Seatific, Vol. 1, Issue. 1, pp. 37–50, December 2021

Seatific
https://seatific.yildiz.edu.tr
DOI: https://doi.org/10.14744/seatific.2021.0003

Research Article

Metamodels for seakeeping assessment of fishing vessels

Giorgio TRINCAS*[1], **Roberto ROCCHI**[2]

[1]*Department of Engineering and Architecture, Section of Naval Architecture, University of Trieste, Trieste, Italy*
[2]*Senior Researcher, Rome, Italy*

ARTICLE INFO

Article history
Received: 03 July 2021
Revised: 27 October 2021
Accepted: 05 November 2021

Key words:
Metamodels;
Seakeeping;
Fishing vessels

ABSTRACT

The most significant goals of this paper are: (i) to provide additional insight on the influence of hull form parameters on seakeeping performance of typical Mediterranean fishing vessels; (ii) to develop efficient and reliable metamodels for fast and reliable evaluation of seakeeping performance in a multiattribute decision-making environment; (iii) to facilitate and speed up the selection of the design with the best possible seakeeping performance at conceptual design stage. To enhance the accuracy and applicability of predictions of seakeeping characteristics and to find out guidelines for design scope, new metamodels have been developed from an extended database of 57 cases, which comprehends the hull form geometrical data, heave (h), pitch (p) and vertical acceleration (a_v) rms values of both old 39 cases studied previously as well as new 18 cases of Mediterranean coastal fishing vessels previously analysed for resistance assessment. Main statistical parameters of the derived regression equations show a substantial improvement of statistical accuracy in h, p and a_v estimates, particularly when geometrical descriptors of forebody and afterbody hull form are included as independent variables. Statistical homogeneity of the N57 extended database was verified by cluster analysis of selected responses with classical hull form coefficients/parameters, and new descriptors data altogether taken as discriminant variables in two nucleus clustering analysis. Values of heave, pitch and vertical acceleration yielded by the metamodels have been compared to the ones determined by means of direct computations. Low residuals have confirmed reliability of the proposed prediction metamodels to determine since conceptual design stage seakeeping performance of fishing vessels with hull forms and main dimensions which could be included in the design space defined by the population forming the extended database.

Cite this article as: Trincas G, Rocchi R. Metamodels for seakeeping assessment of fishing vessels. Seatific 2021;1:1:37–50.

INTRODUCTION

Pressure to design and build safe and efficient fishing vessels compels scientists and designers to review current design practices. Whichever methods, computer codes, and/or approaches are used through the design process, it is well known that design requirements for seakeeping and other issues (resistance, static stability and so forth) are generally in conflict. Whilst important reductions of the wave making resistance and powering are still achievable as a result of even small changes in both hull foremost and aftermost local details, seakeeping performance is normally governed

---

***Corresponding author.**
*E-mail address: trincas@units.it

Published by Yıldız Technical University Press, İstanbul, Turkey

by the main geometrical characteristics and gross overall hull form. Thus, seakeeping characteristics have to be incorporated into the design process since the very initial stages, as related enhancement is difficult and expensive to obtain in design stages following the concept design. Indeed, despite continuous advances in computing power and speed, the expense of running computer-intensive codes remains non-trivial and makes their application impractical.

Several prediction models (regression equations) developed for fishing vessels, are available in the specialized international literature for assessment of heave (h), pitch (p), and vertical stern acceleration (a_v) in head sea in regular and irregular seas. They have been applied to a set of Mediterranean fishing vessels, but what resulted is their inadequacy as reliable design tools, even for ranking among existing vessels or competitive designs.

This fact suggested the opportunity for an approach that should take into account hull form descriptors directly obtainable from the lines plans and 'physically close-correlated' to seakeeping responses.

The first strip-theory was developed by Korvin-Kroukovsky (1955), whilst the first solution to the inverse problem (design problem) was suggested only twenty-five years later by Bales (1980) who used analytical seakeeping responses to build a regression formula correlating the performance of destroyer-type hull forms in head seas and at various speeds to a set of geometrical variables. Since then, many simplified approaches have been proposed, based on multivariate regression analysis. These approaches to predictive models range from approximate prediction of seakeeping qualities for conventional merchant ships (Loukakis & Chryssostomidis, 1975; Moor & Murdey, 1968) and gulets (Cakici & Aydin, 2014), to generation of design charts (Hearn et al., 1991) and to application of different forms of seakeeping rank (Kishev, 1992; McCreight, 1983; Nabergoj et al., 2003; Trincas et al., 2000; Trincas & Nabergoj, 2000; Trincas et al., 2001; Walden & Grundmann, 1985; Wijngaarden, 1984; Zborowski & Shiaw-Jyh, 1992) to identify the comparative merit of alternative hull forms.

The first approach is absolutely unfeasible for modern ships, which have proportions and hull forms quite different from the ones tested and analyzed many decades ago. The other approaches found their limitation in a single objective optimization, whereas the problem can be undertaken only by multicriterial optimization in a probabilistic environment. Finally, the so-called rank factor is derived as a weighted summation of a number of seakeeping responses yielding an empirical relationship between selected hull form parameters and an operational estimator, described by a linear regression formula. The drawback of rank estimator scheme consists in a certain ambiguity deriving from subjective preference in the procedure of their building and the absence of a clear physical content. Therefore, approaches based on seakeeping indices possessing a clear physical meaning are preferable, provided they are more sensitive to variations of hull form geometry.

Among different approaches, at concept design the most promising strategy to model vessel hydrodynamics is to employ approximating functions, which describe single responses. That is particularly true as regards seakeeping assessment. Statistical techniques are widely used in multicriterial design to build surrogate models, the so-called metamodels, since they are much more efficient to run and easier to integrate in a comprehensive design suite. At the same time, they may yield insight into the functional relationship between design variables and performance responses carrying out screening tests preliminary to sensitive analysis.

The very scope of this paper is to develop efficient seakeeping prediction models as analytical modules to insert into a multiattribute optimization procedure. For the time being, multivariate linear regression equations are proposed to predict heave, pitch and vertical accelerations of small and medium-sized Mediterranean fishing vessels stored in an extended database with 57 cases considered. Domain of applicability of independent variables is given, while sea state and other specifications are available in publications (Moor & Murdey, (1968; Trincas et al., 2001).

It is demonstrated that the very simple and design-oriented metamodels here proposed fit well with the design responses obtained from direct computations. At the same time, metamodels provide information on the range of the responses values, thus allowing the designer and the customer to identify feasible targets at top-level specifications. This bulk of structured information constitutes the basic data to create more robust predictive metamodels.

NEED FOR A SIMPLIFIED APPROACH IN DESIGN FOR SEAKEEPING

Evolution and practice in design for seakeeping highlights a return to simple and efficient models as suggested by the first scientists who studied the influence of hull form parameters on seakeeping performance. Turning to simplification is intrinsic also to the strip-theory and the concept of regular design wave. Lewis cleverly supported simplification in using a regular sea instead of an irregular one, stating in his comment to the paper by St. Denis and Pierson (1953) that

> *"It is not clear why an irregular sea will give better criteria of ship performance than a regular one. At intervals any irregular sea will become sufficiently regular so that the motion of the vessel, for a short time, will approach that attained in resonance.... Why is not this motion as 'realistic' a criterion of ship performance as any other? A 'realistic' irregular sea is at intervals regular".*

So, provided simplified models and theories reflect physics with acceptable accuracy for engineering purposes, this statement is far away from that of the researchers who were scandalized by the poor 'mathematical philosophy' of the strip-theory, as quoted by Salvesen et al. (1970), who replied to harsh critics that 'purists felt that the theory was not derived in a rational mathematical manner but rather by use of physical intuition'. Nevertheless, the strip-theory turned out to be superior to expectations of the authors themselves. Once more, one can discover that intuition often helps more than mathematics, especially if one is forgetting the sentence from the eminent mathematician Henry Poincaré who stated that '*mathematics can never tell you what is; only what would be if*. This sentence was quoted also by St. Denis and Pierson (1953) in their milestone paper. As stated in literature through decades, substantial changes in hull form design are necessary to improve seakeeping performance. Moreover, at earlier design stages, it is suitable to simplify the significant attributes down to ship motion level, as all responses involved in the seakeeping estimation are directly correlated to ship motions (Kishev, 1992). That is why analysis in this paper is limited to heave, pitch and vertical acceleration.

Anyway, naval architects do need reliable and actual answers to their own questions about decision making. Sharing of such an approach drove the authors of this paper to co-operate in broadening the research work developed for many years on hand by many researchers. The new prefixed goal has been to model seakeeping responses more accurately following the 'spatial screening' approach introduced since the 1980's by Rocchi (1988, 1992), who derived descriptors of foremost and aftermost hull form for estimation of calm water resistance by means of multivariate linear regression equations. For instance, it was demonstrated that relative longitudinal positions of the centre of buoyancy and centre of flotation, geometry of transom stern, and bow parameters cannot be neglected to build approximate models accurate enough for engineering purposes.

ROLE OF THE METAMODELS

The computation burden in ship design is generally determined by simulation procedures and expensive analysis aimed at reaching a level of accuracy comparable to the one achievable by testing physical models. To this end, metamodeling techniques have been developed from many scientific fields including computer science, chemistry, physics and various engineering disciplines.

Despite continuous advances in computing power, the complexity of analysis codes, such as computational fluid dynamics (CFD) and finite element methods (FEM), makes their application unfeasible at very initial design stage where it is necessary to substitute computation-intensive functions with simpler analytical models. These simple models are generally called metamodels.

The metamodels can be considered as 'surrogates' of the expensive simulations in order to improve efficiency in decision-making and provide tools to assess attributes/objectives of complex technical systems, such as a ship or an aircraft. Nowadays it is accepted worldwide that they are a valuable tool to support modern engineering design especially at concept stage where the most impacting decisions are made.

The advantages of the metamodels can be summarized as follows:

1. building metamodels can better filter the numerical noise than numerical methods;
2. the metamodels encompass the entire design space;
3. they help to detect errors in simulations as the entire design domain is analysed.

In the past decades, intensive research has been carried out in employing metamodeling techniques in engineering design (Fang & Sudijanto, 2006; Fox, 2011; Kleijnen & Sargent, 2000; Li & al., 2016; Logan et al. 2013). Among the others, these techniques concern sampling, design space exploration and reduction, model fitting techniques, optimization methods as well as applying metamodeling as a decision support in design decision-making.

Issues where metamodels can play a role can be listed as follows:

- they can improve the designers' understanding of the problem at hand;
- they can approximate expensive and intensive computation processes across the entire design space, so reducing the computation costs and lead time;
- they may reduce the number and search range of the design variables, so removing ineffective constraints.

