A CONCEPT EXPLORATION MODEL FOR SAILING YACHTS

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SUMMARY

This paper presents the results of a first study into the feasibility of developing a Concept Exploration Model (CEM) for sailing yachts, and a case study for a current project involving the design of a 44 foot cruising yacht. The CEM is used to generate and evaluate a large number of designs, and to derive a concept design that best fits a certain set of performance criteria.
The CEM uses a mathematical model of the design process to derive a matrix of systematically varied designs, of which each design satisfies a set of basic design criteria. These designs are then subjected to a number of performance criteria, such as sailing performance, cost, stability and internal space. The results for these criteria for all the yachts in the designs matrix are then compared to each other, for which a calculation method has been developed. The results of this make it possible to select the optimum design in the designs matrix.

NOMENCLATURE

Symbol	**Definition [*unit*]**
∇	Volume [m^3]
φ	Heel angle [*deg*]
B	Beam or width [*m*]
b_0, b_1	Form stability coefficients [-]
BAD	Boom above deck in the side [*m*]
BM	Metacentric radius above the centre of buoyancy [*m*]
c	Average chord length [*m*]
C_1	Form stability expression [-]
C_B	Block coefficient [-]
C_M	Maximum section coefficient [-]
C_P	Prismatic coefficient [-]
C_{WP}	Waterplane area coefficient [-]
D	Depth [*m*]
E	Mainsail foot length [*m*]
F_B	Freeboard amidships [*m*]
GZ	Righting lever [*m*]
H	Height [*m*]
J	Foretriangle foot length [*m*]
K	The lowest point on the canoe body [-]
KB	Height of centre of buoyancy above *K* [*m*]
KG	Vertical height of the centre of gravity above *K* [*m*]
L	Length [*m*]
LCB	Longitudinal position of the centre of buoyancy, relative to $L_{wl}/2$ [%]
P	Mainsail hoist [*m*]
SA	Sail area (foretriangle + actual mainsail) [m^2]
T	Draught or span [*m*]
Th	Thickness [*m*]
W	Weight [*kg*]
ρ	Density [kg/m^3]

Index	**Description**
B	Bulb
Ballast	Lead ballast
CB	Canoe Body
Deck	Deck Gear
Int	Interior
K	Keelfin
Mach	Machinery and equipment
OA	Overall
R	Rudder
Rig	Rig and sails
W	Water
WL	Waterline

1. INTRODUCTION

1.1 BACKGROUND

When looking at possible design processes in sailing yacht design, the first distinction to be made is that between cruising yachts and racing yachts. The latter is mainly characterised by the importance of the performance of the yacht under sail, which dominates the entire design process. For a cruising yacht things are very different. Usually the performance under sail will be of less importance, and other criteria, e.g. cost, aesthetics and internal space, will dominate the decisions to be taken by the designer.
Even though the criteria and the factors influencing the decisions are very different, the actual process and the approach of the problem will be, more or less, the same. As for all ship types, the design process, the sequence of operations, can be represented by the well known '*design spiral*', see e.g. [1]. In this process, the starting point is of major importance.
To obtain a starting point, the designer will use his experience, or an existing yacht he is confident about. This is only suitable if the designer indeed has the appropriate experience, and if the yacht to be designed is of a well-known concept.
For racing yachts, where the budget for the design work is usually much larger than for cruising yachts, often a large number of point designs is made, and, using certain specified criteria (e.g. the time over a specified race course in specified wind conditions), one can find the point design that suits the criteria best. This is an extremely time-consuming method however, because for each point design, one or two or maybe even more cycles of the design spiral will have to be completed. This is also the main reason why this method is very rarely used for cruising yachts, even though it is the most appropriate method.
Another shortcoming of the conventional approach is that the designer has no standards to judge the design to, apart from the starting point. The designer has no way of assessing how closely he or she is away from an optimum design.

The availability of a so-called *'Concept Exploration Model'* will change this situation drastically.

1.2 CONCEPT EXPLORATION MODEL

A general description of a Concept Exploration Model (CEM) could be: 'a mathematical model of a design process of a certain system or object, that is capable of producing and evaluating a large number of designs, in the entire range of possible dimensions, and of finding the design that best suits a given set of criteria'.
Usually, this will be in the form of a software program, specifically developed for the system or object to be designed. A CEM could be useful in the design process of many different applications, e.g. a car, a conveyor belt, a table lamp, or even a sailing yacht.
The availability of a CEM will not reduce the complexity of the system to be designed, but, if developed well, it may provide an extremely powerful tool in the design process in all its complexity. This will especially be the case if the CEM could be used in the very first stage of the design, with as little data as possible to be input into the program, using as few assumptions as possible.
Using the input data, the CEM will derive a large number of designs. These designs are then evaluated using a number of specified criteria, and the design that best fits the criteria will be selected and output. This conceptual design can then be used as a starting point for the normal design process.

1.3 LITERATURE REVIEW

Over the past 20 or 30 years, a small number of CEM programs have been developed for application in ship design. Two of those are described in [2] and [3], regarding warships and semi-planing vessels, respectively.
For commercial vessels, the criterion that dominates the design process will be of an economic nature. For a shipping company, the optimum design will usually be the vessel with which the most profit can be realized. This simplifies the application of a CEM, because there is a very clear criterion, for which the design has to be optimised. In this context, a publication [4] has been found in which a description is given of an analytical formulation of the optimisation process. The main formula that needs to be optimised in this case is an expression of cost as a function of the main particulars of the vessel.
Though this analytical approach is a very effective method to come quickly to an optimum design, it is very limited. It works in this case because the description of the vessel is reduced to 5 parameters only and there is one very specific criterion the vessel has to comply with, economic efficiency, and this criterion can be expressed quantitatively. For sailing yachts, there are many more criteria than just one and there are more parameters and dimensions involved. Also, the criteria are not always as easy to express quantitatively.
Another very important difference between sailing yachts and commercial (powered) vessels is that the latter are usually optimised for one particular speed, whereas for sailing yachts there are no speed requirements. In some cases an optimisation for a certain course and/or wind speed is required, but very rarely is a cruising yacht optimised for one particular speed. In other words, where for powered vessels the boatspeed is an input (a design criterion), it will be an output (an optimisation criterion) for sailing yachts.

