YILDIZ TECHNICAL UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN SCIENCE AND ENGINEERING

SHIP HULL FORM OPTIMIZATION BY EVOLUTIONARY ALGORITHM

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EVRİMSEL ALGORİTMA YAKLAŞIMIYLA GEMI TEKNE FORMUNUN OPTİMİZASYONU

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NOMENCLATURE

a_j	Lower limit of variable domain
b_j	Upper limit of variable domain
B	Breadth or beam
bint	binary integer value of the chromosome
B_t	Average breadth of the transom
c_a	Correlation allowance
c_{13}	factor related to stern for Holtrop and Mennen
C_F	Frictional resistance coefficient
C_R	Residuary resistance coefficient
C_T	Total resistance coefficient
C_W	Wave resistance coefficient
C_b	Block coefficient
C_m	Midship coefficient
C_p	Prismatic coefficient
C_{wp}	Waterplane coefficient
C_v	Volume coefficient?
C_{vp}	Vertical prismatic coefficient
C_{bulb}	Factor for bow bulb resistance prediction by Holtrop and Mennen
chr_{dec}	Decimal equivalent of a chromosome
$-c$	Steady advancing velocity
D	Depth
D_{min}	Minimum depth
D_t	Average depth at the transom
$f_x(x,z)$	Longitudinal slope over surface of the hull
Fn	Froude number
$Fn(i)$	Froude number at speed *i*
G	Nonlinear function for damping and roll restoring moment
GM	Centre of gravity to metacenter; metacentric height
k_1	Form factor for resistance correlation between model and ship
lcb	longitudinal centre of buoyancy
L	Hull Length
LC	Loading Condition
m_j	Number of bits (1's or 0's) in the chromosome
μ_1	Roll angle
$\ddot{\mu}$	Acceleration of roll
ω	Periodic roll
P_{ct}	Calculated or measured hull form coefficients
P_{dt}	Desired hull form coefficients
R_A	Model-ship correlation resistance
R_{APP}	Appendage resistance
R_B	Bulb resistance
Rn	Reynolds number
R_T	Total resistance

R_{TR}	Transom stern resistance
R_w	Wave Resistance
ρ	Specific mass of water
S	Wetted surface area
S_f	Free Surface
S	Ship surface
T	Draft
T_F	Draft at forward perpendicular
V	Chromosome
V	Ship speed
X	Neural network input vector
x_j	Variable in chromosome
Z	Neural network output vector
W	Matrix chromosome
w_{ij}	Element in matrix chromosome representing next change in offset
WL	Waterline
x_{CB}	Longitudinal centre of buoyancy percentage forward /aft from midships
$y(i,j)$	Hull offset at i^{th} station and j^{th} waterline
Δy	Difference in adjacent hull offsets
w_{upper}	Upper allowable change in offset
w_{lower}	Lower allowable change in offset
$\phi(x,y,z)$	Potential
σ	Source strength
σ_t	Source strength over the transom
Δ	Displacement

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ANN	Artificial Neural Network
BSRA	British Ship Research Association
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DEC	Digital Equipment Corporation
DOUST	Doust Optimized Trawler Forms
EA	Evolutionary Algorithms
FHV	Fish Hold Volume
GA	Genetic Algorithms
GEC	Grubisic Example Concept
IMDC	International Marine Design Conference
IMO	International Maritime Organization
ITTC	International Tow Tank Conference
ITU	Istanbul Technical University
LCB	Longitudinal Centre of Buoyancy
LCF	Longitudinal Centre of Flotation
LOA	Length Over All
LPP	Length Between Perpendiculars
LWL	Length of Waterline
MCDM	Multiple Criteria Decision Making
MCR	Maximum Continuous Rating
MOGA	Multiple Objective Genetic Algorithm
MSI	Motion Sickness Index
NN	Neural Network
NSGA	Non-dominated Sorting Genetic Algorithm
R&D	Research and Development
RANSE	Reynolds Averaged Navier Stokes Equations
RAO	Response Amplitude Operator
RCI	Resistance Coefficient Index
SKI	Seakeeping Index
SOEA	Sequential Objective Evolutionary Algorithm
STIX	Stability Index
RO-RO	Roll On Roll Off Ships
UBC	University of British Columbia
VEGA	Vector Evaluated Genetic Algorithm

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ABSTRACT

This thesis examines the application of Evolutionary Algorithms for ship hull form optimization. In addition the thesis briefly examines the use of an Artificial Neural Network for predicting a particular hull attribute.