Metamodelling techniques are usually categorized according to sampling, model types and model fitting. They evolve from classical Design of Experiments (DoE) theory, in which polynomial functions (regression equations) are used as response surfaces (metamodels). Using computer experiments yields vary small random errors, which might be caused by the random number generation. Since there is no conclusion in the scientific literature about which modelling technique is definitely superior to the others, for the scope of this paper polynomial models have been utilized.

The methodology followed to develop the metamodels is based on the Response Surface Methodology (RSM) where polynomial regressions as finalized equations have been chosen because of their simplicity and low order of non-linearity of the response functions.

We must emphasize that the main scope of inserting metamodels in the mathematical design model at conceptual design stage stays in the following: to help ship designers in searching for a new zone in the design space in which the vessel can be improved as a system more than in finding a point, i.e. a design, of optimum single response. To search for a zone of improved responses we utilized the *method of steepest descent.* Since design economy and metamodel simplicity are very important, a first-order model (a hyperplane) was fitted using an orthogonal design. Then, a path of steepest descent was computed where a set of experimental runs were conducted taking care that no variable goes outside the design space by performing tests for lack of fit. In situations where lack of fit appeared, a second-order response surface model was introduced and the step-by-step procedure was repeated until the diagnostic checks to the residuals and other relevant statistical parameters were satisfactory.

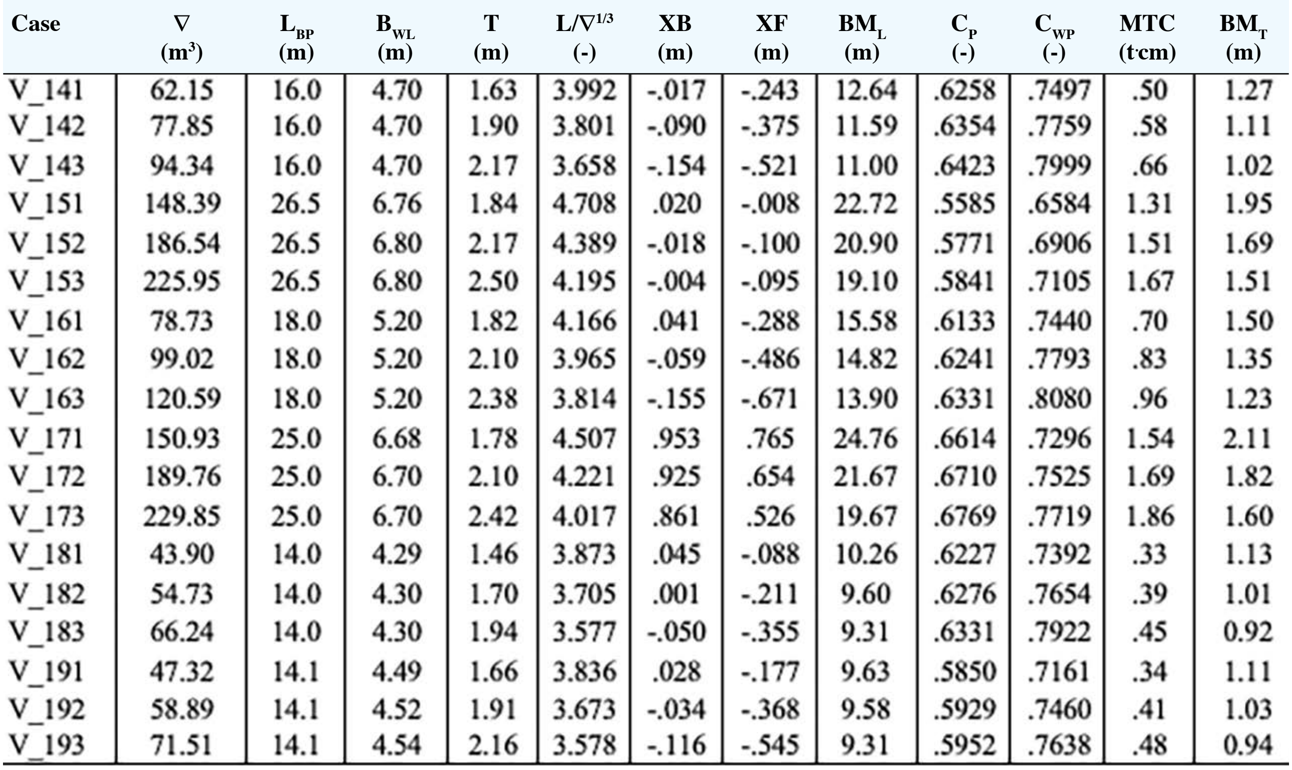
SHORT REVIEW OF SEAKEEPING PREDICTIVE MODELS

Nobody can disagree with Bales & Cummins (1970) in the necessity that "*Seakeeping can be rationally included in the ship design process. The prerequisite is determination of trends in seakeeping variables with changes in hull geometry at an early stage in the design process*". Hence, the ultimate goal is to make available simple tools to designers, that can help the in evaluating the merit index for a new design with respect to a number of competitive vessels of the same class.

General application of available predictive models often brings to evaluations that do not yield reliable ranks among competitive designs. This discouraging result may be the consequence of a bad application of the models by the user, but frequently the main responsibility is attributable to developers of the regression equations. Indeed, at minimum each proposed metamodel should be followed by: (i) its statistical significance tests (R^2_{adj}, *S.E., F, t-Student, k, max-min deviation* of estimates over database samples); (ii) its domain of applicability (ranges of variables values); (iii) detailed specifications of variability of hull form types in the database (round/chine form, predominant U/V forms, bulb vs. no bulb, high/low flare, open stern or not, etc.; (iv) the lines plan of the 'central-case' and 'extreme-cases' of the database should be provided; (v) an exhaustive and clear nomenclature for any mathematical tool should be provided.

Above all, designers should remember that regression equations behave correctly only for vessels that are of the same class of those that constitute the database: cluster analysis can help in establishing how close characteristics of a new design are to hull forms stored in the database. Moreover, regression equations are applicable only for the same sea conditions, and so forth. In other terms, every class and type of vessel requires its own model. Finally, geometrical boundaries of the population from which the model is derived, become a hard constraint in the design process. Hence, designers are strongly invited to pretend aforesaid information from developers of the predictive models.

Table 1. Main geometrical characteristics of the set of 18 new cases



Case	∇ (m^3)	L_{BP} (m)	B_{WL} (m)	T (m)	$L/\nabla^{1/3}$ (-)	XB (m)	XF (m)	BM_L (m)	C_P (-)	C_{WP} (-)	MTC (t·cm)	BM_T (m)
V_141	62.15	16.0	4.70	1.63	3.992	-.017	-.243	12.64	.6258	.7497	.50	1.27
V_142	77.85	16.0	4.70	1.90	3.801	-.090	-.375	11.59	.6354	.7759	.58	1.11
V_143	94.34	16.0	4.70	2.17	3.658	-.154	-.521	11.00	.6423	.7999	.66	1.02
V_151	148.39	26.5	6.76	1.84	4.708	.020	-.008	22.72	.5585	.6584	1.31	1.95
V_152	186.54	26.5	6.80	2.17	4.389	-.018	-.100	20.90	.5771	.6906	1.51	1.69
V_153	225.95	26.5	6.80	2.50	4.195	-.004	-.095	19.10	.5841	.7105	1.67	1.51
V_161	78.73	18.0	5.20	1.82	4.166	.041	-.288	15.58	.6133	.7440	.70	1.50
V_162	99.02	18.0	5.20	2.10	3.965	-.059	-.486	14.82	.6241	.7793	.83	1.35
V_163	120.59	18.0	5.20	2.38	3.814	-.155	-.671	13.90	.6331	.8080	.96	1.23
V_171	150.93	25.0	6.68	1.78	4.507	.953	.765	24.76	.6614	.7296	1.54	2.11
V_172	189.76	25.0	6.70	2.10	4.221	.925	.654	21.67	.6710	.7525	1.69	1.82
V_173	229.85	25.0	6.70	2.42	4.017	.861	.526	19.67	.6769	.7719	1.86	1.60
V_181	43.90	14.0	4.29	1.46	3.873	.045	-.088	10.26	.6227	.7392	.33	1.13
V_182	54.73	14.0	4.30	1.70	3.705	.001	-.211	9.60	.6276	.7654	.39	1.01
V_183	66.24	14.0	4.30	1.94	3.577	-.050	-.355	9.31	.6331	.7922	.45	0.92
V_191	47.32	14.1	4.49	1.66	3.836	.028	-.177	9.63	.5850	.7161	.34	1.11
V_192	58.89	14.1	4.52	1.91	3.673	-.034	-.368	9.58	.5929	.7460	.41	1.03
V_193	71.51	14.1	4.54	2.16	3.578	-.116	-.545	9.31	.5952	.7638	.48	0.94

Hereinafter some seakeeping estimation models are reported from international technical literature in a functional form for the seakeeping rank to highlight that different hull form variables have been utilized.

-Bales model $\hat{R} = f\left[C_{WPF}, C_{WPA}, L/T, c/L, C_{VPF}, C_{VPA}\right]$

-McCreight model $\hat{R} = f[BM_L\nabla, C_{VPF}, C_{VPA}, BM_L/(L^3/B), L, T/B, A_{WP}/\nabla^{2/3}, BF\cdot\nabla, XB/\nabla^{1/3}, L^2/(B\cdot T)]$

-Wijngarden model $\hat{R} = f\left[XB, XF, C_{WP}, C_P, L/B.L/T\right]$

-Walden model $\hat{R} = f\left[C_{WPF}, C_{WPA}, L/T, c/L, C_{VPF}, C_{VPA}, \nabla\right]$

-Trincas and Nabergoj model $\hat{R} = f[BM_L\nabla, C_{VPF}, C_{VPA}, BM_L/(L^3/B), L, T/B, A_{WP}/\nabla^{2/3}, BF\cdot\nabla, XB/\nabla^{1/3}, L^2/(B\cdot T), C_P]$

-Nabergoj et al. model

$$R_h = f\left[L/\nabla^{\frac{1}{3}}, T/B, XB/L, C_P, C_{VPF}\right]$$

$$R_p = f\left[L/\nabla^{\frac{1}{3}}, T/B, XB/L, XF/L, BM_L, C_{VPF}\right]$$

$$R_{a_v} = f\left[L/\nabla^{1/3}, T/B, XB/L, XF/L, BM_L, C_P\right]$$

-Alkan et al. model $\hat{R} = f\left[L/B, L/T, B/T, C_B, C_P, C_X, C_{VP}, C_{WP}, L/\nabla^{1/3}, XB, XF\right]$