1.4 OPTIMISATION METHOD

All these considerations indicate that it will be extremely complicated to develop a mathematical optimisation algorithm. The alternative is an optimisation method that consists of the selection of the best alternative from a large, discrete number of possible designs, rather than to search for the best alternative by variation of parameters.
If the values for the parameters and variations are well chosen, the error compared to the theoretical optimal design will be small and acceptable, especially when considering that the design is a concept design, and not at all finalised in any way.
A mathematical optimisation method may be faster in many cases. However, with the current state of computer hardware, calculation time is hardly an issue. Besides, considering the number of parameters necessary to describe a sailing yacht in sufficient detail, and the number of possible criteria, it is doubtful if a mathematical method is any faster at all.

1.5 CURRENT APPROACH

In this paper a first version of a CEM for sailing yachts is presented. It provides a very fast way of exploring all realistic ranges of dimensions of hull and appendages, rig and sailplan, as an additional way of obtaining a starting point for the design process.
The current CEM is limited in the following:

- One (fixed) hull configuration: keelfin with a bulb, containing all the (lead) ballast, and a free-hanging rudder, placed behind the keelfin;
- One (fixed) rig configuration: masthead rig, consisting of mainsail and genoa only;
- One (user-definable) construction material: scantlings are derived based on single skin fibreglass.

2. CEM METHODOLOGY

2.1 DESIGN CRITERIA

For cruising yacht design, the design criteria will be the result of client demands, and the requirements directly resulting from those. Those demands will be the input to the program and, ideally, the CEM should not need more input than those. With Larsson and Eliasson [1] a summary of these can be made as follows:

- Length of the yacht;
- Restrictions in overall draught;
- Type of yacht, styling;
- Number of berths;
- Intended use and sailing region;
- Requirements by regulations and class rules.

In addition, the client will also have certain demands concerning the interior, the available equipment and machinery onboard, which will also have to be taken into account.

2.2 DESIGNS MATRIX

With the input data described above, the CEM derives the parameters that are not input by the user and applies the variations on the main dimensions. This will create a matrix $\overline{Y}$. If p represents the number of varied parameters, this matrix will be p-dimensional. If y is the number of yachts and n represents the number of variations applied, then:

$$y = n^p$$

formula 1

In the first stages of the design, not all parameters are as important. Some parameters may perhaps be so well known in advance that no variations are necessary. In those cases, variations will not be necessary, and an estimate, by 'good practice', will be sufficient. This way the number of varying parameters, and thus the number of variations, can be reduced.

2.3 PERFORMANCE CRITERIA

Unlike design criteria, performance criteria are not criteria that need to be satisfied, but are those to which a design will be subjected and judged. Examples of performance criteria are: the interior space of the cabins and saloon, building cost and sailing performance.
The performance criteria incorporated in the current model have been chosen as follows:

- Sailing performance;
- Stability and safety;
- Cost;
- Volume and internal space.

Of course, there are many more criteria of relevance to sailing yacht design, e.g. seakeeping behaviour, manoeuvrability, possible interior arrangement, etc. These will be the topic of future studies.
The above-mentioned criteria are calculated for each yacht in the designs matrix, and used to give each design a certain performance index. Based on this, a selection of the optimal design can be made.

3. CEM DESIGN PROCESS

3.1 DERIVATION OF POSSIBLE DSIGNS

The designs to be derived are described by a total of 35 parameters. Of these 35 parameters, there are 21 parameters that can vary at a time, independently. These are listed in table 1.
For each parameter, defaults have been derived, where possible as a function of L_{WL}, from a database containing over 1000 yachts for the main dimensions (length, beam, draught, sail area, displacement), and about 100 yachts for the form parameters, coefficients, weights and stability characteristics. The lengths of the yachts in the database have a range from 5 to well over 35 meter, and contain both cruising and racing yachts.
These defaults consist of an average value, an upper limit and a lower limit. It is possible to either use the average value, a variation between the upper and lower limit, or to manually input a fixed value, range, minimum or maximum, together with the number of variations required.

3.2 CANOE BODY AND RIG DIMENSIONS

In figure 1, a schematic overview is shown that represents the design process that derives the particulars of an entry in the designs matrix. This process needs to be repeated for every wanted combination of the varying parameters.
Either the desired length on the waterline, or the length over all, needs to be input to the program. Together with an input for the styling (either by means of a default characterization, or by means of a sketch defining the profile view and a midship section), the other can be derived, or varied.
With a value for the length-displacement ratio, beam, freeboard, LCB, LCF, C_{WP} (all dependent on L_{WL}), and for C_P (dependent on length-displacement ratio), the canoe body is described, except for the draught, block coefficient and maximum section coefficient. Setting one of these values will automatically determine the other two.
Also dependent on the length, a sail area can be estimated, and dependent on this, the other dimensions of the sailplan can be derived.

table 1 Independent (varying) parameters in the model

Canoe body	L_{WL} or L_{OA}
	$L_{WL}/\nabla_{CB}^{1/3}$, F_B, B_{WL}, B_{OA}, C_P, C_{WP}, LCB
	T_{CB} or C_M or C_B
Appendages	T_K, c_K, Th_K
	T_R, c_R, Th_R
	L_B, H_B/B_B
Rig and sails	SA, P
	J and E or $(J+E)$ and E

