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Parametric Modeling and Shape Optimization of Offshore Structures

Lothar Birk*
School of Naval Architecture and Marine Engineering, University of New Orleans, USA

Abstract – The paper presents an optimization system which integrates a parametric design tool, 3D diffraction-radiation analysis and hydrodynamic performance assessment based on short and long term wave statistics. Controlled by formal optimization strategies the system is able to design offshore structure hulls with superior seakeeping qualities. The parametric modeling tool enables the designer to specify the geometric characteristics of the design from displacement over principal dimensions down to local shape properties. The computer generates the hull form and passes it on to the hydrodynamic analysis, which computes response amplitude operators (RAOs) for forces and motions. Combining the RAOs with short and long-term wave statistics provides a realistic assessment of the quality of the design. The optimization algorithm changes selected shape parameters in order to minimize forces and motions, thus increasing availability and safety of the system. Constraints ensure that only feasible designs with sufficient stability in operation and survival condition are generated. As an example the optimization study of a semisubmersible is discussed. It illustrates how offshore structures can be optimized for a specific target area of operation.

Key Words : **Parametric modeling, Shape optimization, Offshore structures, Seakeeping**

1. Introduction

Design of complex systems consists of a series of decisions which lead up to the definition of the final product. As introduced by Evans [10], the process is often depicted as a spiral which repeatedly visits certain aspects (hull, hydrostatics, stability, arrangements, etc.) each time fixing design characteristics in greater detail and allowing less and less changes in the design. In contrast to designs in automobile and aeronautic industry, ships and offshore structures are one-of-a-kind designs, eliminating the prototype stage of the design which could be used to detect and correct design flaws. As a consequence, unfavorable design decisions can rarely be corrected without significant adverse impacts on the financial success of the project.

Impact and occurrence of design flaws can be minimized by basing design decisions on first principle analysis wherever possible. Design decisions taken during the preliminary or concept design phase have the largest impact, because large changes are possible without negative effects. However, knowledge of details of the final system is only sketchy. This knowledge gap prevents the application of advanced and more accurate analysis tools which rely on a detailed model of the system. In addition, time constraints may prohibit the use of already available analysis techniques, because their pre-processing, computing and post-processing time may well exceed the preliminary design phase. As a result, final products often become just feasible designs rather than optimal designs.

Traditionally, the knowledge gap is bridged by designing conservatively with ample safety margins. Of course, prior design experience is exploited by the design team whenever it is accessible. With markets becoming more competitive and profit margins becoming smaller, the need to develop superior products is growing. This is only possible if advanced first principle based analysis is already applied in early stages of the design, when considerable changes to the design are still possible. The obstacles mentioned before can be overcome by integrating analysis tools into the design process and by automating pre- and post-processing. In order to achieve optimum results, sections of the design process are combined into optimization loops controlled by formal optimization strategies. This requires the selection of computable design objectives, free variables and constraints. The focus of work shifts from the actual execution of steps in the analysis to the definition of design goals and to the evaluation of the optimization outcome.

Formal optimization is already common practice in structural design, where finite element methods developed along with improved computer hardware allow considerable reductions in weight and cost. In hydrodynamics application of optimization is less advanced due to the difficult formulation of design objectives and the deficiencies still present in numerical analysis tools. Pre- and post-processing is tedious and in some areas accuracy of the methods available is still insufficient or computation time too long. In addition, current hull design is based on interactive 3D-modeling which is useless in formal optimization processes. This paper presents a non-interactive,

*Corresponding author:
Tel: +1-504-280 6183
Fax: +1-504-280 5542
E-mail: lbirk@uno.edu

form parameter controlled method to generate offshore structure hulls and shows how to integrate it in optimization processes aimed at increasing the seakeeping capabilities of the vessel.

The idea of applying formal optimization in the hydrodynamic design of offshore structures is of course not new. Several researchers developed optimization procedures to improve various seakeeping aspects of offshore vessels. Most notably is the work of Chou [6], who already used short term wave statistics in the assessment of seakeeping performance. However, in all previous work, the range of application is restricted to special and small classes of geometries, due to very limited parametric modeling capabilities. An overview of previous work is given in [8].

In the next section a short outline of the hydrodynamic optimization procedure is given before the parametric modeling of offshore structures is described. A brief overview of the hydrodynamic analysis and performance assessment is presented. For details the reader will be referred to the references. An extensive study of the optimization of a semisubmersible illustrates the application and the possibilities of the procedure. Conclusions, acknowledgements and references close the paper.

2. Hydrodynamic Shape Optimization

In a very general form all optimization problems can be formulated as the well known constrained minimization problem. We are looking for the minimum of the objective function f while satisfying additional constraints g_j.

Find the vector $\{\underline{x}^* \mid \underline{x} \in \Re^n\}$ for which

$$f(\underline{x}^*, \underline{P}) \leq f(\underline{x}, \underline{P})$$

$$\text{and } g_j(\underline{x}^*, \underline{P}) \geq 0 \quad \text{with } j = 1,2,3,\ldots,M \qquad (1)$$

Formal optimization relies on the possibility that the design objective f can be computed for different designs and that these values are sufficient to decide which design is most favorable. The computation of this design quality is captured in the mathematical model of the objective function $f(\underline{x}, \underline{P})$. In hydrodynamic shape optimization objective f becomes a function of the parameters describing the hull shape. A subset $\underline{x} = (x_1, x_2, \ldots, x_n)^T$ of these parameters is selected as free variables. The other parameters $\underline{P}$ remain unchanged during the optimization.

The objective function is usually not given explicitly but is the result of a multi-stage computation process (Fig. 1). In a first step, a hull is created from the free variables and constant form parameters (parametric modeling). The hull shape is then passed on to the hydrodynamic analysis, which in our case computes the seakeeping behavior of the vessel in terms of response amplitude operators of forces and motions. The response amplitude operators are subsequently used to assess the overall seakeeping performance considering short and long term wave statistics. The result is summarized in a single numerical value.

In addition to the mathematical model of the objective function other models are needed to compute constraints, which have to ensure that all considered designs are feasible and satisfy whatever standards are applied to the design task. The constraints are also dependent on the free variables and the other parameters. They are formulated as equality or inequality constraints $g_j(\underline{x}, \underline{P}) \geq 0$. Bounds on geometric properties and hydrostatic stability are used as constraints in the optimization study.