Table 2. Ranges of variables and attributes

N	Min	Max	Variable	Min	Max	N
39	**3.599**	4.854	$L/\nabla^{1/3}$	**3.577**	4.854	57
39	1.013	1.388	$B/\nabla^{1/3}$	1.013	1.388	57
38	**0.346**	0.563	$T/\nabla^{1/3}$	**0.334**	0.563	57
39	**5.191**	6.194	CS	**5.029**	6.194	57
39	3.008	4.372	L/B	3.008	4.372	57
39	2.017	3.795	B/T	2.017	3.795	5
39	**7.188**	**12.897**	L/T	**6.876**	**13.547**	57
39	0.343	**0.556**	C_B	0.343	**0.576**	57
39	0.559	**0.887**	C_M	0.559	**0.891**	57
39	**0.512**	0.691	C_P	**0.482**	0.690	57
39	**0.691**	0.856	C_{WP}	**0.658**	0.856	57
39	0.427	**0.685**	C_{PV}	0.427	**0.746**	57
39	**0.550**	2.023	BF	**0.028**	2.023	57
39	**19.250**	39.120	BM_L	**9.310**	39.120	57
39	**1.680**	3.720	BM_T	**0.920**	3.720	57
39	**0.980**	2.580	TPC	**0.440**	2.580	57
39	**1.270**	5.490	MTC	**0.330**	5.490	57
39	**0.397**	1.950	X_{i1}	**0.066**	1.950	57
39	**0.796**	2.096	X_{i3}	**0.449**	2.096	57
39	**0.271**	1.853	X_{i0}	**0**	1.853	57
39	**0.149**	0.445	X_{i19}	**0.097**	0.478	57
39	0	0.296	X_{i20}	0	0.296	57
39	**1.416**	2.444	Y_{i19}	**0.954**	2.444	57
39	**1.763**	2.931	B_{i16}	**1.499**	2.931	57
39	**20.341**	32.907	L_{OS}	**13.663**	32.907	57
39	**107.3**	541.3	Δ	**45.0**	541.3	57
N	**Min**	**Max**	**Attribute**	**Min**	**Max**	**N**
39	**0.498**	0.685	Heave	**0.407**	0.685	57
39	2.940	**3.867**	Pitch	2.940	**4.166**	57
39	1.075	**1.500**	Vert. Acc.	1.075	**2.019**	57

Table 3. Values of responses from theoretical computations

Vessel	Case	Heave (m)	Pitch (deg)	Vert. Acc. (m/s^2)
dinko	V_011	0.644	3.649	1.245
dinko	V_012	0.643	3.653	1.248
dinko	V_013	**0.685**	3.663	1.244
cost08	V_021	0.585	3.114	1.164
cost08	V_022	0.582	3.093	1.141
cost08	V_023	0.582	3.092	1.316
flori	V_031	0.569	3.234	1.277
flori	V_032	0.574	3.232	1.252
flori	V_033	0.566	3.444	1.495
gemma	V_041	0.567	3.216	1.280
gemma	V_042	0.580	3.203	1.261
gemma	V_043	0.570	3.323	1.401
genova	V_051	0.586	3.114	1.156
genova	V_052	0.584	3.125	1.135
genova	V_053	0.589	3.319	1.301
greben	V_061	0.650	3.715	1.375
greben	V_062	0.647	3.694	1.349
greben	V_063	0.652	3.867	1.495
ligny	V_071	0.600	3.198	1.131
ligny	V_072	0.562	3.131	1.138
ligny	V_073	0.569	3.196	1.215
tropea	V_081	0.602	3.192	1.329
tropea	V_082	0.601	3.080	1.252
tropea	V_083	0.598	3.314	1.409
aus25	V_091	0.637	3.574	1.291
aus25	V_092	0.635	3.607	1.290
aus25	V_093	0.638	3.665	1.344
mazara	V_101	0.498	2.963	**1.075**
mazara	V_102	0.498	2.989	1.082
mazara	V_103	0.499	3.056	1.118
nt28	V_111	0.646	3.596	1.293
nt28	V_112	0.643	3.602	1.299
nt28	V_113	0.651	3.776	1.426
russo	V_121	0.546	2.953	1.209
russo	V_122	0.546	**2.940**	1.203
russo	V_123	0.602	3.020	1.270
ubcbig	V_131	0.535	3.015	1.184
ubcbig	V_132	0.541	3.026	1.167
ubcbig	V_133	0.531	3.075	1.240
latina	V_141	0.442	3.721	**2.019**
latina	V_142	0.458	3.819	1.825
latina	V_143	0.470	3.753	1.747
napoli	V_151	0.440	3.176	1.944
napoli	V_152	0.459	3.320	1.964
napoli	V_153	0.471	3.397	1.943
matera	V_161	0.452	3.723	1.792
matera	V_162	0.464	3.543	1.740
matera	V_163	0.473	3.469	1.644
lipari	V_171	0.470	3.025	1.816
lipari	V_172	0.483	3.124	1.825
lipari	V_173	0.497	3.208	1.821
circeo	V_181	0.407	3.744	1.821
circeo	V_182	**0.422**	3.830	1.787
circeo	V_183	0.435	3.910	1.749
foggia	V_191	0.453	**4.166**	2.018
foggia	V_192	0.439	3.979	1.845
foggia	V_193	0.453	3.858	1.736

Table 4. Statistical characteristics of regression equations for heave (N39)

Regression model	L/T	MTC	BF	TPC	cost.
$h^{k=4}$	-.013418	-.052342	+.026450	+.068027	0.733051
t	9.2	4.9	4.8	2.2	35.8

Regression model	$B/\nabla^{1/3}$	Y_{i9}	Y_{i13}	Y_{i6}	A_{iO}	CS	BF	B_{i17}	A_{i15}	BM_T	cost.
$h^{k=10}$	.42830	1.2322	-.5128	-.5467	-.0309	-.0511	.0326	-.1119	.0290	-.0333	0.310554
t	8.6	6.3	5.4	4.1	5.3	4.0	3.9	3.9	3.8	3.1	3.5

Regression model	R^2_{adj}	F	S.E.	t_{min}	max error (%)	k	N
$h^{k=4}$	0.944	160	0.011	2.20	-5.6 + 3.1	4	39
$h^{k=10}$	0.970	126	0.008	3.10	-3.1 + 3.1	10	39

We applied all these models to the database of Mediterranean fishing vessels described in the next section. The results were poor enough from a statistical viewpoint, thus making those models unfeasible for conceptual design of Mediterranean fishing vessels. They do not present descriptors of aftermost and foremost hull form and/or details of the sectional area curve and design water line as independent variables. However, the MEDIT models developed by Nabergoj et al. (2003) were the most accurate statistically, also being the more corresponding to physics of seakeeping. They yielded reliable rankings of merit for heave, pitch and vertical accelerations.

A relevant enhancement of modelling the seakeeping behaviour of fishing vessels was reached by Şayli et al. (2010) through development of nonlinear metamodels.

DATABASE DEFINITION

Seakeeping modelling requires previous building of a database comprising geometric variables and parameters (hull form database) of vessels as well as their responses in specific seaways and operating conditions.

In this paper, the starting point was the so-called *historical database* consisting of thirteen modern Mediterranean fishing vessels, analyzed with the main scope of investigating the effect of different hull forms on seakeeping behaviour in rough sea (Nabergoj et al., 2003). The hull forms were faired with accuracy to predict vertical motions correctly. Evaluation of seakeeping responses for each fishing vessel was performed in three loading conditions giving rise to 39 cases (N39).

The main geometrical characteristics derived from the faired lines plans of six small and medium-sized Mediterranean fishing vessels have been derived at three loading conditions to build a new relational geometric database, which has been extended with respect to the historical one (N39). The main geometric particulars of the new 18 cases only are given in Table 1, being those of the old thirteen vessels reported in Nabergoj et al. (2003). The set of new eighteen cases were then incorporated in the historical database giving rise to the extended database (N57). The *extended database* has a total population of nineteen vessels and comprehends a large variety of single-screw hull forms: from ‘U’ to ‘V’ sections forward, from rounded sections to underwater chines; from no bulb to large bulbous bows fitted.

In Table 1, the locations of the longitudinal centres are given in meters and are relative to amidships (positive forward, negative aft). Static stability of each vessel was checked in detail using hydrostatic curves from hull forms. In defining hull form coefficients and parameters, length was assumed as the overall submerged length (L_{OS}).

The ranges of the independent variables and dependent attributes for the samples with N=39 and N=57, respectively, are illustrated in Table 2. Bolded max-min values are those that changed because of the extension of the database.

SEAKEEPING PERFORMANCE ATTRIBUTES

The seakeeping performance of the family of fishing vessels was evaluated in head sea by means of a suite of seakeeping codes based on a strip-theory which solves the potential by means of a modified closed-fit method. For each case the assumption was made that vessels are always in even keel condition with radius of gyration for pitch equal to 0.25 L_{PP}.

Each fishing vessel has been evaluated at three loading conditions, denoted by the last digit in each label readable in the first column of Table 1. In particular, digits 1, 2, and 3 refer to leaving to the fishing ground (100% consumables), leaving from the fishing ground (full holds and 40% consumables), and arriving to port (full holds and 10% consumables), respectively.

Table 5. Statistical characteristics of regression equations for pitch (N39)

Regression model	BM_L	TPC	BF	BM_T	$B/\nabla^{1/3}$	cost.
$p^{k=5}$	-.028725	-.388145	-.106514	+.173015	+.523031	+3.84103
t	13.5	8.5	5.2	3.2	2.2	15.6

Regression model	BM_L	L_{OS}	BM_T	B_{i16}	X_{i1}	Y_{i19}	BF	cost.
$p^{k=7}$	-.029058	-.026270	+.232990	-.171695	-.223765	+.169687	-.057512	+4.71754
t	14.9	9.0	7.2	6.4	4.7	2.8	2.2	23.0

Regression model	R^2_{adj}	F	S.E.	t_{min}	max error (%)	k	N
$p^{k=5}$	0.977	328	0.0415	2.19	-2.4 + 3.0	5	39
$p^{k=7}$	0.985	361	0.0311	1.98	-2.1 + 2.0	7	39

Seakeeping performance of existing fishing vessels was estimated assuming a Froude number Fn = 0.10 and significant wave height H_S=2.5 m. The selected wave condition corresponds to approximately an 18% probability of exceedance in the East Mediterranean areas. To compare results from statistical metamodels with the theoretical predictions, only average *rms* single amplitude responses are formulated by separate regression analyses of linear seakeeping computation results.