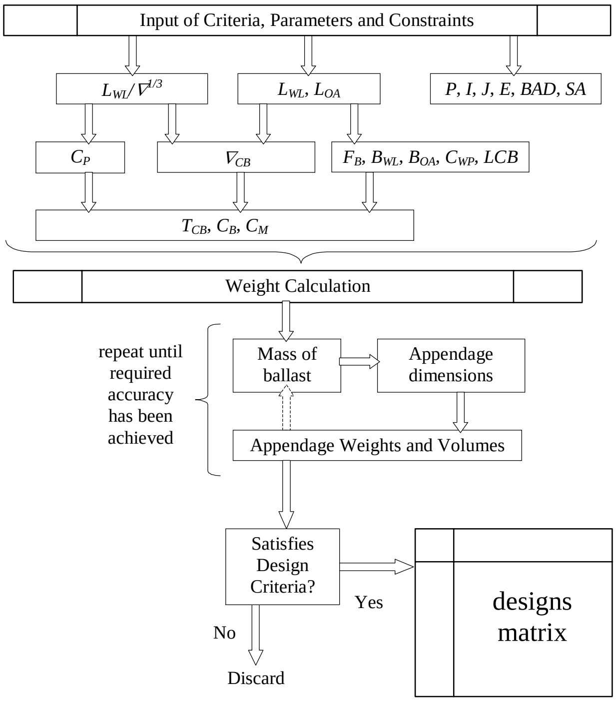

figure 1 Schematic CEM design process flowchart

3.3 CONSTRUCTION SCANTLINGS AND WEIGHT CALCULATION

3.3 (a) General

As expressed in numerous publications, the weight calculation constitutes an extremely important stage in the design process of every ship, and the importance of obtaining a reliable result is often underestimated, even by the most experienced of naval architects. In the CEM, this also is a crucial part of the process, and especially “fuzzy”, because of the lack of an exact hull form, interior layout and equipment and machinery list.
The method described in the following paragraphs, is a first attempt to come to a realistic value for both the weight as well as the location of the centre of gravity.
The following weight groups have been distinguished:

- Construction;
- Rig and sails;
- Deck gear;
- Machinery;
- Interior;
- Payload;
- Appendages;
- Ballast.

The primary inputs to the weight calculation are the dimensions and coefficients of the canoe body and rig, obtained as described in the previous paragraph. It is again possible to override the default program estimates, and input custom values for the weights and corresponding centres of gravity, in case this can be more accurately determined in another way, or if available beforehand.

3.3 (b) Construction Scantlings and Weight

The dimensions and coefficients of the canoe body are used to determine the construction scantlings, using the method developed by Gerr [5]. At the current stage of the CEM, only the construction scantlings for a single skin fibreglass hull, using plywood bulkheads, has been allowed for, using user-defined laminates. To model a sandwich construction, it is possible to input certain reduction coefficients for the weights of the various construction parts.
Using a mathematical estimate of the curve of sectional areas, to either the design waterline or to the deck, as developed by Van Oossanen [6], it is possible to calculate girths, deck areas, and the areas of the various regions of the hull shell, at every position needed, including the corresponding centre of gravity. Using these, together with the specified laminate, a reasonable weight estimate for the construction is obtained.

3.3 (c) Rig and Sails Weight

Using the database mentioned previously, an average function has been determined, dependent on (upwind) sail area only:

$$W_{Rig} = 0.45 \cdot SA^{1.50}$$

formula 2

The corresponding centre of gravity is:

$$KG_{Rig} = D + 0.4 \cdot (BAD + P)$$

formula 3

3.3 (d) Deck Gear, Machinery and Interior Weight

The weight of deck gear, machinery and interior are determined using statistical data, until a better, more accurate method has been developed.
Functions have been derived that describe an envelope containing all, or most, of the yachts in the database. For each group, a separate index has to be input, determining the amount of ‘luxury’. This index is in the form of a percentage, and can be interpreted as the difference between a very well equipped super yacht, and a very sober racing yacht. Using the various indices, a linear interpolation between the lower and upper limits of the envelope is carried out, to achieve the final value.

table 2 Estimates for the weights and centres of gravity for deck gear, interior and machinery and equipment.

	Lower limit	**Upper limit**	***KG***
Deck gear	$0.165 \cdot L_{WL}^{2.89}$	$26.6 \cdot L_{WL}^{1.70}$	D
Interior	$0.042 \cdot L_{WL}^{3.66}$	$2.94 \cdot L_{WL}^{2.75}$	$T_{CB} + \sqrt[3]{\frac{B_{WL}}{L_{WL}}} \times (0.6 \cdot F_B - 0.4 \cdot T_{CB})$
Machinery	$0.096 \cdot L_{WL}^{3.16}$	$10.4 \cdot L_{WL}^{2.21}$	

In table 2, the formulas for the weight estimates and corresponding estimates for the centre of gravity are given.

3.3 (e) Payload Weight

The payload is assumed to consist of the people onboard the yacht, their luggage and personal possessions, the amount of fresh water and the amount of fuel. For this there are inputs created concerning the number of persons, and the average duration of the trips the yacht is to be capable of. The fuel tank capacity is dependent on the output power of the engine, which is in turn dependent on the length.
The design condition is assumed to be for half full tanks. The centre of gravity is assumed to be at 60 percent of the depth.

3.3 (f) Ballast Weight

With having set the length on the waterline and the length-displacement ratio previously, the canoe body volume is determined and the first estimate for the amount of ballast can be calculated, using:

$$W_{Ballast} = \nabla_{CB} \cdot \rho_W - W$$

formula 4

Where W is the summation of the weights of the distinguished groups. This value will be revised after dimensioning the appendages.

3.4 APPENDAGE DIMENSIONS

Before defining the appendages, two important assumptions have had to be made in this version of the program. First, it is assumed that all the ballast is located in the bulb, attached to the bottom of the keelfin, and second, it is assumed that the yacht with the largest draught allowed will always be the best design.
The latter can be justified as follows: with increasing draught, the side force production per degree of leeway will increase due to increasing aspect ratio of the keel, and stability will increase as well, due to a lower KG value for the ballast, also positively influencing the sailing performance. The total volume will not change much and the building cost will not either, both as long as realistic draught values are input.
With these assumptions made, and the amount of ballast (and ballast material) determined, the volume of the bulb can be calculated, using inputs or defaults for thickness-chord ratio and height-width ratio (determined using a viscous resistance optimisation).
Having the total draught of the yacht set equal to the maximum allowable draught, and the canoe body draught determined earlier, the span of keel and rudder can be set. Using input or default thickness-chord ratios for those as well, together with a (yet to be improved) estimate of the total lateral area of the appendages, using [7], to determine the respective chord lengths, the appendages are determined.
The weight of the keelfin and rudder can now be added to the weight of the canoe body and rig, as well as their respective volumes to the total volume of the yacht. These new values will result in a new mass of the ballast, and thus new bulb dimensions, after which the appendages can be determined again. This calculation is repeated until the change in volume between two consecutive loops is small enough.