A method is developed where different chromosomes are combined to model the hull. A matrix chromosome is used to model the hull offsets. A one-dimensional array or single chromosome is used to model the principal parameters. The method allows both optimization of the principal parameters to obtain an initial design satisfying the requirements as well as concurrent optimization of the hull form to minimize resistance and maximize other performance attributes of seakeeping and stability.

Hull form optimization is conducted using hydrodynamic evaluations of key performance attributes. In particular, performance in terms of ship resistance, seakeeping and stability are evaluated. The design methodology uses multiple objective optimizations and a novel multiple objective optimization technique is developed.

The search for potential designs uses evolutionary algorithms to optimize both the hull form and determine the principal parameters satisfying the design requirements. A multi-species genetic algorithm is developed to enable competition between alternate hull forms.

In order to obtain a reasonable approximation of the resistance some modifications of classical linearised thin-ship theory is utilized. A particular problem for vessels with low length to beam ratio and with transom sterns is investigated. In addition to resistance the candidates are evaluated in terms of seakeeping performance. Seakeeping is evaluated using a hydrodynamic evaluation of the hull forms in a regular seaway. A two dimensional strip theory analysis of seakeeping provides the input to develop a vertical motion seakeeping index.

With respect to stability an analysis of vessel candidates is conducted using a regression based formulation and an artificial neural network. A database of typical candidates is required to provide data on vessel attributes that are required for training the neural network. The determination of the center of gravity or KG is then used as input for the seakeeping evaluation as well as to satisfy the constraint for a maximum KG.

Key Words: Hull Form Optimization, Genetic Algorithms, Neural Networks, Hydrodynamics, Ship Design.

ÖZET

Bu tez, gemi gövde formu optimizasyonunda Evrimsel Algoritmaların uygulanması konusunu araştırmaktadır. Tezde ayrıca Yapay Sinir Ağlarından faydalanarak belirli bir tekne niteliğinin tahmini de incelenmiştir.

Gövde formu optimizasyonu, kısıtlamalar dahilinde dizayn isteklerini yerine getirirken önemli bazı gemi performans niteliklerinin hidrodinamik analizlerini kullanarak en iyi çözümü araştırmaya yönelik bir bakış açısına sahiptir. Teknenin hidrodinamik performansı; gemi direnci, denizcilik ve stabilite özellikleri cinsinden değerlendirilmiştir. Optimizasyon yöntemi tek ve çok amaçlı optimizasyonları dikkate almaktadır. Dizayn uzayındaki potansiyel teknelerin araştırabilen bir arama motoru, hem tekne formunu ve hem de tasarım isteklerini yerine getirecek temel parametreleri belirlemeyi optimize eden evrimsel algoritmaları kullanmaktadır. Alternatif tekne formları arasında rekabeti sağlamak amacıyla çok cinsli genetik algoritma kullanımı geliştirilmiştir.

Tekne formunun optimizasyonu hidrodinamik ana performans niteliklerinin değerlendirilmesi ile yapılmıştır. Çalışmada hidrodinamik performans; gemi direnci, denizcilik ve stabilite açılarından belirlenmiştir. Önerilen dizayn yöntemi, yeni gelişltirilen bir teknik dahil olmak üzere çok amaçlı çok amaçlı optimizasyonları kullanmaktadır.

Teknenin modellenmesinde farklı kromozomların birleştirildiği bir metod geliştirilmiştir. Tekne ofset verilerini modellenmesinde matris kromozomu yöntemi kullanılmıştır. Aday teknelerin ana parametrelerini modellenmesi tek bir kromozom (tek boyutlu bir dizi) yardımıyla gerçekleştirilmiştir. Bu yöntem, şartları sağlayan bir ön tasarımın ana parametrelerini optimize edilmesini ve ayrıca direnci minimize, diğer performans niteliklerinden denizcilik ve stabiliteyi maksimize eden tekne formunu elde etdecek uzlaşmalı bir optimizasyonu sağlamaktadır.