On basis of the objective function and constraints values the optimization algorithm decides how to change the free variables for the next design. It also checks the convergence criteria which are used to terminate the optimization loop. The best design found which does not violate constraints is reported as the optimum. Note, that the result generally represents only a local minimum. Other, even more favorable, designs

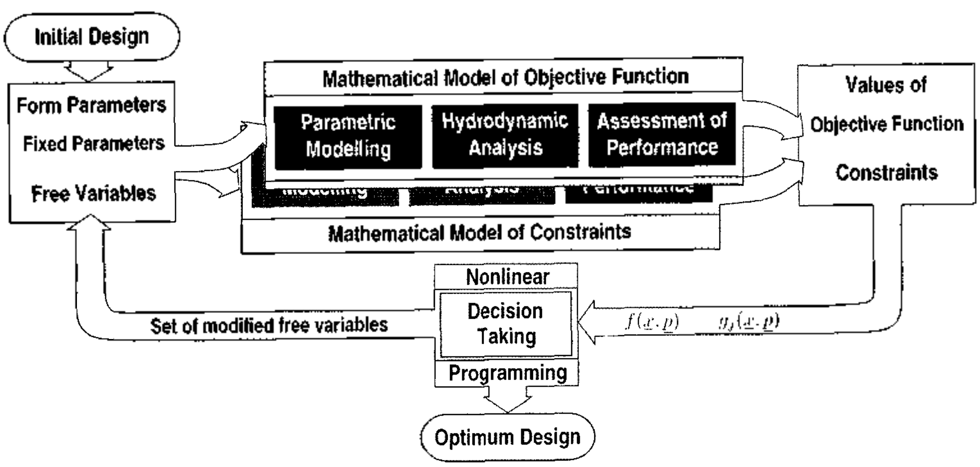


Fig. 1. Flow chart of hydrodynamic shape optimization [4].

could exist in other regions of the design space. Careful review of the optimization results is required. A reformulation of the optimization problem may be necessary to find better answers.

The list of optimization algorithms suitable for solving engineering design problems is very long. They can be subdivided into deterministic and stochastic algorithms. The former algorithms compute new free variables depending on information from previous steps and in some cases derivatives of the objective function. Stochastic algorithms use a random number generator to create new designs. Values and development of the objective function control the probabilities of the changes in free variables. For an extensive overview see books on nonlinear programming. A short application oriented summary can be found in [2].

Some algorithms claim to be able to find all optima and ultimately the best so called global optimum. However, most methods are unable to provide a proof of the global optimum. In a recent hydrodynamic shape optimization study, the application of two global optimization algorithms was presented. Genetic algorithm and simulated annealing were compared to a classical – so called local– sequential quadratic programming (SQP) algorithm [5]. In some instances the global algorithms detected better designs. However, they needed at least ten times as many evaluations of the objective function and constraints. Restarting the local optimization method with different initial designs usually reported equally good results. Thus, application of global algorithms has to be carefully considered trading off cost and merit.

The optimization study presented here applies the standard Nelder-Mead simplex algorithm [16]. Usually, a gradient based method would provide faster convergence towards an extreme value of the objective function. However, they require continuous first order and sometimes also second order derivatives. This essential requirement is not satisfied in our application, due to the discrete long-term wave statistics used in assessing the seakeeping performance. Small changes in the free variables may result in the same objective function value thus spoiling any attempt to approximate derivatives of the objective function numerically. The simplex algorithm does not support constraints. Therefore an exterior penalty function is added, which forces the algorithm back into the feasible region. The sum of squared differences between constraint limit and value is added to the objective function for all constraints which are violated [2].

The following two sections describe details of the mathematical model of the objective function.

3. Parametric Modeling

The objective of parametric modeling is to prescribe the properties of the hull. This reverses the process flow of traditional hull modeling with interactive CAD systems. As shown on the left side of Fig. 2., modeling starts with the interactive creation of the lines plan with support from the interactive CAD system (1). Most CAD systems today are based on parametric curves like B-splines or NURBS. Shape modifications are performed through modeling operations which change positions of curve or surface control vertices. Once the lines plan is completed the system evaluates form parameters and hydrostatic properties (2) which have to be checked by the naval architect (3). Modeling operations will iteratively lead to the desired shape properties.

Parametric modeling starts on top with the specification of the desired form parameters and properties by the naval architect (1). The form parameters are passed on to the parametric modeling system, which creates a lines plan (2). Finally the modeling system evaluates properties not previously specified and returns the data to the user (3). Since no interactive user input is needed, parametric modeling systems are well suited for batch processing and formal optimization.

Work on the parametric modeling of offshore

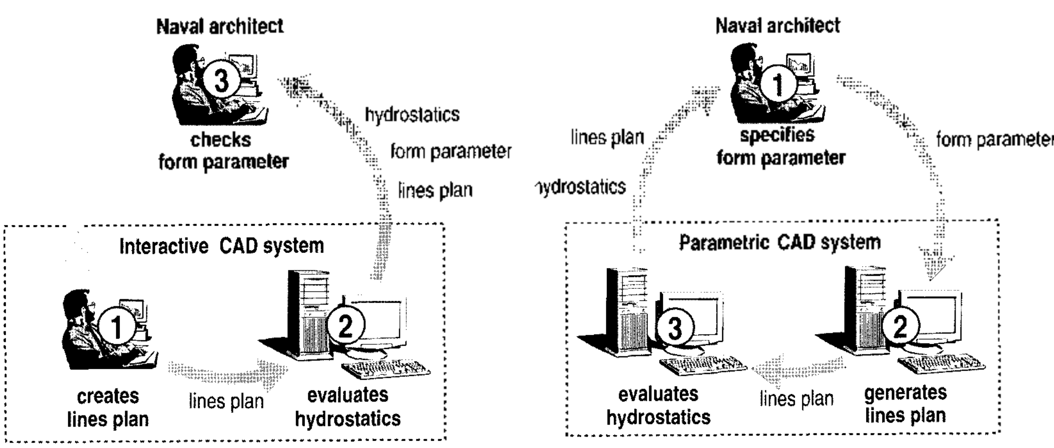


Fig. 2. Differences between interactive and parametric CAD systems.