The theoretical performance values for the fishing vessels in all 57 cases are illustrated in Table 3. For the heave motion at centre of gravity, it can be seen that V_013 case presents the highest value, while V_182 case has the best performance. The pitch motion is maximum for V_191 case and minimum for V_122 case. For vertical acceleration at stern working area, it is seen that V_141 case has the highest and V_101 case has the lowest value. Figure 1 shows the body plans of some ‘best extreme type’ (Mazara, V_103),‘centred type’ (Flori, V_031; Gemma, V_041) and ‘worst extreme type’ (Foggia, V_191; Dinko, V_013).

SEAKEEPING MODELLING

The strategy was to develop a metamodel for each response, thus renouncing to define a mathematical model for the global rank. Ranks of Mediterranean fishing vessels were estimated for each seakeeping characteristic applying the specific metamodel for each response, namely, heave, pitch, and vertical acceleration at stern working area. ‘Step’, ‘forward’ and ‘backward’ regression techniques were applied recursively to obtain the metamodels.

Metamodels from the Historical Database (N39)

To improve accuracy of predictive models through introduction of descriptors for foremost and aftermost bodies, the N39 sample of heave, pitch and vertical acceleration reported in the upper part of Table 3 has been reconsidered first. Different regression equations have been developed for the original family of thirty-nine cases. For each response, the preferred models have been distinguished between a model which considers main geometrical characteristics only and a model which includes some geometrical details of hull form. The former is more suitable in the phase of concept design generation of feasible alternative solutions, while the latter is more dedicated to the phase of optimisation, that is, the robustness analysis of non-dominated designs.

The symbolic signs (+) and (-) in the functional relationships described hereinafter mean that the variable has a positive partial correlation or a negative partial correlation with the seakeeping response.

Heave

For heave at centre of gravity, two models are proposed as a function of either four or ten independent variables. The functional relationships are respectively:

$$h^{k=4} = \mathrm{f}\left[L/T\,(-), MTC\,(-), BF\,(+), TPC\,(-)\right] \tag{1}$$

$$h^{k=10} = \mathrm{f}\left[B/\nabla^{1/3}\,(+), Y_{i9}\,(+), Y_{i13}\,(-), Y_{i6}\,(-), A_{i0}\,(-), C_S\,(-), BF\,(+), B_{i17}\,(-), A_{i15}\,(+), BM_T\,(-)\right] \tag{2}$$

The coefficients of the regression equations and main statistical characteristics are given in Table 4.

Pitch

The preferred models for pitch are function of either five or seven independent variables. The functional relationships are respectively:

$$p^{k=5} = \mathrm{f}\left[BM_L\,(-), TPC\,(-), BF\,(-), BM_T\,(+), B/\nabla^{1/3}\,(+)\right] \tag{3}$$

Table 6. Statistical characteristics of regression equations for vertical acceleration (N39)

Regression model	X_{i0}	BM_L	BF	BM_T	cost.
$a_v^{k=4}$	-0.20734	-0.00821	-.05608	+.05396	1.662385
t	1.2.2	6.3	3.4	3.3	39.0

Regression model	BM_L	BF	X_{i19}	X_{i3}	L_{OS}	$B_{i16.}$	BM_T	X_{i1}	Y_{i19}	X_{i20}	cost.
$a_v^{k=10}$	-.02184	-.25396	+1.09815	-.81677	+.025187	-.204565	+.202789	+.51538	-.23681	-.30445	2.13132
t	15.0	12.2	11.0	10.2	9.2	8.9	8.5	7.3	6.6	4.7	18.2

Regression model	R^2_{adj}	F	S.E.	t_{min}	max error (%)	k	N
$a_v^{k=4}$	0.891	78	0.0350	3.30	-5.1 + 5.2	4	39
$a_v^{k=10}$	0.970	123	0.0018	4.70	-2.2 + 2.8	10	39

$$p^{k=7} = \mathrm{f}\,[BM_L\,(-), L_{OS}\,(-), BF\,(-), BM_T\,(+), B_{i16}\,(-), X_{i1}\,(-),\ Y_{i19}\,(+)] \tag{4}$$

where the latter (k=7) includes details of fore and aft hull form. The B coefficients of the corresponding equations together with t-Student for each variable, and statistics of the two regression equations are illustrated in Table 5.

Vertical Acceleration

The preferred models for vertical acceleration at stern working area are functional of either four or ten independent variables. The functional relationships are respectively:

$$a_v^{k=4} = \mathrm{f}\,[X_{i0}\,(-), BM_L\,(-), BM_T\,(+), BF\,(-)] \tag{5}$$

$$a_v^{k=10} = \mathrm{f}\,[BM_L\,(-), BF\,(-), X_{i19}\,(+), X_{i3}\,(-), L_{OS}\,(+),$$

$$B_{i16}\,(-), BM_T\,(+), X_{i1}\,(+), Y_{i19}\,(-), X_{i20}\,(-)] \tag{6}$$

where the latter includes many details of entrance and run bodies. The B coefficients of the corresponding equations together with main statistical parameters are given in Table 6.

DISCUSSION

In approximation models for vertical acceleration it can be observed that variables BM_L, BM_T, and B_F are important in both the models with k=4 and k=10 variables. Moreover, these independent variables are present also in models for pitch and result coherent in their effect, in the sense that both responses are reduced by increasing BM_L and decreasing BM_T and BF values. These indications confirm the physical intuition that vertical motions and induced effects are strongly affected by the longitudinal separation between centre of gravity and centre of flotation (B_F) and by metacentric radii.

Tables 7 and 8 permit a detailed comparison between theoretical and statistical values of pitch and vertical acceleration, respectively, while considering the simple and the more detailed models. Fishing vessels have been ranked in each subgroup starting from the vessel that presents the best performance for the response considered. Bolded cases and related vessels indicate an exactly alike position in the ranking between theoretical and statistical results. In general, the relative capability of a fishing vessel is confirmed whichever is the approach used to estimate its responses. Maximum and minimum absolute errors, as defined in the nomenclature, are displayed too. It is evident that the models with higher number of independent variables are more accurate in prediction.

Metamodels from the Extended Database (N57)

For the extended database with nineteen fishing vessels, each at three load conditions for a total of 57 cases, the following functional relationships were derived, which provide a good statistical accuracy while showing consistent physical meaning.

$$h = \mathrm{f}\,[BF\,(+), C_X\,(-), MTC\,(-), Y_{i19}\,(+), TPC, T/\nabla^{1/3}\,(-), L/T\,(-)\,, X_{i20}\,(+)] \tag{7}$$

$$p = \mathrm{f}\,[BF\,(-), C_{PV}\,(+), MTC\,(+), X_{i20}\,(+),$$

$$B/\nabla^{1/3}\,(+), L/T\,(+), X_{i3}\,(+), B/T\,(-), TPC\,(-)] \tag{8}$$

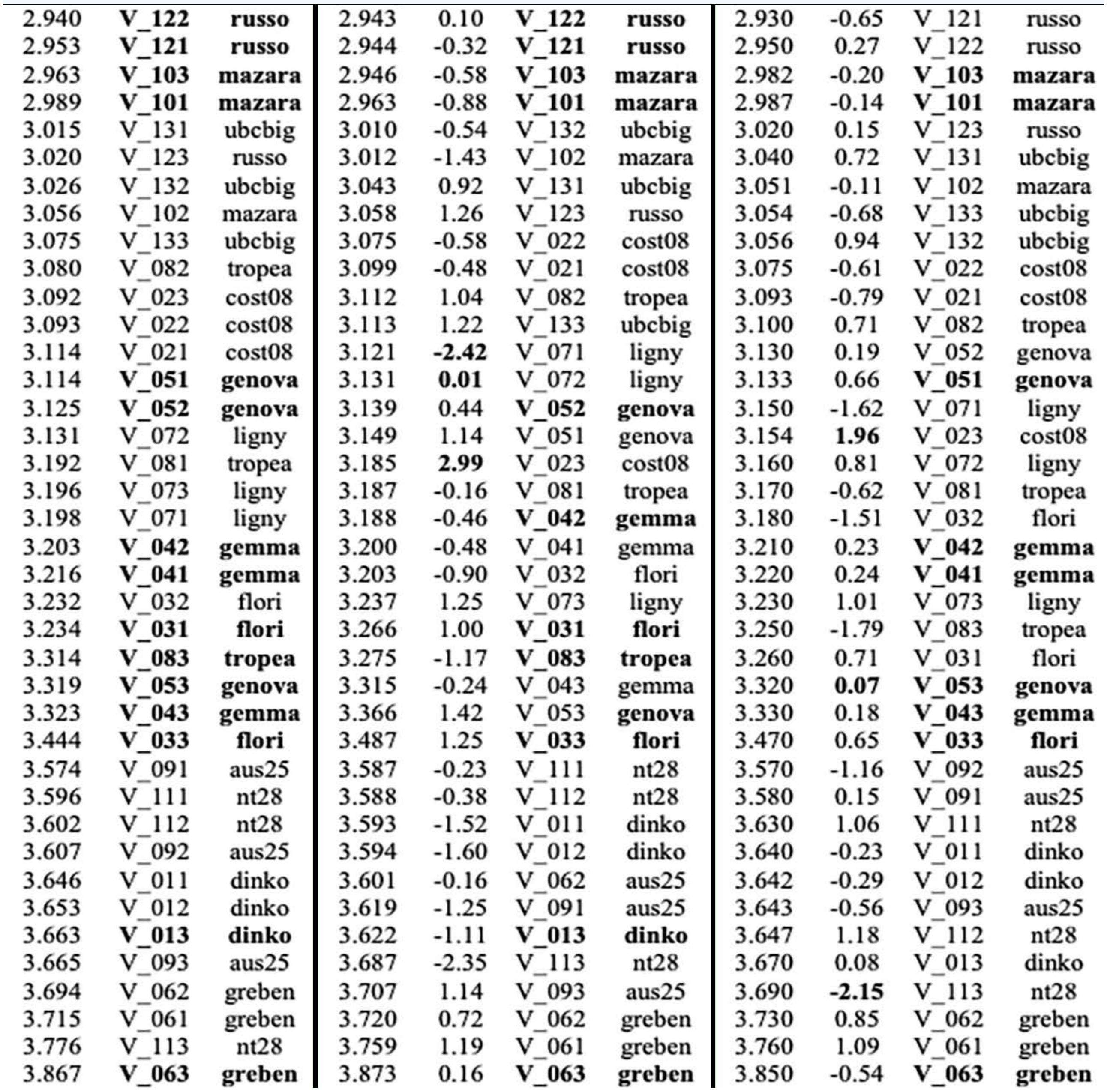
$$a_v = \mathrm{f}\,[BF\,(-), C_{WP}\,(-), MTC\,(-), X_{i20}\,(-), B/\nabla^{1/3}\,(-), L/T\,(+), X_{i19}\,(+), BM_L\,(-)] \tag{9}$$

It is worth noticing from these relationships that the extension of the database yielded an inversion of correlation for some hull form variables such as MTC, X_{i20}, and $B/\nabla^{1/3}$.