Makul bir direnç yaklaşımı elde etmek için klasik olarak lineerleştirilmiş ince gemi (thin ship) teorisindeki bazı değişikliklerden faydalanılmıştır. Boy-genişlik oranı düşük ayna kıçlı gemilerin özel bir problemi incelenmiştir. Aday tekne formlarının direnç karakteristikleri ile birlikte dikkate alınan denizcilik özellikleri teknenin düzgün dalgalardaki hidrodinamik davranışını içermektedir. İki boyutlu şerit teorisini kullanan denizcilik analizi, dikey hareketlere ait denizcilik indeksini elde eden girdiyi oluşturmaktadır. Yöntem, diğer serbestlik derecelerindeki gemi hareketlerine ait indeksler için de benzer olarak uygulanabilir.

Stabilite ile ilgili olarak, tekne adaylarının analizi ilk önce formüle dayalı bir regresyonla ve daha sonra Yapay Sinir Ağları kullanılarak gerçekleştirilmiştir. Yapay Sinir Ağını eğitmek için gereken gemi özellikleriyle ilgili bilgileri elde etmek amacıyla tipik adaylara ait bir veritabanına gerek duyulmuştur. Ağırlık merkezinin enine yeri olan KG'nin tayini, denizcilik değerlendirmesi için girdi olarak ve ayrıca maksimum KG kısıtlamasını sağlamak amacıyla kullanılmıştır.

Anahtar Kelimeler: Tekne Formu Optimizasyonu, Genetik Algoritma, Yapay Sinir Ağları, Hidrodinamik, Gemi Dizaynı.

EXECUTIVE SUMMARY

Optimization of a ship hull form can lead to considerable benefits, as the cost of a vessel is substantially derived from the concept design stage. Therefore changes in the hull can lead to major savings in construction or improvements in performance can increase efficiency during the life cycle of the ship.

Hull form optimization traditional focuses on single objectives such as improvements in resistance for fuel savings, or reductions in wave making for creating less wash. Better seakeeping could be an objective for operations of specific vessels such as high-speed ferries. Stability may be an important safety issue for small vessels such as fishing boats.

While other studies have used Genetic Algorithms (GAs) for optimization of a ship hull, the focus in this thesis is to be able conduct a multi-objective optimization of the ship hull form where the ship hull is modeled in such a manner as to provide advanced performance analysis at or nearly at the concept design stage. In order to do that the ship hull is modeled in terms of the principal parameters as well as through the hull offsets so that all aspects of the hull can be varied and the effect on performance studied and optimized.

The use of Evolutionary Algorithms (EAs) or GAs as an optimization tool is a proven and powerful method for which to conduct optimization. In order to use this optimization method the hull must be encoded in a form useful for the EA. That means the elements of the hull are encoded as chromosomes and by changing these chromosomes through genetic operators, the hulls are varied and the optimization can progress. Figure 1 shows the form of the simple GA.

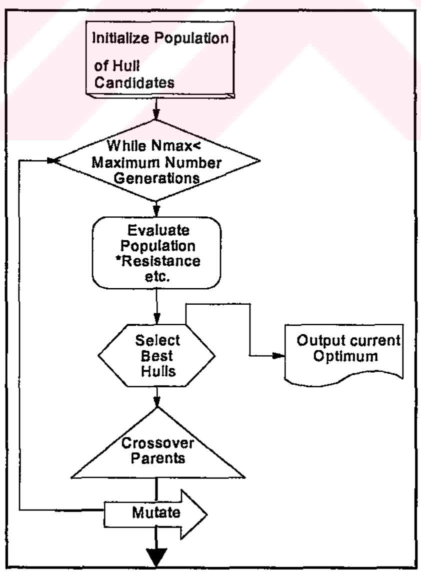


Figure 1. Simple Genetic Algorithm General Structure

To model the full elements of the hull, the principal parameters were encoded as a single string chromosome that is essentially a one-dimensional array of bits encoding the length, beam and draft of the hull. To model the offsets a unique method using a matrix chromosome was developed that models offsets in stations and waterlines in a normal and intuitive manner. Together the single and matrix chromosome represent the hull so that all the elements of the hull are captured and can be modified. Figure 2 shows the form of a single chromosome V for length, beam and draft. Figure 3 shows the matrix chromosome W for the hull offsets.