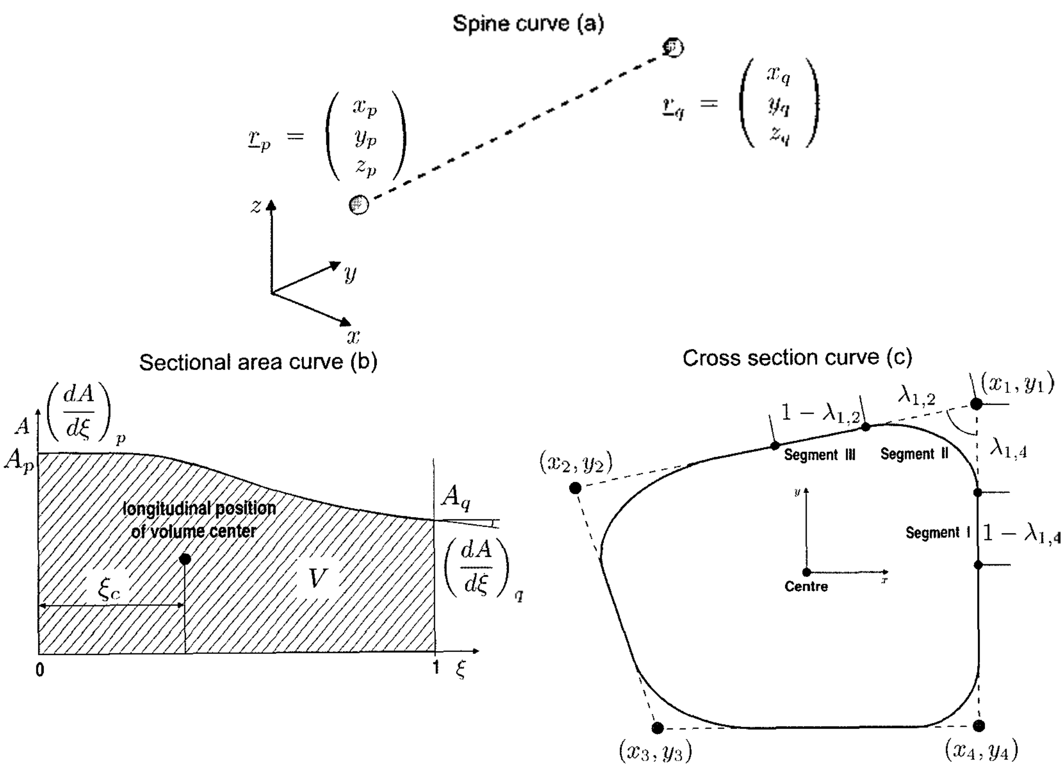


Fig. 3. Form parameters available to specify spine curve, sectional area curve and cross section curve of a single component.

structures started in 1991 at the Technical University of Berlin under the guidance of G.F. Clauss [7]. The first version was implemented in Fortran 90. It soon became apparent that in order to efficiently create structures with different topology a more flexible, script-type form definition language is needed. Instead of creating a new scripting language, the well known interpreter language Python is employed [20]. Today, the complete shape definition and generation is implemented in Python, utilizing its extensive support for numeric programming [14]. Python is also used to program the optimization framework and the performance assessment using short and long term wave statistics.

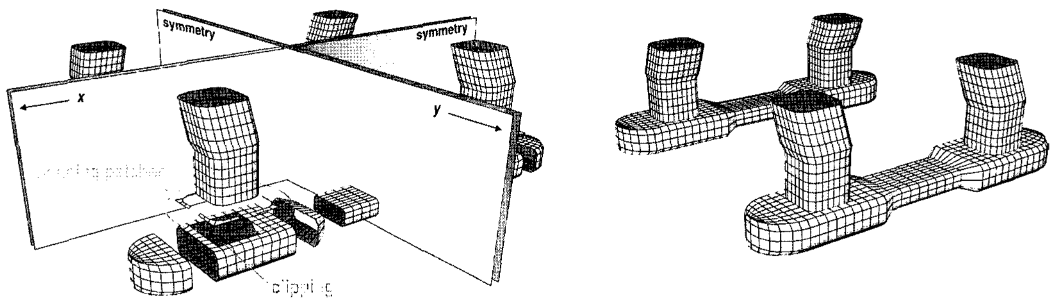
Each component is generated from the form parameters shown in Fig. 3. The form parameters define three basic curves:

- spine curve,
- sectional area curve, and
- cross section curve.

The spine curve represents the location of the area center of each cross section. It consists of a straight line connecting start point $\underline{r}_p$ and end point $\underline{r}_q$. Points along the spine curve are specified by ξ (ξ in [0,1]). The sectional area curve determines the actual size of each cross section. Generally any NURBS curve may be used as a sectional area curve. However, in most cases it is convenient to apply the method of influence functions [17] and compute a polynomial from the parameters shown in Fig. 3(b). Volume V, longitudinal center of buoyancy ξ_c, cross section areas at end points A_p, A_q and their derivatives $(dA/d\xi)_p$, $(dA/d\xi)_q$ represent the volume distribution of the component. The volume distribution significantly affects seakeeping behavior of the structure.

The third basic curve prescribes the shape of the cross section (Fig. 3(c)). Four corner points (x_i,y_i) (with $i = 1,2,3,4$) specify the general form of a quadrilateral. The mid-points of the quadrilateral mark the starting and end points of quadrants. Each quadrant consists of up to three curve segments. Segments I and III are straight lines whereas segment II is an elliptical or circular arc depending on the eight rounding factors $\lambda_{i,left}$ and $\lambda_{i,right}$ (two per corner). Either segment may vanish in a quadrant ($\lambda = 1$ or $\lambda = 0$, respectively). The specified cross section curve is normalized to unit area and stored as a second degree NURBS curve.

During component generation the cross section area at ξ is inflated to the size derived from the sectional area curve. Normally, the same scaling factor is applied to both coordinate directions (x,y). An additional parameter may lock one direction to the scaling factor of the first cross section at the starting point of the spine curve $\underline{r}_p$, thus maintaining for example the height of a component while adjusting the cross section area by modifying width only. The cross section curve is scaled while sweeping it along the spine curve creating a modified swept NURBS (Non Uniform Rational B-Spline) surface [13]. Components with different cross section shapes at either end are supported by ruled surfaces. The internal NURBS representation enables export of the hull shape to the hydrodynamic analysis via simple transfer tools.



All components and blending patches created (a) Completed semisubmersible (b)

Fig. 4. Components before and after merging.

Connecting the different components is a challenging task if they do not align longitudinally but form a T-type connection as shown in Fig. 4(a) between column and pontoon of a semisubmersible. Huang [13] implemented an algorithm which automatically clips an opening in one of the components and fills the gap with four Gregory-Charrot patches [11]. A complete description of the wetted hull surface is obtained (Fig. 4(b)). Although the method elegantly connects components, it is unable to cope with more general types of connections, especially if components intersect only partially. It will have to be replaced by a surface-surface intersection algorithm in the near future to further improve the parametric modeling capabilities.