3.5 VALIDITY

After all the dimensions and parameters have been derived, the design is complete. The next step is to check the values of the parameters of the design with the validity ranges of the various calculations and (optional) to either discard or keep the design.
After the design has passed the test, it is subjected to the required regulations, as specified by the user. Currently, only the ISO 12217-2 Stability Standard is incorporated (see paragraph 4.2).
Another possible filter is the maximum building cost allowed, however, it is currently disabled, as this calculation is not yet properly incorporated (see paragraph 4.3).

4. PERFORMANCE CRITERIA

4.1 SAILING PERFORMANCE

To calculate the sailing performance, a modified version of the Van Oossanen & Associates in-house developed Velocity Prediction Program (VPP) is used, as described in [8]. For the CEM, the calculation of the force-moment equilibrium in the horizontal plane for determining the rudder angle has been removed. This has mainly been done for simplification, and, to a lesser extent, to improve calculation time.
This VPP, unlike other contemporary VPPs, starts with setting a matrix for boatspeed and leeway angle and calculating the hydrodynamic properties first, rather than setting a wind speed and wind angle and first calculating the aerodynamic properties, and searching for the matching hydrodynamic setting of the yacht.
This approach especially proves its benefits in the CEM, as it is much more sensitive to small changes in the hull and appendage dimensions and parameters.
Using the VPP, all the yachts in the design matrix can be evaluated, using the following criteria:

- Maximum VMG upwind;
- Maximum VMG downwind;
- Boatspeed;
- Circular random;
- Linear random;
- Time necessary to complete a certain course.

For all these criteria, a custom true wind speed, true wind angle and leg length (all, if applicable) can be input.

4.2 STABILITY AND STIX CALCULATION

The stability of a sailing yacht is, obviously, a very important design aspect. It is not only important for the sailing performance, but also the safety and seaworthiness of the yacht are dependent on it, as well as the comfort on board when sailing.
Usually stability calculations are only carried out when the hull form is defined exactly by the lines drawing and by using the weight data to calculate the hydrostatics at various angles of heel. However, in the design stage where the CEM is used, the exact hull form is not yet known.
To solve this, a new method has been developed, specifically for use in the CEM, to estimate the curve of righting levers.

The stability of a ship can be thought of as consisting of two parts: form stability and weight stability. The formula for the righting lever $\overline{GZ}_\varphi$ is:

$$\overline{GZ}_\varphi = \left(\overline{KB} + \overline{BM}_\varphi - \overline{KG}\right)\cdot \sin(\varphi)$$

formula 5

This can be separated in a part for the form stability:

$$\overline{GZ}_{\varphi,form} = \left(\overline{KB} + \overline{BM}_\varphi\right)\cdot \sin(\varphi)$$

formula 6

and a part for the weight stability:

$$\overline{GZ}_{\varphi,weight} = \left(\overline{KG}\right)\cdot \sin(\varphi)$$

formula 7

where $\overline{KG}$ is the result of the weight calculation. An approximate expression for the canoe body $\overline{KB}$ is:

$$\overline{KB}_{CB} = \left(0.8423 - \frac{C_B}{3\cdot C_{WP}}\right)\cdot T_{CB}$$

formula 8

This value for $\overline{KB}_{CB}$ needs to be corrected for the $\overline{KB}$ values of the appendages, to come to the total $\overline{KB}$ of the yacht. The height of the metacentre above the centre of buoyancy is the parameter that is purely dependent on hull form and heel angle. At zero heel this can be expressed as:

$$\overline{BM} = \left(0.07032\cdot C_P + 0.01039\cdot C_P{}^2\cdot C_{WP}{}^2\right)\cdot \frac{B_{WL}{}^3\cdot L_{WL}}{\nabla_{CB}}$$

formula 9

With $\nabla_{CB} = C_B\cdot L_{WL}\cdot B_{WL}\cdot T_{CB}$, it follows that $\overline{BM}$ can be written as:

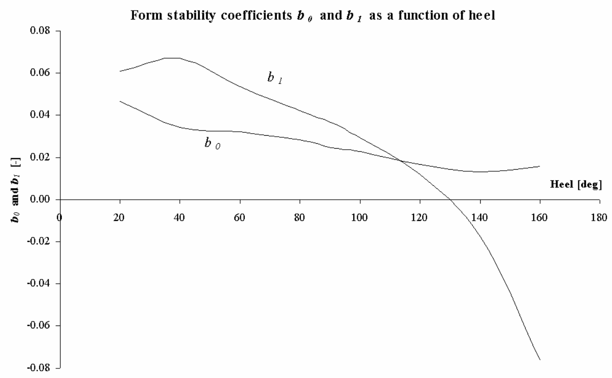

figure 2 Form stability coefficients b_0 *and* b_1 *as a function of heel.*

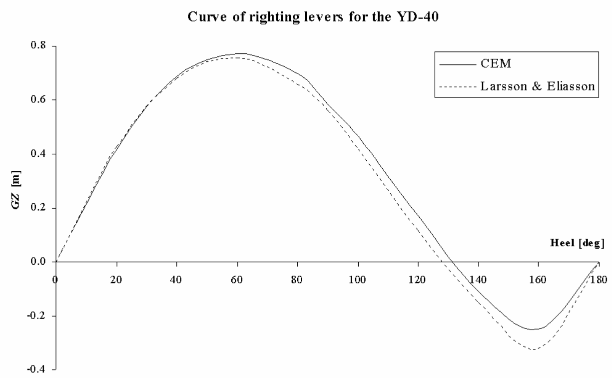

figure 3 Illustration of stability calculation results using Larsson and Eliasson's YD-40 [1].

