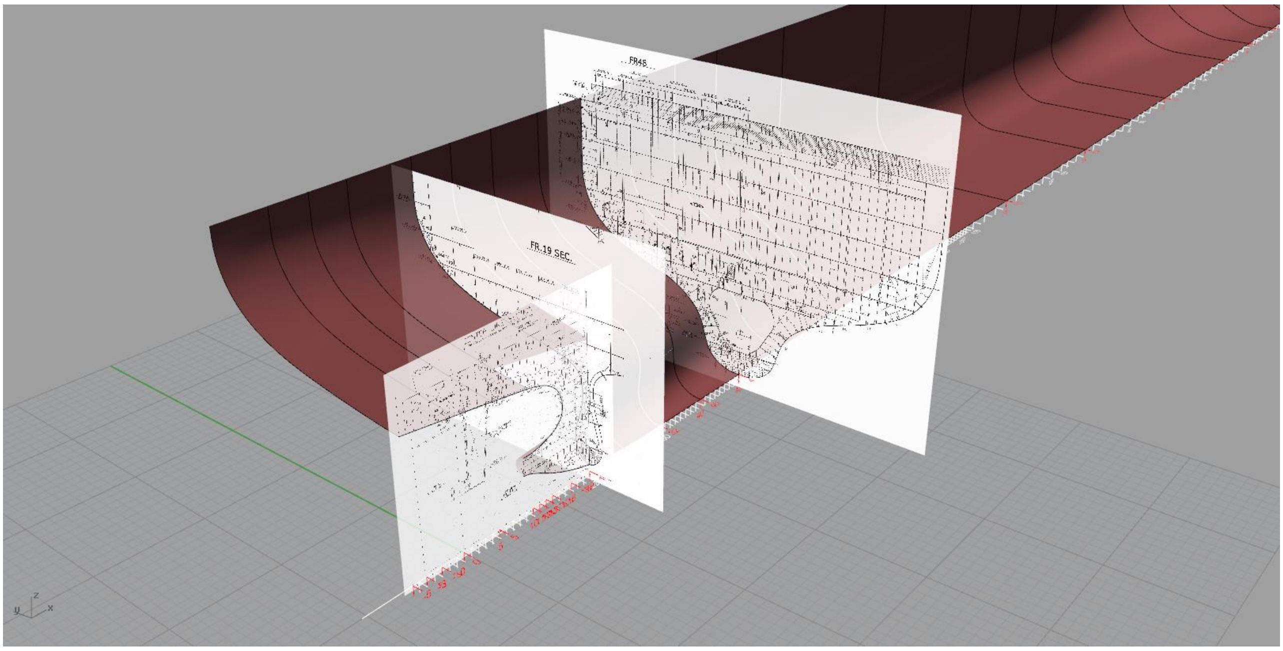

Figure 4: Example of a frame based 3D hull surface showing selected underlying frames and pictures