Typically, total displacement is kept constant in all designs, although the method allows using total displacement as a free variable. In order to keep the displacement constant, displacement ratios are set up between the components. This may be done directly like in $V_{ratio} = V_{comp2}/V_{comp1}$ or indirectly via cross section area or length ratios. Eliminating unknown volumes from the total displacement then results in a nonlinear equation which is solved for one of the displacements. The others follow recursively from the ratios. The specific equation depends on the actual application.

In addition to the geometry description the model can be extended with other properties relevant for the hydrodynamic analysis or the computation of the constraints. For instance, the vertical center of gravity (VCG) is computed from a simplified model of the mass distribution. VCG is needed to compute vessel motions and is used to approximate initial hydrostatic stability.

4. Hydrodynamic Analysis and Performance Assessment

The computation of response amplitude operators for forces and motions (RAOs) of the vessel in waves is performed with the linear 3D diffraction-radiation program WAMIT® (Wave Analysis Massachusetts Institute of Technology, WAMIT Inc., [15]). The RAOs represent the wave frequency dependent ratio of vessel response s to wave amplitude ζ_a : $H_{s\zeta}(\omega) = s/\zeta_a$. Lower values are more favorable, however, their distribution over the wave frequency is equally important. This is captured by the well established spectral analysis method first introduced by St. Denis and Pierson [19].

Irregular seas are interpreted as a random superposition of a great number of harmonic waves of different amplitudes ζ_{ai} and frequencies ω_i. The wave crests are assumed to be of infinite length. Each component wave contributes an amount of energy to the seaway proportional to its squared wave amplitude. The spectral density S_ζ (ω) represents the energy distribution as a function of wave frequency ω. Two parameter Pierson-Moskowitz spectra are used for fully developed wind seas in our example. Its parameters are significant wave height H_s and mean zero-up-crossing period T_0.

Corresponding to the wave spectrum $S_\zeta(\omega)$ of the seaway the response spectrum $S_S(\omega)$ represents the energy distribution of the output signal. Utilizing the response amplitude operator $H_{s\zeta}$ wave and response spectra are related by

$$S_S(\omega) = |H_{S\zeta}|^2 S_\zeta(\omega) \tag{2}$$

A significant vessel response amplitude $(2s_a)_s$, similar to the significant wave height H_s, follows from integration of the response spectrum over the whole frequency range [9]:

$$(2S_a)_s = 4\sqrt{\int S_S(\omega)d\omega} \tag{3}$$

These significant double amplitudes characterize the behavior of offshore structures in stationary short-term sea states.

Long term wave statistics record the occurrence r_{ij} of sea states described by pairs of significant wave height H_{si} and mean zero-up-crossing period T_{0j}. The value r is the total number of observed sea states. The duration T_{ij} of all occurrences of an individual sea state (H_{si}, T_{0j}) during a selected time period T_T is given by

$$T_{ij} = \frac{r_{ij}}{r} T_T \tag{4}$$

Assuming that operational requirements limit the significant double amplitude of vessel response to $(2s_a)_{s,\mathrm{lim}}$, an expected downtime can be computed. Evaluating Equation (3) for all classes of the zero-up-crossing periods in the wave scatter diagram yields the significant response amplitude operator for a unit significant wave height as a function of T_0 [1]:

$$\frac{(2s_a)_S}{H_S}=f(T_0) \tag{5}$$

From Equation (5) follows the highest acceptable significant wave height for a given zero-up-crossing period T_0.

$$H_{S,\mathrm{lim}}=(2s_a)_{S,\mathrm{lim}}\left[\frac{(2s_a)_S}{H_S}\right]^{-1} \tag{6}$$

The values $H_{s,\mathrm{lim}}(T_0)$ represent in the wave scatter diagram the boundary between feasible ($H_s \le H_{s,\mathrm{lim}}$) and an infeasible ($H_s > H_{s,\mathrm{lim}}$) sea states. The summation of all time periods spend in infeasible sea states related to the total time yields an estimate for the expected probability of downtime $P_{d\beta}$.

$$P_{d\beta}=\frac{\sum\limits_{H_S>H_{S,\mathrm{lim}}} T_{ij}}{T_T} \tag{7}$$

Often wave scatter diagrams for a specific location are subdivided into several wave directions. To account for the non-uniform distribution of wave directions the computed values of expected downtime $P_{d\beta}$ are multiplied by the probability of occurrence q_β of sea states with wind and wave heading β. Summing up yields the averaged downtime considering all wave directions:

$$P_d=\sum_\beta q_\beta P_{d\beta} \tag{8}$$

Expected downtime probability is a statistical estimate of the vessel performance in a real ocean environment. Its absolute values are of minor importance and should be only exploited with great care. However, the expected downtime probability represents an elaborate measure suitable for comparing different designs. Examples of other objective functions for the optimization of offshore structures are given in [1] and [3].

5. Optimization Study

Implementation of the methods described above resulted in the arrangement of software modules depicted in Fig. 5. The overall optimization process is controlled by the optimization algorithm. It handles the user input and initiates the selected optimization algorithm. To define a specific optimization task the user adjusts the modules for geometric modeling, objective function and constraints. The hull shape is defined in the parametric modeling module which defines all parameter relations and handles input and interpretation of free variables. An extensive subroutine library helps the user to assemble and adjust the module for new structures with different topologies and shapes. Once the module has computed the NURBS hull surface from free variables $\underline{x}$ and fixed parameters $\underline{p}$ an integrated postprocessor creates a panel description for the hydrodynamic analysis with WAMIT®. Other post-processors for IGES, DXF or other formats can be included if required.

Data exchange between the modeling and the analysis stage is done by files. This is arguably not the most efficient method, however, it suits many hydrodynamic analysis programs designed for batch operation. It is easily adjusted to new tasks and requires no changes in the CFD code. After completion of the hydrodynamic analysis the required response amplitude operators are imported back into the objective function module. On the basis of the wave statistics (wave scatter diagrams) provided by the user, the module computes the objective function value. The third module defines the constraints which may need additional input depending on the required computations. Objective function value and constraint values are passed back to the optimization algorithm which uses the outcome to derive a new set of variables and start a new cycle of modeling and analysis.