$$\overline{BM}_\varphi = C_1(\varphi)\cdot \frac{B_{WL}{}^2}{T_{CB}}$$

formula 10

Here, $C_1(\varphi)$ is an expression, dependent on heel angle, which can be estimated by:

$$C_1(\varphi) = b_0(\varphi) + b_1(\varphi)\cdot \left(\frac{B_{OA}}{B_{WL}}\right)^2 \cdot \left(\frac{T_{CB}}{B_{WL}}\right)\cdot \frac{1}{C_B}$$

formula 11

where b_0 and b_1 are a function of the heel angle φ, see figure 2, determined by regression analysis from the database mentioned in paragraph 3.1. It has been chosen to use one expression for the entire range of heel angles, rather than different expressions at different angles. This is the reason why other important parameters, e.g. the depth of the canoe body, do not appear in the expression. In the future, this method will be improved further, to also take other parameters into account.
To demonstrate the validity of the method, the curve of righting levers has been calculated using this method for the YD-40, a 10 meter cruiser-racer, which is used throughout [1]. The results are presented in figure 3. It shows that especially for heel angles up to about 50 degrees, the results are accurate.
Using the righting lever approximation method as

described here, it is possible to obtain all the stability characteristics of the yachts in the designs matrix, necessary to make a proper evaluation and judgement.
Its main purpose is the calculation of the Stability Index and the associated design category as defined in ISO standard 12217, which is also one of the (optional) design criteria the designs have to comply with.
The stability performance criteria implemented in the CEM are:

- Stability Index (ISO-12217-2);
- Angle of vanishing stability;
- Downflooding angle;
- Maximum $\overline{GZ}_{\varphi}$;
- Dynamic stability up to a user-defined angle.

4.3 COST ESTIMATE

At the current time, the cost criterion is not properly incorporated. For the time being, a formula is used, based on regression analysis for the selling price of newly built *production* yachts. The outcome of this formula in itself is not very useful, but it allows a comparison with other yachts.
From literature, it is known that the cost of a ship is often dependent on the length over-all to the power 3 or 4. For sailing yachts it appears that L_{oa}^{4} gives the best results. This has accordingly been set as the main variable. The following expression is currently used:

$$Price = \left(1.90 \cdot \frac{m_{Ballast}}{\Delta_{Tot}} + 0.54 \cdot B_{OA} + 0.023 \cdot SA\right) \cdot L_{OA}{}^{4} + 132 \cdot W_{Tot} \cdot \frac{\nabla_{CB}{}^{1/3}}{L_{WL}}$$

formula 12

Where the prices are in Euros, for the year 2002.

4.4 INTERNAL SPACE CALCULATION

The only information about the interior created within the CEM, is the division by the bulkheads and web frames as adopted in the construction calculation. Here, the structural bulkheads are used to divide the interior in three parts: a forward compartment (in front of the mast bulkhead, to the fore peak bulkhead), a main compartment (from the aft end of the deckhouse to the mast bulkhead), and an aft compartment (underneath the cockpit).
Calculating the volumes of these compartments, using the estimated curve of sectional areas, and deducting the space taken by the other structural members, gives a good impression of the space available in the interior of the yacht.

5. CRITERIA ASSESSMENT AND VALIDATION

When judging a design based on a number of different criteria, and attempting to decide which is the design that performs best, two main problems arise. The first problem is the relative importance of the various criteria; the second problem is constituted by the differences in the order of magnitude of the various criteria, and also in the degree of variation of the absolute values (see e.g. [10]).
The first problem is solved by using a weighting factor for each criterion and the second problem by using a normalization method.

Suppose the results of the criteria calculations are specified in a 2 dimensional matrix $\overline{C}$, with dimensions *y* (the number of yachts) and *c* (the number of criteria). Besides the matrix $\overline{C}$ there is also a vector $\underline{w}$, with *c* entries, representing the weighting factor for each criterion (input by the user).
The first step in the process is to normalize the results in matrix $\overline{C}$, to a normalized matrix $\underline{\overline{C}}$. For criteria that need to be maximized:

$$\underline{\overline{C}}_i = \frac{\overline{C}_i - \min(\overline{C})}{\max(\overline{C}) - \min(\overline{C})}$$

formula 13

For criteria that need to be minimized:

$$\underline{\overline{C}}_i = \frac{\overline{C}_i - \max(\overline{C})}{\min(\overline{C}) - \max(\overline{C})}$$

formula 14

Here, $\overline{C}_i$ represents the ***i***-th entry in the matrix $\overline{C}$, corresponding with the ***i***-th entry in the designs matrix. By utilizing this method, the problem with the order of magnitude of the absolute values has been solved, as well as that associated with the degree of variation.
The final score, the performance index, for a particular design is then calculated by:

$$\underline{f}_i = \underline{\overline{C}}_i \cdot \underline{w} = \bar{c}_{1,i}\,\underline{w}_1 + \bar{c}_{2,i}\,\underline{w}_2 + \ldots + \bar{c}_{c,i}\,\underline{w}_c$$

formula 15

In which $\underline{f}_i$ represents the ***i***-th entry of the vector $\underline{f}$, which contains the score for all the yachts. To come to the final performance index vector $\overline{\underline{f}}$, the vector $\underline{f}$ is normalized according to formula 13.
The optimal design, which is the design that obtained the highest performance index, will be the maximum of the vector $\overline{\underline{f}}$, which will be equal to 1, by definition.

6. CASE STUDY: 44 FOOT PERFORMANCE CRUISER

6.1 DESIGN BRIEF

The CEM was recently used in a project at Van Oossanen & Associates, involving the design of a 44 ft performance cruiser. For this paper, the relevant specifications of the design brief are as follows:

- Favoured windspeed: 16 knots;
- All-round performance, no favoured courses;
- Short handed sailing;
- Maximum draught 1.90m.

The design will have to satisfy STIX Design Category A.