Statistical characteristics of the metamodels for h, p, and a_v, as derived from the extended database (N 57), are illustrated in Table 9, while the corresponding B coefficients and t_{min} values are given in Tables 10 through 12. In these tables, percentage of errors is given too, showing an acceptable accuracy of the proposed models from an engineering viewpoint.

Tables 13 through 15 illustrate the position in rank for the fishing vessels. In the right side of the table one can read the rank for the 57 cases according to the response values as derived from theoretical calculations. In the left side the rank is given according to the results yielded by the statis-

Table 7. Comparison between computed and estimated values for pitch with two different models and (historical database, N39)



p (theory)	Case	Vessel	$p^{k=5}$ (model)	Error (%)	Case	Vessel	$p^{k=7}$ (model)	Error (%)	Case	Vessel
2.940	**V_122**	**russo**	2.943	0.10	**V_122**	**russo**	2.930	-0.65	V_121	russo
2.953	**V_121**	**russo**	2.944	-0.32	**V_121**	**russo**	2.950	0.27	V_122	russo
2.963	**V_103**	**mazara**	2.946	-0.58	**V_103**	**mazara**	2.982	-0.20	**V_103**	**mazara**
2.989	**V_101**	**mazara**	2.963	-0.88	**V_101**	**mazara**	2.987	-0.14	**V_101**	**mazara**
3.015	V_131	ubcbig	3.010	-0.54	V_132	ubcbig	3.020	0.15	V_123	russo
3.020	V_123	russo	3.012	-1.43	V_102	mazara	3.040	0.72	V_131	ubcbig
3.026	V_132	ubcbig	3.043	0.92	V_131	ubcbig	3.051	-0.11	V_102	mazara
3.056	V_102	mazara	3.058	1.26	V_123	russo	3.054	-0.68	V_133	ubcbig
3.075	V_133	ubcbig	3.075	-0.58	V_022	cost08	3.056	0.94	V_132	ubcbig
3.080	V_082	tropea	3.099	-0.48	V_021	cost08	3.075	-0.61	V_022	cost08
3.092	V_023	cost08	3.112	1.04	V_082	tropea	3.093	-0.79	V_021	cost08
3.093	V_022	cost08	3.113	1.22	V_133	ubcbig	3.100	0.71	V_082	tropea
3.114	V_021	cost08	3.121	**-2.42**	V_071	ligny	3.130	0.19	V_052	genova
3.114	**V_051**	**genova**	3.131	**0.01**	V_072	ligny	3.133	0.66	**V_051**	**genova**
3.125	**V_052**	**genova**	3.139	0.44	**V_052**	**genova**	3.150	-1.62	V_071	ligny
3.131	V_072	ligny	3.149	1.14	V_051	genova	3.154	**1.96**	V_023	cost08
3.192	V_081	tropea	3.185	**2.99**	V_023	cost08	3.160	0.81	V_072	ligny
3.196	V_073	ligny	3.187	-0.16	V_081	tropea	3.170	-0.62	V_081	tropea
3.198	V_071	ligny	3.188	-0.46	**V_042**	**gemma**	3.180	-1.51	V_032	flori
3.203	**V_042**	**gemma**	3.200	-0.48	V_041	gemma	3.210	0.23	**V_042**	**gemma**
3.216	**V_041**	**gemma**	3.203	-0.90	V_032	flori	3.220	0.24	**V_041**	**gemma**
3.232	V_032	flori	3.237	1.25	V_073	ligny	3.230	1.01	V_073	ligny
3.234	**V_031**	**flori**	3.266	1.00	**V_031**	**flori**	3.250	-1.79	V_083	tropea
3.314	**V_083**	**tropea**	3.275	-1.17	**V_083**	**tropea**	3.260	0.71	V_031	flori
3.319	**V_053**	**genova**	3.315	-0.24	V_043	gemma	3.320	**0.07**	**V_053**	**genova**
3.323	**V_043**	**gemma**	3.366	1.42	V_053	**genova**	3.330	0.18	**V_043**	**gemma**
3.444	**V_033**	**flori**	3.487	1.25	**V_033**	**flori**	3.470	0.65	**V_033**	**flori**
3.574	V_091	aus25	3.587	-0.23	V_111	nt28	3.570	-1.16	V_092	aus25
3.596	V_111	nt28	3.588	-0.38	V_112	nt28	3.580	0.15	V_091	aus25
3.602	V_112	nt28	3.593	-1.52	V_011	dinko	3.630	1.06	V_111	nt28
3.607	V_092	aus25	3.594	-1.60	V_012	dinko	3.640	-0.23	V_011	dinko
3.646	V_011	dinko	3.601	-0.16	V_062	aus25	3.642	-0.29	V_012	dinko
3.653	V_012	dinko	3.619	-1.25	V_091	aus25	3.643	-0.56	V_093	aus25
3.663	**V_013**	**dinko**	3.622	-1.11	**V_013**	**dinko**	3.647	1.18	V_112	nt28
3.665	V_093	aus25	3.687	-2.35	V_113	nt28	3.670	0.08	V_013	dinko
3.694	V_062	greben	3.707	1.14	V_093	aus25	3.690	**-2.15**	V_113	nt28
3.715	V_061	greben	3.720	0.72	V_062	greben	3.730	0.85	V_062	greben
3.776	V_113	nt28	3.759	1.19	V_061	greben	3.760	1.09	V_061	greben
3.867	**V_063**	**greben**	3.873	0.16	**V_063**	**greben**	3.850	-0.54	**V_063**	**greben**

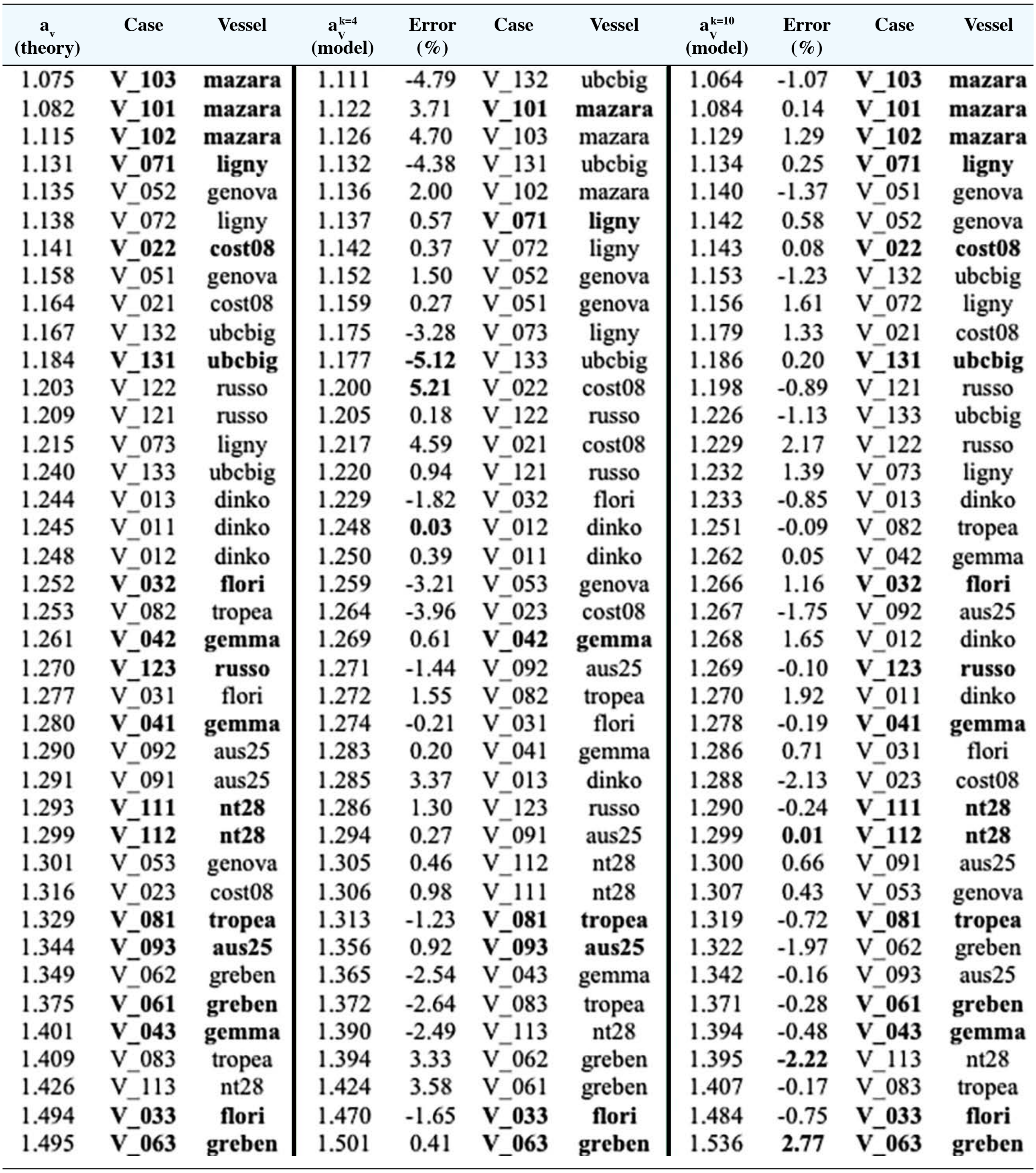
tical model. The percentage error between estimated and computed values for each case is given too. One can observe that positions in the rank are generally maintained when comparing the two situations. Really, the rank position is exactly kept on by many cases; in particular, the best fishing vessel results the same whichever the method followed to determine vertical acceleration *rms*. The cases presenting an estimated value with error 2.5 percent and higher than theoretical value are bolded in Tables 13 through 15.