$$
\begin{aligned}
&V = (150,30,15)\\
&= (2^7 + 2^4 + 2^2 + 2^1, 2^4 + 2^3 + 2^2 + 2^1, 2^3 + 2^2 + 2^1 + 2^0)\\
&= (10010110,11110,1111)\\
&= '100101101111101111'
\end{aligned}
$$

Figure 2. Singe Chromosome for Principal Parameters

$$
W = \begin{bmatrix} station1, waterline1 & station2, waterline1 & \cdots & station\ m, waterline1 \\ station1, waterline2 & station2, waterline2 & \cdots & station\ m, waterline2 \\ \vdots & & \cdots & \\ station1, waterline\ n & station2, waterline\ n & \cdots & station\ m, waterline\ n \end{bmatrix}
$$

Figure 3. Matrix Chromosome for Hull Offsets

In order to evaluate each candidate from a population of hulls that are randomly varied initially within the limits imposed by the designer, each hull is required to be evaluated and the performance measured such that a fitness measurement can be assigned to the hull. By selecting candidates that are fitter the process of evolving the hulls can be achieved by combining elements of different hulls that show better potential for performance.

The performance selected to demonstrate the methodology in this thesis are some basic naval architecture requirements of stability, resistance and seakeeping. Measuring the hydrostatics of each hull and developing a GZ curve provides the stability analysis. The resistance is evaluated using a modified thin ship theory to obtain the wave resistance that is combined with an equivalent skin frictional resistance. The seakeeping performance is obtained by using strip theory to derive the motions of the ship hull in a given sea state that is based on the maximum length being considered for the hull.

For each performance objective a performance index is developed to quantity each performance into a single parameter. The single parameters are used in each objective to give a fitness of the candidate hull for that objective. The stability index is based on the area under the GZ curve combined with the angle at which maximum GZ occurs as given by (1). The resistance index is developed from the total resistance coefficient at each speed or Froude number as given by (2). The area under the curve is used to give a resistance index similar to a power density curve. The seakeeping performance is limited to the vertical heave and pitch that are combined with the heave acceleration of the hull as shown in Figure 4. At each speed this measure is given and the area under this curve is also used in a similar manner to resistance.

$$STIX = \phi_m \int_0^{\varphi_v} GZ(\phi)d\phi \tag{1}$$

$$RCI = \sum_{i=1}^{N-1} \frac{1}{2} * \left(Ct(i)) + Ct(i+1)\right) * \left(Fn(i+1) - Fn(i)\right) \tag{2}$$

$$SKI = \frac{1}{2}\sum_{i=1}^{N-1}\left(Vert(i) + Vert(i+1)\right)\times\left(V(i+1) - V(i)\right) \tag{3}$$

$$Vert = H_{rms}\left(\frac{L}{2}\sin(\phi_{rms})\right)\times \ddot{H}_{rms} \tag{4}$$