6.2 CALCULATION INPUT

The CEM has been used with the objective of finding the best length-displacement ratio, waterline beam and sail area combination. It has been used next to a VPP, as a means of verifying the results.
The following variations have been applied:

$L_{WL}/\nabla^{1/3}$	4.5 to 6.5	(17 values)
B_{WL}	2.0 to 5.0 m	(16 values)
SA	70 to 115 m^2	(10 values)

In this variation, a length-displacement ratio of 4.5 implies a ballast ratio ($W_{Ballast}/\nabla_{Tot}$) of 67%; 6.5 implies (almost) no ballast at all. All the remaining parameters have been estimated using the default values.
For the weight calculation inputs, a specification of the interior and the equipment has been used to find the best values for the luxury indices. In table 3, the results of the weight calculation for one particular yacht are shown.

For presentational purposes, the variation has been divided into two parts: a length-displacement ratio - beam variation, with a constant sail area (90 m^2), and a sail area - beam variation, using a constant length-displacement ratio (5.375).

6.3 LENGTH-DISPLACEMENT RATIO – BEAM VARIATION

All the derived designs have been subjected to the ISO 12217-2 criteria, see the results in figure 4. It is clear that the lighter yachts, the yachts with the highest length-displacement ratios, especially when combined with a low beam, do not satisfy the criteria. The decrease in STIX for the higher beam values can be explained by the very high B_{WL}/T_{CB} ratio for those designs.
After filtering all of the designs on all the design criteria, the population that remains is as shown in figure 5. The various regions are clear. The lighter boats, with a high beam, have more weight than there is volume in the canoe body (on the specified draught). In the CEM, this results in negative ballast, and hence, these are not valid designs. The designs marked with "filtered", are the designs that are theoretically possible, but are outside of the validity range of the calculations (mainly the Delft Systematic Yacht Series resistance calculation as used in the VPP and the stability calculations). Those have been omitted as well. The last group that has been discarded are those that do not satisfy the stability index criterion, as explained above.

table 3 Weight calculation results, for $L_{WL}/\nabla^{1/3}$ = 5.5, B_{WL} = 3.2, SA = 90m^2, and luxury index settings.

Group	Mass [kg]		$\overline{KG}$ [m]
Bottom & Side Shell:	607		
Deck & Coachroof:	319		
Stiffeners & Bulkheads:	293		
Subtotal:		1219	1.01
Rig and sails (hoisted):	464		8.92
Interior (30%):	853		0.92
Machinery (55%):	1252		0.62
Deck Gear (30%):	766		1.77
Payload:	364		1.06
		3699	
Total:		4918	1.77

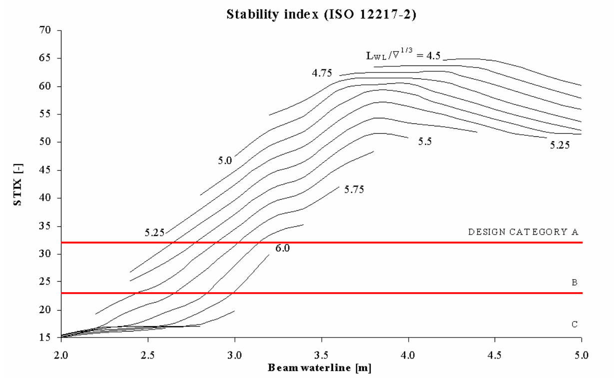

figure 4 Stability Index as a function of beam on the waterline, for length-displacement ratios.4.5 – 6.5 (design categories shown without the requirements for vanishing angle taken into account).

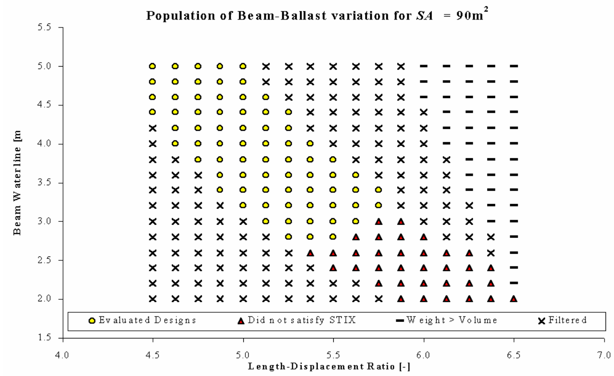

figure 5 Population of beam-ballast variation for a sail area of 90 m^2.

The remaining designs have here been analysed on three criteria: upwind VMG, downwind VMG, and boatspeed when reaching, all for a true wind speed of 16 knots. The results are presented in figure 6, as a function of the beam on the waterline, for the specified length-displacement ratios.
In the upwind condition, the influence of stability can be clearly seen. The lighter yachts (with higher length-displacement ratio values), with small beam, need more stability and a small increase in beam gives a relatively large improvement in VMG, until an optimum has been reached. This gain is also dependent on the need to reef in the VPP calculations; more stability will result in a

smaller reefing influence.
Increasing the beam over the optimum will make the increase in resistance (wave making and viscous) outweigh the gained stability, and a loss of VMG (and boatspeed) is the result.
Besides the previously mentioned optimum in beam for each length-displacement ratio, there is also an optimum in length-displacement ratio for each sail area. A length-displacement ratio of 5.5 (a ballast ratio of 42%), and a waterline beam of 3.8 m yield the highest VMG.
In the downwind condition, it is clear that the lightest and narrowest yachts are the fastest. Stability is clearly not of influence here, as was to be expected, since heel angles are negligible.
When reaching, a change in beam has a small influence on boatspeed. Here, the effects associated with the gain in stability and the increase in resistance cancel each other out almost entirely. Here too, the lightest designs are the fastest.

6.4 SAIL AREA VARIATION

The second part of the variation concerns the sail area. The variation in sail area is carried out with a fixed base length (*J+E*), due to other requirements, and varying mainsail hoist *P*, and foretriangle height *I*. In figure 7, the results for the upwind VMG are shown, for a constant length-displacement ratio of 5.375 (ballast ratio is 50%).
It is clear from the results, that VMG keeps on increasing, with increasing sail area, until the point is reached where the sails need to be reefed in order to limit the heel angle (to 25 degrees in this case). This is the reason VMG reduces on further increasing sail area, for all except the two highest beams.
Downwind and reaching results (not shown here) indicate that in those cases a narrow yacht with a large sail area is always the fastest.