SOME DESIGN GUIDELINES

Analyses of proposed models provide the following design guidelines aimed to reduce values of dynamic characteristics. They can be translated into criteria for hull form optimization purpose such as:

- increase BM_L to reduce both pitch and vertical acceleration;
- increase longitudinal separation between centre of buoyancy and centre of flotation, *BF*, to reduce pitch and vertical acceleration;

Table 8. Comparison between computed and estimated values for vertical acceleration with two different models: and (historical database, N39)



a_v (theory)	Case	Vessel	$a_V^{k=4}$ (model)	Error (%)	Case	Vessel	$a_V^{k=10}$ (model)	Error (%)	Case	Vessel
1.075	**V_103**	**mazara**	1.111	-4.79	V_132	ubcbig	1.064	-1.07	**V_103**	**mazara**
1.082	**V_101**	**mazara**	1.122	3.71	**V_101**	**mazara**	1.084	0.14	**V_101**	**mazara**
1.115	**V_102**	**mazara**	1.126	4.70	V_103	mazara	1.129	1.29	**V_102**	**mazara**
1.131	**V_071**	**ligny**	1.132	-4.38	V_131	ubcbig	1.134	0.25	**V_071**	**ligny**
1.135	V_052	genova	1.136	2.00	V_102	mazara	1.140	-1.37	V_051	genova
1.138	V_072	ligny	1.137	0.57	**V_071**	**ligny**	1.142	0.58	V_052	genova
1.141	**V_022**	**cost08**	1.142	0.37	V_072	ligny	1.143	0.08	**V_022**	**cost08**
1.158	V_051	genova	1.152	1.50	V_052	genova	1.153	-1.23	V_132	ubcbig
1.164	V_021	cost08	1.159	0.27	V_051	genova	1.156	1.61	V_072	ligny
1.167	V_132	ubcbig	1.175	-3.28	V_073	ligny	1.179	1.33	V_021	cost08
1.184	**V_131**	**ubcbig**	1.177	**-5.12**	V_133	ubcbig	1.186	0.20	**V_131**	**ubcbig**
1.203	V_122	russo	1.200	**5.21**	V_022	cost08	1.198	-0.89	V_121	russo
1.209	V_121	russo	1.205	0.18	V_122	russo	1.226	-1.13	V_133	ubcbig
1.215	V_073	ligny	1.217	4.59	V_021	cost08	1.229	2.17	V_122	russo
1.240	V_133	ubcbig	1.220	0.94	V_121	russo	1.232	1.39	V_073	ligny
1.244	V_013	dinko	1.229	-1.82	V_032	flori	1.233	-0.85	V_013	dinko
1.245	V_011	dinko	1.248	**0.03**	V_012	dinko	1.251	-0.09	V_082	tropea
1.248	V_012	dinko	1.250	0.39	V_011	dinko	1.262	0.05	V_042	gemma
1.252	**V_032**	**flori**	1.259	-3.21	V_053	genova	1.266	1.16	**V_032**	**flori**
1.253	V_082	tropea	1.264	-3.96	V_023	cost08	1.267	-1.75	V_092	aus25
1.261	**V_042**	**gemma**	1.269	0.61	**V_042**	**gemma**	1.268	1.65	V_012	dinko
1.270	**V_123**	**russo**	1.271	-1.44	V_092	aus25	1.269	-0.10	**V_123**	**russo**
1.277	V_031	flori	1.272	1.55	V_082	tropea	1.270	1.92	V_011	dinko
1.280	**V_041**	**gemma**	1.274	-0.21	V_031	flori	1.278	-0.19	**V_041**	**gemma**
1.290	V_092	aus25	1.283	0.20	V_041	gemma	1.286	0.71	V_031	flori
1.291	V_091	aus25	1.285	3.37	V_013	dinko	1.288	-2.13	V_023	cost08
1.293	**V_111**	**nt28**	1.286	1.30	V_123	russo	1.290	-0.24	**V_111**	**nt28**
1.299	**V_112**	**nt28**	1.294	0.27	V_091	aus25	1.299	**0.01**	**V_112**	**nt28**
1.301	V_053	genova	1.305	0.46	V_112	nt28	1.300	0.66	V_091	aus25
1.316	V_023	cost08	1.306	0.98	V_111	nt28	1.307	0.43	V_053	genova
1.329	**V_081**	**tropea**	1.313	-1.23	**V_081**	**tropea**	1.319	-0.72	**V_081**	**tropea**
1.344	**V_093**	**aus25**	1.356	0.92	**V_093**	**aus25**	1.322	-1.97	V_062	greben
1.349	V_062	greben	1.365	-2.54	V_043	gemma	1.342	-0.16	V_093	aus25
1.375	**V_061**	**greben**	1.372	-2.64	V_083	tropea	1.371	-0.28	**V_061**	**greben**
1.401	**V_043**	**gemma**	1.390	-2.49	V_113	nt28	1.394	-0.48	**V_043**	**gemma**
1.409	V_083	tropea	1.394	3.33	V_062	greben	1.395	**-2.22**	V_113	nt28
1.426	V_113	nt28	1.424	3.58	V_061	greben	1.407	-0.17	V_083	tropea
1.494	**V_033**	**flori**	1.470	-1.65	**V_033**	**flori**	1.484	-0.75	**V_033**	**flori**
1.495	**V_063**	**greben**	1.501	0.41	**V_063**	**greben**	1.536	**2.77**	**V_063**	**greben**

- increase the beam at fore shoulder, B_{i16}, to reduce both pitch and vertical acceleration;
- flatten aftermost sections by increasing values of X_{i0} and X_{i3}, to reduce vertical acceleration;
- modify shape of section 19 by increasing X_{i19} value and decreasing Y_{i19}, to reduce vertical acceleration;
- modify shape of section at forward perpendicular by increasing X_{i20} value; cylindrical bulbs should be preferred to elliptical bulbs;
- increase L_{OS} and X_{i1} to reduce pitch; the opposite, even minor, effect is yielded for higher vertical acceleration;

Table 9. Statistical characteristics of regression equations from the extended database (N57)

Response	k	R^2_{adj}	F	S.E.	t_{min}	max error (%)
h_{57}	8	0.958	162	0.015	3.5	-6.5 + 6.3
p_{57}	9	0.964	170	0.060	2.4	-3.7 + 3.6
$a_v{}^{57}$	8	0.973	249	0.048	3.8	-6.8 + 6.6

Table 10. Regression equation and t statistic of independent variables in heave metamodel (N57)

Heave model	BF	C_X	MTC	Y_{i19}	TPC	$T/^{\nabla 1/3}$	L/T	X_{i20}	cost.
B_i	+0.084887	-0.423258	-0.083964	+0.116433	+0.155645	-0.870162	-0.016044	+0.113951	+1.108521
t	11.2	9.0	8.0	5.7	4.6	45	4.0	3.5	8.4

% of errors <6.0%=55/57=96%, % of errors <5.0%=52/57=91%, % of errors <3.0%=48/57=84%

Table 11. Regression equation and t statistic of independent variables in pitch metamodel (N57)

Pitch model	BV	TPC	B/T	C_{PV}	X_{i20}	BF	X_{i3}	MTC	L/T	cost.
B_i	+5.419802	-0.833161	-1.268079	+2.558548	+0.671832	-0.149733	+0.429531	+0.134940	+0.086205	-1.451648
t	8.3	7.0	5.7	5.6	5.0	4.4	4.3	2.8	2.4	2

% of errors <3.0%=54/57=95%, % of errors <2.5%=50/57=88%, % of errors <2.0%=46/57=81%

Table 12. Regression equation and t statistic of independent variables in vertical acceleration metamodel (N57)

Vert.Acc. model	BM_L	X_{i20}	C_{WP}	$B/\nabla^{1/3}$	MTC	BF	L/T	X^{i19}	cost.
B_i	-0.019861	-0.812488	-2.159049	-0.481660	-0.050354	-0.119615	+0.04897	+0.491518	+3.827245
t	7.0	5.8	5.7	4.6	4.6	4.5	4.5	5.8	10.1

% of errors <5.0%=52/57=91%, % of errors <4.0%=49/57=86%, % of errors <3.0%=44/57=77%

- reduce values of BM_T, to get low values for both pitch and vertical acceleration.

CONCLUSIONS

The most significant contribution of this paper is twofold. It provides additional insight on the influence of hull form parameters on seakeeping performance of fishing vessels and develops related metamodels to facilitate and speed up the selection of the 'best possible' solution at concept design stage, so improving hull design.

Results of the analysis carried out on the extended database (N57) of fishing vessels are very promising. They lay the foundations for a more extensive work aimed to determine more accurate and reliable estimation models of seakeeping responses. In this respect, it is interesting to quote Bales and Cummins (1970):

"*...It is believed to permit variations in all parameters which have a significant effect upon seakeeping. The shape of the waterline effectively governs the longitudinal distribution of both damping and restoring forces. The end values of the sectional area coefficient curve control the longitudinal distribution of displacement and the longitudinal centre of buoyancy can be shifted independently of the longitudinal centre of flotation, a quality which strongly affects the coupling between heave and pitch*".

Foundation of the previous statement has been verified for the examined family of the Mediterranean fishing vessels as shown by the presence in the present metamodels of the variable BF (which depends on waterline and sectional area curve shape) and variables A_{i0}, A_{i15}, B_{i16}, B_{i17}, X_{i1}, X_{i19}, X_{i3}, X_{i1}, X_{i20}, Y_{i9}, Y_{i13}, Y_{i6}, Y_{i19} which depend on local section shapes.

On the contrary, these metamodels do not allow agreement with Bales and Cummins (1970), when they state:

"*As ship motions do not appear to be sensitive to local details of hull shape, it is possible to select a simplified family of mathematical forms, each of which have motions in waves very near that of many ships in the total population. That this-is-so is demonstrated by the success of the 'strip theory' technique for computing ship motions, which replaces the ac-*