The specific tasks selected for this study is to

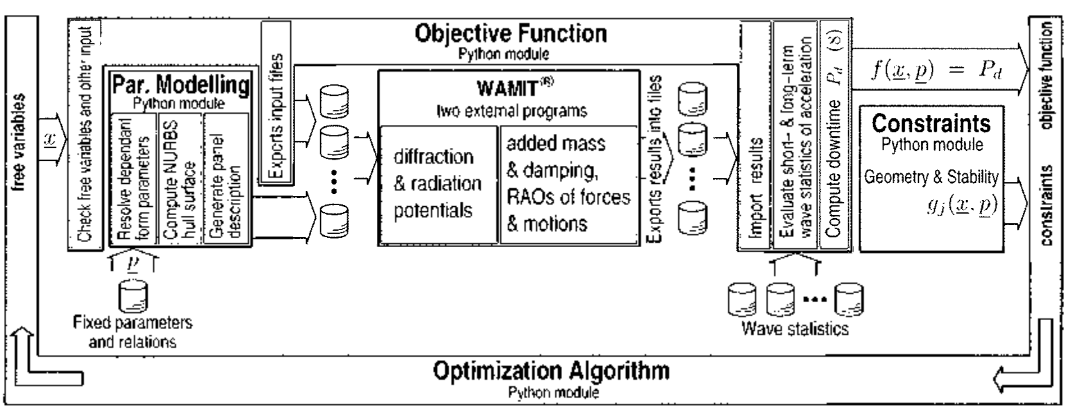


Fig. 5. Software modules and input/output flow for the optimization study.

optimize a semisubmersible for a target location in the northeast Atlantic off the coast of Scotland (Marsden square 182). The wave scatter diagrams are given for wind directions in 30 degree intervals [12]. Sea states from a south-westerly direction have the highest probability. About 45% of waves are expected to come from this direction. For the purpose of this design study we assume that the pontoons of the semisubmersible are aligned in North-South direction.

As objective function the downtime probability P_d from Equation (8) for exceeding the significant double amplitude of acceleration is minimized at a virtual point on the deck, 30 m above the waterline, 30 m to starboard and 30 m forward of the vessel center. Choosing an off-center point makes motions in all degrees of freedom contribute and subject to minimization. The limit double amplitude of acceleration is 5% of the gravitational acceleration.

All designs have a constant displacement of 50,000 m^3. A standard topology of two parallel pontoons with four columns is used. Nine free variables have been selected from the set of parameters. See Fig. 6 for a summary and explanation of the geometric properties used in their definition. $P_{sep}(=x_1)$ is the distance between the centerlines of starboard and port pontoon. The draft of the vessel is controlled by $T_p(=x_2)$ measured vertically from the waterline to the pontoon centerline. Free variables x_3 and x_4 represent non-dimensional ratios of main pontoon section (subscript pm) and central pontoon section (subscript pc) dimensions. x_3 adjusts the cross section area ratio A_{pm}/A_{pc} and x_4 controls the length ratio L_{pm}/L_{pc}. x_5 and x_6 control the aspect ratios of beam and height of main B_{pm}/H_{pm} and central pontoon section B_{pc}/H_{pc} respectively. Free variable x_7 allows an additional vertical shift of the central pontoon section only, thus that the central pontoon section center line has a draft of $(T_p + \Delta z_{pc})$. The free variable $D_c(=x_8)$ determines the width of the column cross section. The inclination of the columns in a beam-wise direction is controlled with the free variable $\Delta y_c(=x_9)$.

Besides some geometric constraints all designed vessels must have sufficient initial stability on working draft and in the survival condition. In survival condition total draft is reduced by 5 meter thus increasing the air gap between the underside of the deck and the water surface. The draft reduction is achieved by removing adequate ballast from the pontoons. The distance GM between the center of gravity G and the so-called initial metacenter M serves as a measure of stability. The metacenter M is defined as the intersection between the vertical lines through the center of buoyancy in (a) the upright equilibrium condition and (b) at a small heel angle [18]. The metacenter has to be located above the center of gravity (GM is positive) at all times for the vessel to develop a righting moment when it heels due to external forces. Otherwise the vessel will capsize.

In summary, the optimization task can be noted as follows:

Find the vector $\{\underline{x}^* \mid \underline{x} \in \Re^n\}$ for which

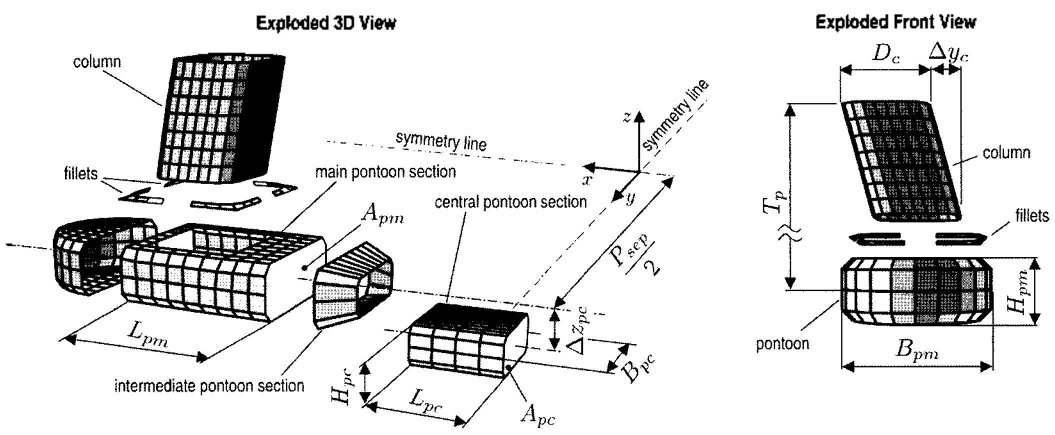
$$f(\underline{x},\underline{p}) = P_d \text{ (Equation (8)) is a a minimum} \quad (9)$$

and

$$g_1(\underline{x},\underline{p}) = GM_{\text{workingdraft}} \geq 1.2 \text{ m}$$

$$g_2(\underline{x},\underline{p}) = GM_{\text{survivaldraft}} \geq 0.6 \text{ m}$$

In total, five optimization runs have been performed with five different initial designs named A, B, C, D, and E. Table 2 summarizes their free variable values. In addition to different initial designs the sequence of the free variables was also changed. Run A uses the sequence



x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
P_{sep}	T_p	A_{pm}/A_{pc}	L_{pm}/L_{pc}	B_{pm}/H_{pm}	B_{pc}/H_{pc}	Δz_{pc}	D_c	Δy_c

Fig. 6. Free variables x_i used in the optimization study and their geometric definitions.

Table. 1. Properties of the five initial designs.