6.5 COMPARISON & SELECTION OF OPTIMUM DESIGN

The performance criteria and corresponding weighting factors used to derive the “optimal” design, are defined as listed in table 4. From the design brief it is known that the yacht should be all-round, so all the sailing performance criteria have been weighted equally. As it concerns a cruising yacht, the safety (represented by the stability index) and the cost have been weighted higher. The volume criterion has been given less importance, as it concerns a performance cruiser.

table 4 Performance criteria and weighting factors.

Criterion	Weighting
VMG Upwind (V_{TW} = 16 kts):	3
VMG Downwind (V_{TW} = 16 kts)	3
Boatspeed (V_{TW} = 16 kts, B_{TW} = 90 deg)	3
Stability Index	6
Volume of Main Compartment	1
Cost	4

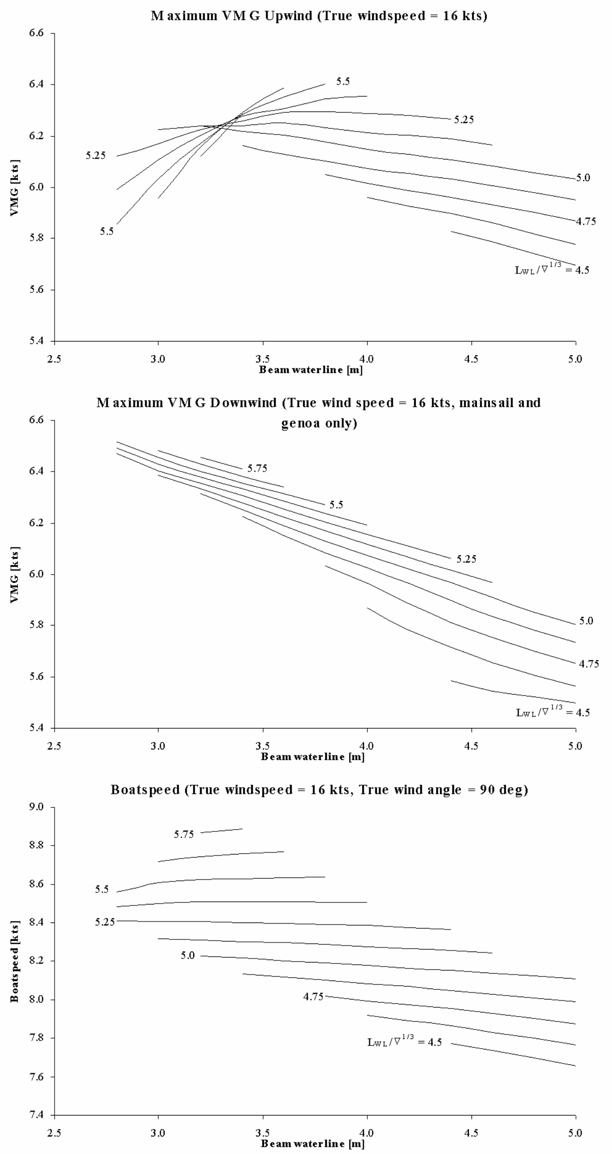

figure 6 Upwind VMG, Downwind VMG and boatspeed at a true wind angle of 90 degrees, in 16 knots true wind, as a function of beam on the waterline, for length-displacement ratios.4.5 to 5.75, and a constant sail area of 90 m^2.

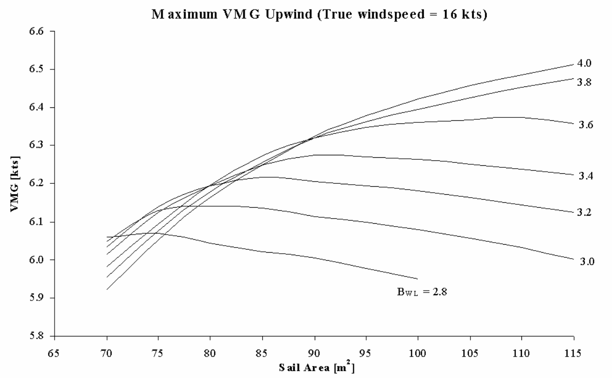

figure 7 Upwind VMG in 16 knots of true wind, as a function of sail area, for various beams, and a constant length-displacement ratio of 5.375.

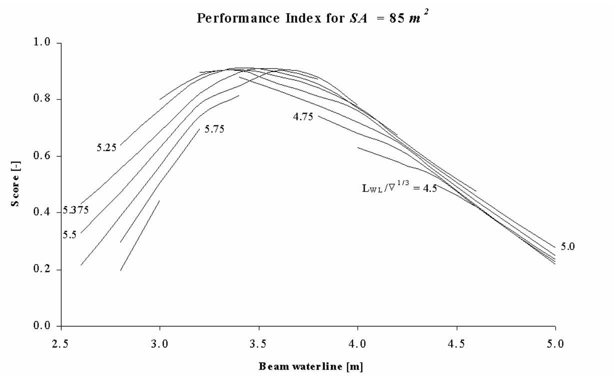

figure 8 Performance index as a function of waterline beam, for length-displacement ratios.4.5 to 5.875, and constant sail area, using the criteria and weightings as listed in table 4.

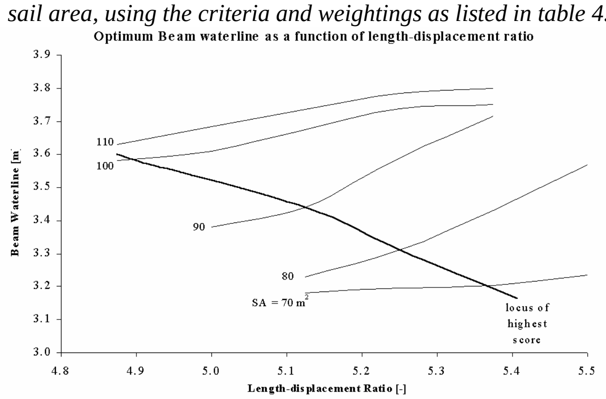

figure 9 Optimal waterline beam, as a function of length-displacement ratio, for sail areas of 70 to 110 m^2, using the criteria and weightings as listed in table 4.