Table 13. Comparison between computed and estimated values for heave (N57)

h57 (statistics)	Error (%)	h (theory)	Vessel	Case	Case	Vessel	h (theory)
0.4174	**2.56**	0.407	circeo	**V_181**	**V_181**	circeo	0.407
0.4195	-0.60	0.422	circeo	**V_182**	**V_182**	circeo	0.422
0.4259	-2.08	0.435	circeo	**V_183**	**V_183**	circeo	0.435
0.4392	-0.19	0.440	napoli	**V_151**	**V_192**	foggia	0.439
0.4395	-0.56	0.442	latina	**V_141**	**V_151**	napoli	0.440
0.4434	-2.12	0.453	foggia	**V_191**	**V_141**	latina	0.442
0.4435	**-3.17**	0.458	latina	**V_142**	V_161	matera	0.452
0.4468	2.24	0.439	foggia	**V_192**	**V_191**	foggia	0.453
0.4489	**-4.48**	0.470	latina	V_143	**V_193**	foggia	0.453
0.4521	-0.20	0.453	foggia	**V_193**	**V_142**	latina	0.458
0.4615	0.55	0.459	napoli	V_152	V_152	napoli	0.459
0.4726	0.34	0.471	napoli	V_153	V_162	matera	0.464
0.4757	1.21	0.470	lipari	V_171	V_143	latina	0.470
0.4845	0.31	0.483	lipari	V_172	V_171	lipari	0.470
0.4806	**6.33**	0.452	matera	V_161	V_153	napoli	0.471
0.4913	**5.89**	0.464	matera	V_162	V_163	matera	0.473
0.4952	-0.36	0.497	lipari	V_173	V_172	lipari	0.483
0.4972	-0.36	0.499	mazara	V_102	V_173	lipari	0.497
0.4987	**5.43**	0.473	matera	V_163	V_101	mazara	0.498
0.5018	0.76	0.498	mazara	V_101	V_103	mazara	0.498
0.5039	1.18	0.498	mazara	V_103	V_102	mazara	0.499
0.5248	-1.17	0.531	ubcbig	V_133	V_133	ubcbig	0.531
0.5328	-2.24	0.545	russo	V_123	V_131	ubcbig	0.535
0.5362	-1.79	0.546	russo	V_121	V_132	ubcbig	0.541
0.5362	-1.79	0.546	russo	V_122	V_123	russo	0.545
0.5405	-0.09	0.541	ubcbig	V_132	V_121	russo	0.546
0.5462	**-3.49**	0.566	flori	V_033	V_122	russo	0.546
0.5624	**5.12**	0.535	ubcbig	V_131	V_072	ligny	0.562
0.5667	**-3.78**	0.589	genova	V_053	V_033	flori	0.566
0.5670	-0.34	0.569	ligny	V_073	V_041	gemma	0.567
0.5703	-2.35	0.584	genova	V_052	V_031	flori	0.569
0.5726	-2.29	0.586	genova	V_051	V_073	ligny	0.569
0.5731	0.71	0.569	flori	V_031	V_043	gemma	0.570
0.5778	2.81	0.562	ligny	V_072	V_032	flori	0.574
0.5788	1.54	0.570	gemma	V_043	V_042	gemma	0.580
0.5815	**-3.09**	0.600	ligny	V_071	V_022	cost08	0.582
0.5818	1.36	0.574	flori	V_032	V_023	cost08	0.582
0.5839	2.98	0.567	gemma	V_041	V_052	genova	0.584
0.5852	0.90	0.580	gemma	V_042	V_021	cost08	0.585
0.5907	1.49	0.582	cost08	V_022	V_051	genova	0.586
0.5917	1.67	0.582	cost08	V_023	V_053	genova	0.589
0.5926	-0.90	0.598	tropea	V_083	V_083	tropea	0.598
0.5935	-1.25	0.601	tropea	V_082	V_071	ligny	0.600
0.5962	1.91	0.585	cost08	V_021	V_082	tropea	0.601
0.5991	-0.48	0.602	tropea	V_081	V_081	tropea	0.602
0.6094	**-6.54**	0.652	greben	V_063	V_092	aus25	0.635
0.6270	-2.65	0.644	dinko	V_011	V_091	aus25	0.637
0.6288	**2.81**	0.647	greben	**V_062**	**V_093**	aus25	0.638
0.6315	**-2.85**	0.650	greben	**V_081**	**V_012**	dinko	0.643
0.6389	-1.86	0.651	nt28	**V_113**	**V_112**	nt28	0.643
0.6452	1.60	0.635	aus25	V_092	V_011	dinko	0.644
0.6495	1.01	0.643	nt28	**V_112**	**V_111**	nt28	0.646
0.6508	1.21	0.643	dinko	**V_012**	**V_062**	greben	0.647
0.6512	2.08	0.638	aus25	**V_093**	**V_061**	greben	0.650
0.6527	2.46	0.637	aus25	V_091	**V_113**	nt28	0.651
0.6562	1.57	0.646	nt28	V_111	V_063	greben	0.652
0.6957	1.56	0.685	dinko	**V_013**	**V_013**	dinko	0.685

Table 14. Comparison between computed and estimated values for pitch (N57)

p57 (statistics)	Error (%)	h (theory)	Vessel	Case	Case	Vessel	p (theory)
2.8983	-1.85	2.953	russo	**V_121**	**V_122**	russo	2.940
2.9142	-1.65	2.963	mazara	**V_103**	**V_121**	russo	2.953
2.9448	0.16	2.940	russo	**V_122**	**V_103**	mazara	2.963
2.9573	-2.08	3.020	russo	**V_123**	**V_101**	mazara	2.989
2.9817	-0.24	2.989	mazara	**V_101**	**V_131**	ubcbig	3.015
3.0085	-0.22	3.015	ubcbig	**V_131**	**V_123**	russo	3.020
3.0480	0.78	3.025	lipari	**V_171**	**V_171**	lipari	3.025
3.0583	1.07	3.026	ubcbig	**V_132**	**V_152**	ubcbig	3.026
3.0825	-1.01	3.114	genova	V_051	V_102	mazara	3.058
3.0827	0.25	3.075	ubcbig	**V_133**	**V_133**	ubcbig	3.075
3.0885	0.14	3.093	cost08	V_022	V_082	tropea	3.080
3.0911	-1.09	3.125	genova	V_052	V_023	cost08	3.092
3.1136	-0.01	3.114	cost08	V_021	V_022	cost08	3.093
3.1265	2.31	3.056	mazara	**V_102**	**V_051**	genova	3.114
3.1289	1.59	3.080	tropea	V_082	V_021	cost08	3.114
3.1527	-0.92	3.124	lipari	V_172	V_172	lipari	3.124
3.1837	--0.60	3.203	gemma	V_042	V_052	genova	3.125
3.1842	-0.43	3.198	ligny	V_071	V_072	ligny	3.131
3.1867	**3.06**	3.092	cost08	V_023	V_151	napoli	3.176
3.1940	0.06	3.192	tropea	V_081	V_081	tropea	3.192
3.1956	**-3.72**	3.319	genova	V_053	V_073	ligny	3.196
3.2096	0.43	3.196	ligny	V_073	V_071	ligny	3.198
3.2106	-0.17	3.216	gemma	V_041	V_042	gemma	3.203
3.2164	-0.48	3.232	flori	V_032	V_173	lipari	3.208
3.2164	**2.79**	3.131	ligny	V_072	V_041	gemma	3.216
3.2227	0.46	3.208	lipari	V_173	V_032	flori	3.232
3.2612	0.84	3.234	flori	V_031	V_031	flori	3.234
3.2689	**2.92**	3.176	napoli	V_151	V_083	tropea	3.314
3.2906	-0.71	3.314	tropea	V_083	V_053	genova	3.319
3.3073	-0.47	3.323	gemma	V_043	V_152	napoli	3.320
3.3195	-0.02	3.320	napoli	V_152	V_043	gemma	3.323
3.3438	-1.57	3.397	napoli	V_153	V_153	napoli	3.397
3.3701	-2.14	3.444	flori	V_033	V_033	flori	3.444
3.5943	**3.61**	3.469	matera	V_163	V_163	matera	3.469
3.5962	-0.30	3.607	aus25	V_092	V_162	matera	3.543
3.5975	0.66	3.674	aus25	V_091	V_091	aus25	3.574
3.6077	0.16	3.602	nt28	V_112	V_111	nt28	3.596
3.6288	0.91	3.596	nt28	V_111	V_112	nt28	3.602
3.6335	-0.86	3.665	aus25	V_093	V_092	aus25	3.607
3.6404	-0.35	3.663	dinko	V_012	V_011	dinko	3.649
3.6405	**2.75**	3.543	matera	V_162	V_012	dinko	3.653
3.6467	-0.44	3.663	dinko	V_013	V_013	dinko	3.663
3.6851	-1.02	3.723	matera	V_161	V_093	aus25	3.665
3.7011	-1.38	3.753	latina	V_143	V_062	greben	3.694
3.7095	1.66	3.649	dinko	V_011	**V_061**	greben	3.715
3.7222	0.76	3.694	greben	V_062	**V_141**	latina	3.721
3.7264	-2.43	3.819	latina	V_142	V_161	matera	3.723
3.7344	0.35	3.721	latina	V_141	**V_181**	circeo	3.744
3.7517	-0.64	3.776	nt28	**V_113**	**V_143**	latina	3.753
3.7534	1.03	3.715	greben	V_061	**V_113**	nt28	3.776
3.7956	-1.85	3.867	greben	**V_063**	**V_142**	latina	3.819
3.8126	**-2.69**	3.918	circeo	**V_183**	**V_182**	circeo	3.830
3.8651	0.92	3.830	circeo	**V_182**	**V_193**	foggia	3.858
3.8776	**3.57**	3.744	circeo	**V_182**	**V_063**	greben	3.867
3.8946	0.95	3.858	foggia	**V_193**	**V_183**	circeo	3.918
3.9742	-0.12	3.979	foggia	**V_192**	**V_192**	foggia	3.979
4.0413	**-2.99**	4.166	foggia	**V_191**	**V_191**	foggia	4.166

tual section shape at each section by a so-called ‘Lewis section’ having the same breadth, draft, and area”.

Conversely, on the basis of the results achieved for the extended database, at least for the type of vessel considered the authors arrive to the provisional conclusion that

> *a: ship motions appear to be sensitive to local details of the hull form,*
>
> *b: there is no more need for any replacement of actual section shapes, since* nowadays it is not at all expensive and time consuming to draw a lines plan.

Really, all variables in the metamodels here presented refer to values obtained directly from the lines plan without any alteration.