	Free variable values of initial designs								
Run	P_{sep}	T_p	A_{pm}/A_{pc}	L_{pm}/L_{pc}	B_{pm}/H_{pm}	B_{pc}/H_{pc}	Δz_{pc}	D_c	Δy_c
Unit	m	m	-	-	-	-	m	m	m
A	80.0	20.0	1.0	1.2	1.96	1.96	0.0	12.5	4.0
B	80.0	20.0	1.6	1.2	1.96	1.96	0.0	12.5	0.0
C	80.54	20.27	1.74	1.19	1.972	1.972	-0.76	12.57	0.03
D	81.64	22.4	2.04	1.12	1.995	1.877	-1.545	13.06	0.02
E	82.0	22.4	2.04	1.127	1.995	1.877	-1.545	13.06	4.0

Table. 2. Properties of the optimized designs.

	Free variable values of optimized designs								
Run	P_{sep}	T_p	A_{pm}/A_{pc}	L_{pm}/L_{pc}	B_{pm}/H_{pm}	B_{pc}/H_{pc}	Δz_{pc}	D_c	Δy_c
Unit	m	m	-	-	-	-	m	m	m
A	82.21	24.26	0.974	1.12	1.955	1.950	−0.582	12.56	3.55
B	80.78	20.84	1.64	1.19	1.978	1.978	−0.807	12.6	0.02
C	82.1	22.4	2.04	1.127	1.994	1.876	−1.545	13.06	0.0
D	82.74	24.4	2.1	1.143	1.986	1.80	−1.216	12.97	0.07
E	82.57	23.86	2.04	1.122	2.01	1.888	−1.66	13.1	4.07

listed. Runs B, C, D, and E use the sequence (x_3, x_2, x_4, x_1, x_5, x_6, x_7, x_8, x_9). Changing the sequence usually affects the optimization outcome, if simple search algorithms like Nelder-Mead are used.

As shown in Fig. 7, all optimization runs yield considerable reduction in expected downtime probability P_d derived from Equation (8). Run A develops a good design mainly by increasing the draft. A further increase in draft is prohibited by the hydrostatic stability requirements for the vessel in survival condition. Fig. 8 shows an optimization history typical for search algorithms. Improvement is achieved quite soon, but the final convergence is slow. Between steps 100 and 162 size of the simplex is gradually reduced to enclose the optimum without significant change in vessel performance.

The improvements in seakeeping behavior are caused by complex changes in hydrodynamic properties of the vessel. As an example selected properties of initial and optimized design of run A are compared in Fig. 9. The wave heading 120 degree corresponds to the most probable waves originating from a south-westerly direction. The optimized design is characterized by reduced heave and pitch motions as well as by reduced exciting forces over the complete range of wave frequencies. The same holds true for other degrees of freedom. Heave resonance frequency of the optimized design A is negligibly higher. In addition, changes in added mass and wave damping occur. Here both are decreased for heave and pitch. As a general observation may be noted that vessels with better seakeeping performance have added mass distributions which show less variation with wave frequency ω than worse designs. As mentioned, in run A increased draft is the change in shape with the most impact on downtime P_d. Fine tuning of pontoon separation and beam-height ratios (B_{pm}/H_{pm} and B_{pc}/H_{pc}) of the pontoon sections helps to adjust exciting forces and added mass and damping to the given environmental conditions.

For run B the inclination of the columns is removed and the volume distribution in the pontoons is changed. By increasing the cross section area ratio A_{pm}/A_{pc} more volume is concentrated towards the pontoon ends. This proved advantageous in prior studies [1]. The result of run B is overall not very promising. The optimization converges too fast and stops in step 30. An intermediate design of run B is used as the initial design of run C. It has the worst performance of the initial designs, but develops a reasonable design within 50 steps. The center pontoon part is shifted downward and more volume is moved towards the pontoon ends. Pontoon separation is slightly increased (see Table 2).

The optimum of run C is used as initial design in run D with only slight changes. A similar performance as in run A is achieved, however, with a considerable different geometry. The columns have no inclination and the pontoons have a more slender central section. In run E the column inclination is re-introduced. Most other parameters are shared with the initial design of run D. Again a similar performance as in run A is obtained.

Comparing the results of runs D and E, shows that the column inclination has no considerable effect on the expected downtime probability P_d. However, it affects the stability reserves of the designs. Studying the results of the constraints reveals, that optimized design A is bordered by the stability constraint of the survival condition, i.e. $GM_{\text{survivaldraft}} = 0.6$ m. Due to the inclined columns and the slightly larger column cross section, optimized design E has the largest stability reserves and therefore can be considered the optimum trade-off solution of this design study. Table 2 summarizes the design characteristics of the optimized designs.