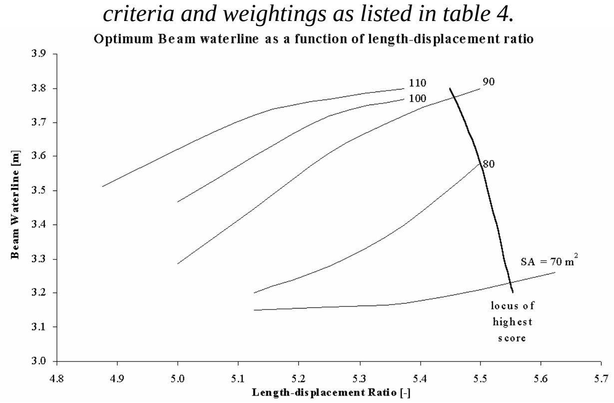

figure 10 Optimal waterline beam, as a function of length-displacement ratio, for sail areas of 70 to 110 m^2, using the criteria as listed in table 4, with equal weighting.

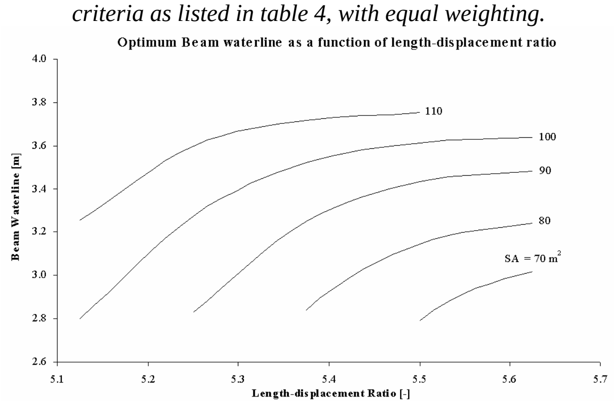

figure 11 Optimal waterline beam, as a function of length-displacement ratio, for sail areas of 70 to 115 m^2, using only upwind and downwind VMG, in 16 knots true wind speed.

In figure 8, the normalized final results are shown for all the designs with a sail area of 85 m^2. It is clear that there is a certain optimum, in beam, for each length-displacement ratio, and in length-displacement ratio, for each sail area. Distilling all these optima from the results, for all sail areas, gives the chart as shown in figure 9. In this figure it is clear that the lighter yachts, the yachts with a higher length-displacement ratio, need more beam, than the yachts with higher ballast ratios.

Also shown in this figure is the line where each sail area has the highest score. Travelling along this line, towards lower length-displacement ratios and higher beam values, the score increases. The locus coincides more or less with the points on the upwind VMG criterion where reefing first occurs.

From the results of the normalization and summation, according to formula 13 to 15, the design with the highest score has a length-displacement ratio of 4.875 (corresponding with approximately a 59% ballast ratio), a waterline beam of 3.6 m and a sail area of 110 m^2.

Taking into consideration that the yacht is meant for short handed sailing, together with the fixed base length of the sail plan, this will result in a very high aspect ratio rig, which is difficult to handle. From this point of view, sail area should not be more than 85 m^2, based on good practice. Interpolation in figure 9 on the locus, gives a waterline beam of 3.35 m and an optimum in length-displacement ratio of 5.2, or a ballast ratio of 50%, for this sail area.

6.6 INFLUENCE OF CRITERIA AND WEIGHTING FACTORS

The method as presented here, using weighting factors for the performance criteria to come to an optimum design, is acknowledged to be a very subjective method. Different users of the program will have different interpretations of the relative importance of the criteria, used for the optimisation of the design, and thus come to a different end result.

In practice, one will never use only one set of criteria and weighting factors, but try various settings. The user will have to obtain experience with the program and the influence of the weighting factors on the result, to make a proper judgement in the selection of the weighting factors.

As an example, the same calculation as discussed in the previous paragraph, is here repeated, with different performance criteria settings. The first case concerns the same criteria, all with an equal weighting, and the second set consists of considering upwind and downwind VMG only, also equally weighted. Following the same method as in the previous paragraph, the charts for optimum beam are shown in figure 10 and figure 11, respectively.

Comparing figure 9 and figure 10, it is seen that the trends are similar, and the optimum beam for each combination of length-displacement ratio and sail area, does not differ much. However, there is a difference in the locus for the highest score. Using equally weighted criteria results in the selection of a yacht with

approximately a length-displacement ratio of 5.5 (corresponding ballast ratio is 43%), a sail area of 77 m^2, and a waterline beam of 3.4 m. Where the first concept design had a score of 0.924, this second selected design received a score of 0.893, using the original criteria set.
In figure 11, results are shown for the upwind and downwind VMG criteria only. Both are equally weighted, so the result will be the best performing yacht on an upwind – downwind race course. Overall, the design with a length-displacement ratio of 5.5, a waterline beam of 3.8 m and a sail area of 110 m^2, performs best. This design also performs best on the upwind VMG criterion and downwind it receives a score of 0.82. For this criteria set, the trends are different as well, compared to the previous calculations.

7. CONCLUSIONS

The CEM, as presented here, is a small first step on the way to a powerful tool in sailing yacht design. The results of the case study as presented, proved to be valuable in the actual design process. Results using a normal VPP, confirmed the results obtained by the CEM, with regard to VMG and boatspeed.
Many of the assumptions in the program, still need further improvement, as do the various calculations. Though the results in absolute terms may not be accurate enough yet, it is believed that for comparison and ranking purposes the results are very useful.
The various presented methods to calculate the various aspects of the designs, all prove to be a good starting point for further development. Especially the newly developed stability method is promising.
The selection method, using weighting factors and normalization to come to an optimal concept design, does not give an *objective* concept design, but a *subjective*, dependent on the user of the program. This is not believed to be a lack of the model, but merely a point of attention. Every design method is subjective because it always is the designer who takes the decisions and chooses which factors and criteria to use.

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