Future efforts will be devoted to demonstrate that the above conclusive sentence holds for all type of dis-

Table 15. Comparison between computed and estimated values for vertical acceleration (N57)

a_v (statistics)	Error (%)	a_v (theory)	Vessel	Case	Case	Vessel	a_v (theory)
1.0524	-2.10	1.075	mazara	**V_103**	**V_103**	mazara	1.075
1.0883	0.58	1.082	mazara	**V_101**	**V_101**	mazara	1.082
1.1206	-1.79	1.141	mazara	**V_022**	V_102	mazara	1.115
1.1262	-0.78	1.135	genova	**V_052**	**V_071**	ligny	1.131
1.1382	0.64	1.131	ligny	**V_071**	**V_052**	genova	1.135
1.1399	-1.39	1.156	genova	**V_051**	**V_072**	ligny	1.138
1.1485	**-2.99**	1.184	ubcbig	V_131	**V_022**	cost08	1.141
1.1503	-1.43	1.167	ubcbig	**V_132**	**V_051**	genova	1.156
1.1506	1.11	1.138	ligny	**V_072**	**V_021**	cost08	1.164
1.1680	0.34	1.164	cost08	**V_021**	**V_132**	ubcbig	1.167
1.1760	-2.25	1.203	russo	V_122	**V_131**	ubcbig	1.184
1.1881	**6.56**	1.115	mazara	**V_102**	V_122	russo	1.203
1.2019	**-3.08**	1.240	ubcbig	V_133	V_121	russo	1.209
1.2179	0.24	1.215	ligny	V_073	V_073	ligny	1.215
1.2265	-2.04	1.252	flori	V_032	V_133	ubcbig	1.240
1.2346	-2.09	1.261	gemma	V_042	V_013	dinko	1.244
1.2368	2.30	1,209	russo	V_121	V_011	dinko	1.245
1.2388	-1.05	1.252	tropea	V_082	V_012	dinko	1.248
1.2533	0.43	1.248	dinko	V_012	V_032	flori	1.252
1.2560	0.88	1.245	dinko	V_011	V_082	tropea	1.253
1.2634	-2.13	1.291	aus25	V_091	V_042	gemma	1.261
1.2735	-0.51	1.280	gemma	V_041	V_123	russo	1.270
1.2849	-0.39	1.290	aus25	V_092	V_031	flori	1.277
1.2879	-0.40	1.293	nt28	V_111	V_041	gemma	1.280
1.2906	-1.93	1.316	cost08	V_023	V_092	aus25	1.290
1.2939	1.25	1.277	flori	V_031	V_091	aus25	1.291
1.2975	**4.30**	1.244	dinko	V_013	V_111	nt28	1.293
1.2984	-0.04	1.299	nt28	V_112	V_112	nt28	1.299
1.3270	2.00	1.301	genova	V_053	V_053	genova	1.301
1.3390	0.75	1.329	tropea	V_081	V_023	cost08	1.316
1.3396	-0.33	1.344	aus25	V_093	V_081	tropea	1.329
1.3403	**-6.01**	1.426	nt28	V_113	V_093	aus25	1.344
1.3541	**6.62**	1.270	russo	V 123	V 062	greben	1.349
1.3617	0.94	1.349	greben	V_062	V_061	greben	1.375
1.3925	1.27	1.375	greben	V_061	V_043	gemma	1.401
1.4442	**3.08**	1.401	gemma	V_043	V_083	tropea	1.409
1.4508	2.97	1.409	tropea	V_083	V_113	nt28	1.426
1.4566	-2.57	1.495	flori	V_033	V_033	flori	1.495
1.5630	**4.55**	1.495	greben	V_063	V_063	greben	1.496
1.6505	0.39	1.644	matera	V_163	V_163	matera	1.644
1.7215	-1.07	1.740	matera	V_162	V_193	foggia	1.736
1.7559	0.51	1.747	latina	V_143	V_162	matera	1.740
1.7839	-2.04	1.821	lipari	**V_173**	V_143	latina	1.747
1.7877	2.21	1.749	circeo	V_183	V_183	circeo	1.749
1.8030	**3.86**	1.736	foggia	V_193	**V_182**	circeo	1.787
1.8056	0.76	1.792	matera	V_161	V_161	matera	1.792
1.8247	-0.01	1.825	latina	**V_142**	V_171	lipari	1.816
1.8313	0.35	1.825	lipari	**V_172**	**V_181**	circeo	1.821
1.8338	-0.60	1.845	foggia	**V_192**	V_173	lipari	1.821
1.8579	**3.96**	1.787	circeo	**V_182**	**V_142**	latina	1.825
1.8629	**2.58**	1.816	lipari	**V_171**	V_172	lipari	1.825
1.8677	**-3.87**	1.943	napoli	**V_153**	**V_192**	foggia	1.845
1.8811	**-6.83**	2.019	latina	**V_141**	**V_153**	napoli	1.943
1.8930	**-3.62**	1.964	napoli	**V_152**	**V_151**	napoli	1.944
1.9070	**-5.50**	2.018	foggia	**V_191**	**V_152**	napoli	1.964
1.9138	**-5.10**	1.821	circeo	**V_181**	**V_191**	foggia	2.018
1.9811	1.91	1.944	napoli	**V_151**	**V_141**	latina	2.019

placement vessels. First step of future work will be the collection of data needed for the construction of other databases selected on the basis of homogeneous design requirements.

Moreover, despite huge improvements in numerical analysis of seakeeping performance, it should be stressed that ship designers have not yet at their disposal practical and user's friendly mathematical tools to design ships for seakeeping. The strategic idea is that only combination of hydrodynamics and statistics may allow appropriate consideration of seakeeping since the very initial design stages. That requires creation of seakeeping databases specialized for classes and types of ships, in order to build metamodels suitable in a multiattribute decision-making environment.

The reference framework of this paper is the vessel's concept design stage where a multiattribute decision making (MADM) technique is considered the most useful approach as opposed to the classical spiral design procedure. The main goal of the paper has been to develop robust equations to assess some seakeeping attributes, as derived from a database of fishing vessels, to be introduced into the mathematical model randomly fed by an adaptive Monte Carlo generator. To facilitate the selection procedure, that is, the core of the MADM, it might be convenient to cluster the feasible solutions into separate groups, as realized by Şayli et al. (2017).

1 This paper is the revised version of the following symposium paper: Rocchi, R., Trincas, G., 2005. The influence of hull form on seakeeping performance of fishing vessels. In: Proceedings of the 10th International Symposium on 'Technics and Technology of Fishing Vessels', Ancona, Italy.

REFERENCES

Alkan, A.D., Ozmen, G. & Gammon, M.A. (2003). Parametric Relation of Seakeeping, Proceedings 9th Symposium on Technics and Technology of Fishing Vessels, Ancona, Italy.

Bales, N.K. (1980). Optimizing the Seakeeping Performance of a Destroyer-Type Hull. Proceedings 13th ONR Symposium on Naval Hydrodynamics, Tokyo.

Bales, N.K. & Cummins, W.E. (1970). The influence of hull forms on seakeeping. Transactions SNAME, 78.

Cakici, F. & Aydin, M. (2014). Effects of Hull Form Parameters on Seakeeping for YTU Gulet Series with Cruiser Stern. International Journal of Naval Architecture and Ocean Engineering, 6, 700–714. [CrossRef]

Fang, K.-T., Li, R & Sudijanto, A. (2006). Design and Modelling for Computer Experiments. Chapman & Hall/CRC.

Fox, J. (2011). A Capability-Based, Metamodel Approach to Combatant Ship Design. MSc Thesis in Systems Engineering, Naval Postgraduate School, Monterey, CA.

Hearn, G.E., Hills, W. & Sarioz, K. (1991). A Hydrodynamic Design Methodology for Conceptual Ship Design, Proceedings ICCAS 91, Brazil.

Kishev, R. (1992). General Considerations on Ship Seakeeping Optimization in Design, Proceedings Osaka Meeting on Seakeeping Performance, 20th ITTC Seakeeping Committee, Osaka.

Kleijnen. J.P.C. & Sargent, R.G. (2000). A methodology for fitting and validating metamodels in simulation. European Journal of Operational Research, no. 120, pp.

14–29. [CrossRef]

Korvin-Kroukovsky, B.V. (1955). Investigations of ship motions in regular waves, Transactions SNAME, 63.

Lewis, F.M. (1929). The inertia of the water surrounding a vibrating ship. Transactions SNAME, 37. [CrossRef]

Li, Dong-qin, Wilson, P.A., Jiang Zhi-yong. & Zhao Xin (2016). Establishment of metamodels for ship seakeeping performance using an effective approximation modeling method. Journal of Ship Mechanics, 20(3) 243–257.

Logan, P. W., Morris, B., Harvey, D. & Gordon, L. (2013). Model-Based Systems Engineering Metamodel: Roadmap for Systems Engineering Process. Proceedings SETE 2013 Conference, Canberra.

Loukakis, T.A. & Chryssostomidis, C. (1975). Seakeeping Standard Series for Cruiser-Stern Ships, Transactions SNAME, 83.

McCreight, V. (1983). Estimating the seakeeping qualities of destroyer-type Hulls, DTNSRDC Report SRD-2074-01.

Moor, D.I. & Murdey, D.C. (1968). Motions and propulsion of single screw models in head sea. Transactions RINA, 110.

Nabergoj, R., Perniciaro, S. & Trincas, G. (2003). Seakeeping Assessment Modelling for Conceptual Design of Fishing Vessels, Proceedings 9th International Symposium on Technics and Technology in Fishing Vessels, Ancona.

Rocchi, R. (1988). A Statistical Prediction Method for Ocean-Going Fishing-Vessels, Proceedings 17th Scientific and Methodological Seminar on Ship Hydrodynamics, Varna.

Rocchi, R. (1992). A Practical Tool for Reliable Prediction of the Speed-Resistance Curve for Fishing Vessels, Proceedings 5th International Symposium on the Practical Design of Ships and Mobile Units, Elsevier Applied Science PRADS'92, Caldwell and Ward Eds., 1.

Salvesen, N.; Tuck, E.P. & Faltinsen, O. (1970). Ship motions and sea loads. Transactions, SNAME, 78.

Şayli, A., Alkan A. D. & Ganiler O. (2010). Nonlinear meta-models for conceptual seakeeping design of fishing vessels. Ocean Engineering, 37(8), 730–741. [CrossRef]

Şayli, A., Alkan A. D. & Aydin, M. (2017). Determination of relational classification among hull form parameters and ship motions performance for a set of small vessels. Brodogradnja, 67(1-4), 1-14. [CrossRef]

St. Denis, M. & Pierson, W.J. (1953). On the motions of ships in confused seas. Transactions SNAME, 61.

Trincas, G., Messina, G. & Nabergoj, R. (2000). Seakeeping Performance for Mediterranean Fishing Vessels, Proceedings IX Congress IMAM 2000, Cassella et al. Eds., Ischia, 2000, Vol. I.

Trincas, G. & Nabergoj, R. (2000). Multicriterial Selection and Ranking of Fishing Vessels for Efficient Operation, Proceedings Fourth Osaka Colloquium on Seakeeping Performance of Ships; Naito and Ikeda Eds., OC 2000, Osaka.

Trincas, G., Nabergoj, R. & Messina, G. (2001). Inverse Problem Solution to Identify Optimum Hull Forms of Fishing Vessels for Efficient Operation, Proceedings 8th Symposium on Technics and Technology of Fishing Vessels, Ancona.

Walden, D.A. & Grundmann, P. (1985). Methods for designing hull forms with reduced motions and dry foredecks. Naval Engineers Journal, 97, 214–223. [CrossRef]

Wijngaarden, van A.M. (1984). The optimum form of a small hull for the North Sea area. International Shipbuilding Progress, 31(359). [CrossRef]

Zborowski, A. & Shiaw-Jyh, L. (1992). Optimization of Hull Form for Seakeeping Performance. Proceedings 5th International on the Practical Design of Ships and Mobile Units, PRADS'92, Applied Science, Caldwell and Ward Eds., 1.