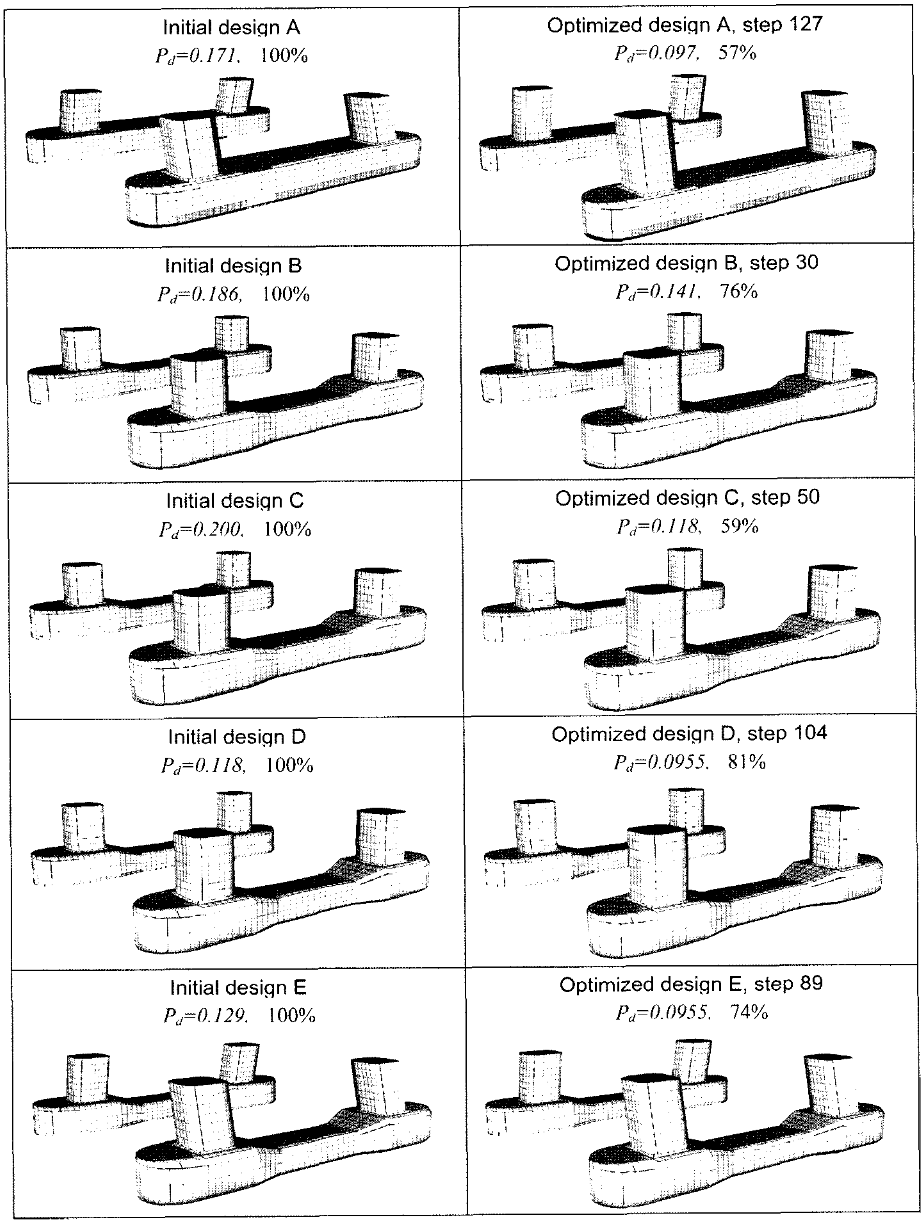


Fig. 7. Comparison of hull shapes and performance of initial and optimized designs for runs A through E.

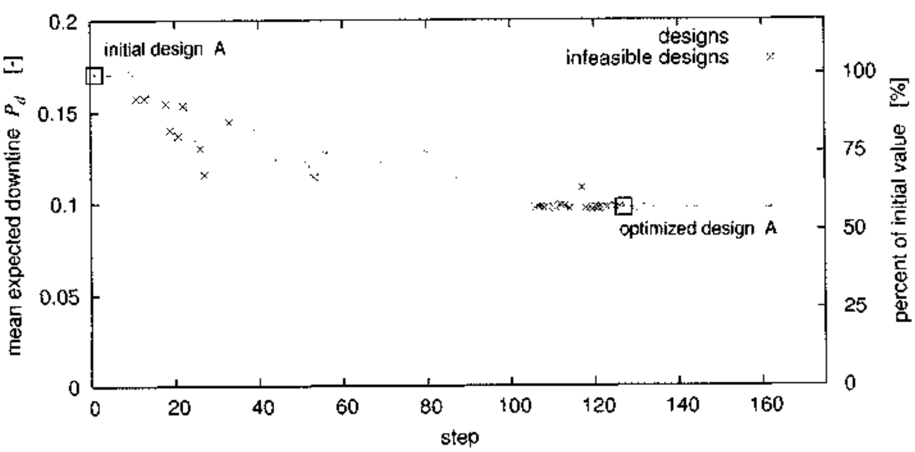


Fig. 8. Optimization history of run A; initial design step 1; optimized design in step 127.

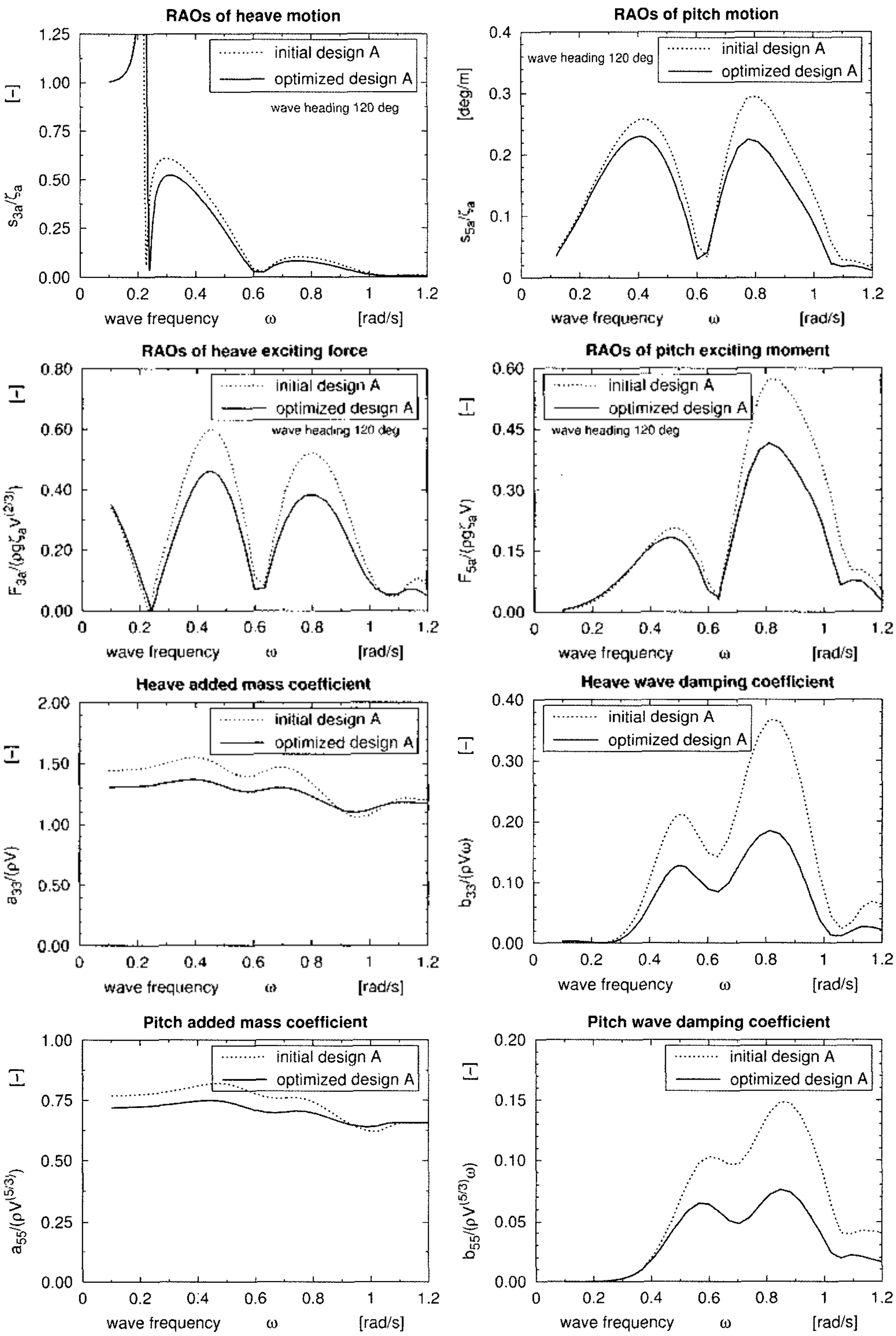


Fig. 9. Comparing selected hydrodynamic properties of initial design and optimized design of run A; initial design step 1; optimized design in step 127.

Although the changes in geometry are not obvious in all cases, each of the optimized designs has specific seakeeping characteristics. Fig. 10 compares response amplitude operators of motions and exciting forces for heave and pitch. Optimized design E has the smallest heave motions, however, optimized designs A and D show less pitch motion in parts of the frequency range. Similar comparisons can be made between other designs except may be for optimized design B which is generally inferior to the others. The complex comparison emphasizes the need of a careful review of optimization results. Different shaped vessels can have similar overall seakeeping characteristics like the integral figure of expected downtime. The differences in detail will have to be assessed by the naval architect and form the basis for a rational design selection.

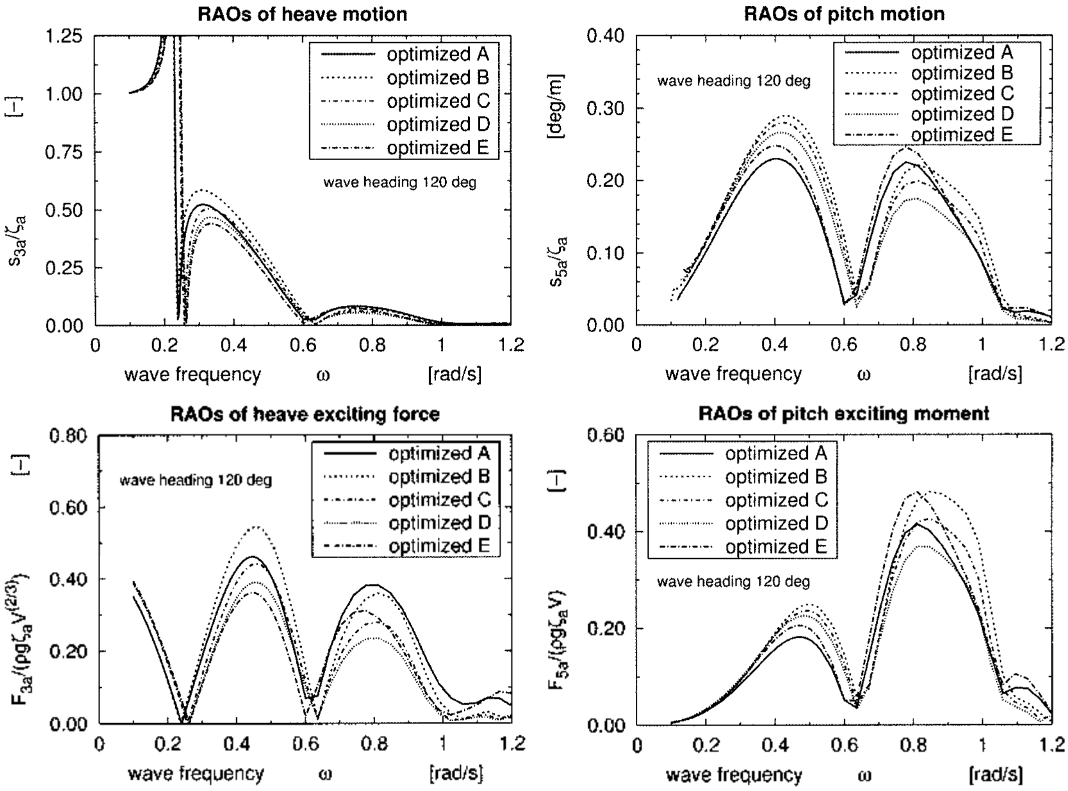


Fig. 10. Comparison of selected hydrodynamic properties for the optimized designs A; B, C, D, and E.

Additional optimizations have been performed selecting other points on the platform to minimize accelerations. The results are similar to the ones shown. Since different points represent independent optimization problems the resulting optimized shapes are difficult to compare.

Setup of an optimization task takes between one and two days depending on the complexity of the targeted topology of the vessel. Table 3 summarizes the computation times spent in the optimization study. All computations were performed on a PC with an Intel Pentium 4 3.4 GHz processor and 1GB of main memory. The computer is operated under the Linux operating system for stability. A single evaluation of the objective function takes about 4 minutes. Obviously, this figure depends on the number of panels used to discretize the geometry for the hydrodynamic analysis. About 820 panels were used on one quarter of the vessel. The hydrodynamic analysis uses an average of 210 CPU seconds. About 25 seconds per design are spent by the parametric modeling tool. The remaining time is consumed by evaluating the expected downtime. The overhead created by the optimization algorithm itself is negligible.

Table. 3. Run times on a Linux PC with Pentium 4 3.4 GHz processor.

Run	Number of objective function evaluations		Total run time
	until optimum is found	total	
A	127	162	10h 48min
B	30	114	7h 36min
C	50	129	8h 36min
D	104	146	6h 56min
E	89	128	8h 32min

6. Conclusions

In this paper a flexible parametric modeling method for offshore structures is described. The non-interactive shape generation is designed for use in formal optimization procedures. A framework for the hydrodynamic optimization of offshore structures has been implemented in the interpreter language Python. It enables a very flexible setup and easy modification for different problem settings.

The presented optimization study clearly shows the possibilities of design improvement by integrating parametric design, advanced numerical analysis and formal optimization strategies. Performing optimization studies yields deeper insight into the design space. It avoids design flaws by using advanced first principle analysis and comparing a large number of designs. Better designs can be developed in a short time span. Further development will consider multi-objective optimization and the integration of structural analysis.

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Lothar Birk is Associate Professor at the School of Naval Architecture and Marine Engineering of the University of New Orleans. He studied naval architecture and ocean engineering at the Technical University Berlin (Dipl.-Ing., 1990) where he also received his doctoral degree (Dr.-Ing., 1998). His research is centered on computer application in marine design. Specifically he works on parametric modeling, shape optimization and numerical hydrodynamics. Dr. Birk is the recipient of the Georg-Weinblum-Award 1999. He is a member of ASEE, SNAME and STG.

Lothar Birk