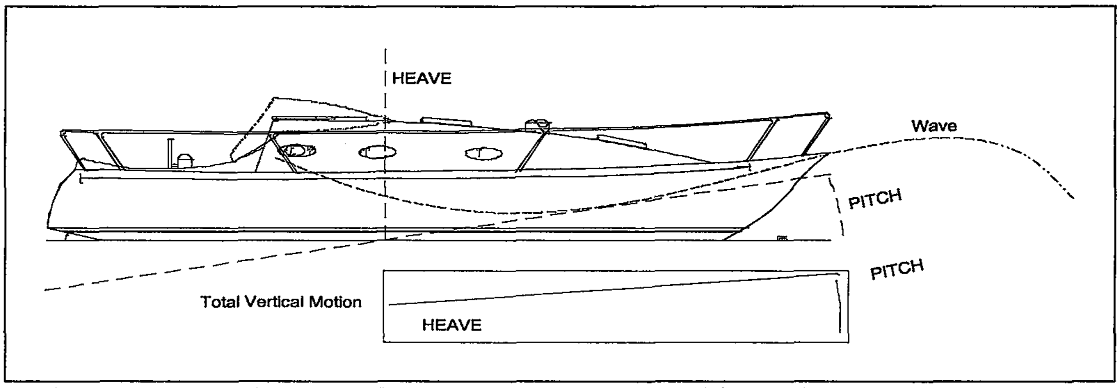


Figure 4. Vertical Motion from Heave and Pitch multiplied by Heave acceleration

Once the hulls are encoded they can be evaluated for their performance in each objective, and the hulls can be optimized through repeated generations, however since the problem is a multi-objective problem combining the three sometime disparate performance objectives, it was necessary to utilize a multi-objective optimization methodology. Although there are numerous methods available including aggregate functions and Pareto frontier non-dominated sorting algorithms, a method was developed that did not require the use of either of these. This methodology is called the Sequential Objective Evolutionary Algorithm (SOEA) and was shown to provide good solutions for a number of test problems. The form of the algorithm is shown in Figure 5.

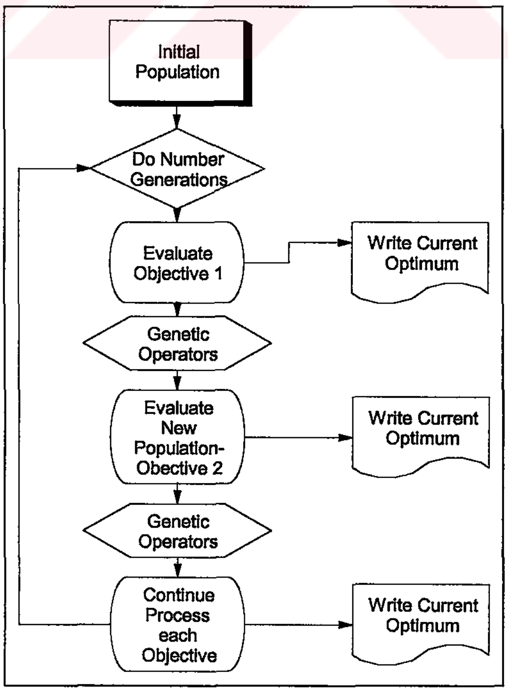


Figure 5. Sequential Objective Evolutionary Algorithm (SOEA) Structure

This methodology combined with the evaluations and was finally used to optimize a number of different hull forms. A number of design requirements were added to make the problem more realistic. For the study using ITU fishing vessels, a fish hold volume and a GM requirement were modeled, the former using a regression equation shown by (3). The latter can be measured with hydrostatics and represents a stability requirement for regulations such as IMO criteria.

$$V_{FH} = 0.38 L_{FH} (B \times D)^{1.08} \tag{6}$$

In addition to these succinct requirements, the displacement was added as a constraint because many of the models did not meet some of the expected displacements. All of these requirements are set as constraints that affect the fitness performance evaluations through a penalty factor. The penalty is derived from the deviation between the required values as the measured values for fish hold volume, GM (4a) and in some cases, volumetric displacement, as given by (4b).

$$penalty = 1.0 - \frac{1}{2} * \left(\frac{D_{FHV}}{D_{FHV\,\max}} + \frac{D_{GM}}{D_{GM\,\max}} \right) \tag{6a}$$

$$penalty = \frac{D_{\nabla}}{D_{\nabla\,\max}} \left[1.0 - \frac{1}{2} * \left(\frac{D_{FHV}}{D_{FHV\,\max}} + \frac{D_{GM}}{D_{GM\,\max}} \right) \right] \tag{6b}$$

In addition to EA for optimization, and regression equations for predicting the fish hold volume, Artificial Neural Networks (ANN or NN) offer alternative methods for data analysis. The use of a NN in this thesis was restricted to the prediction of KG, which is naturally dependent on weight, and somewhat independent of the hull shape. Therefore a method for predicting the KG was required in order to assess the GM and to use as input for the seakeeping program. Figure 6 shows the KG prediction using a neural network.

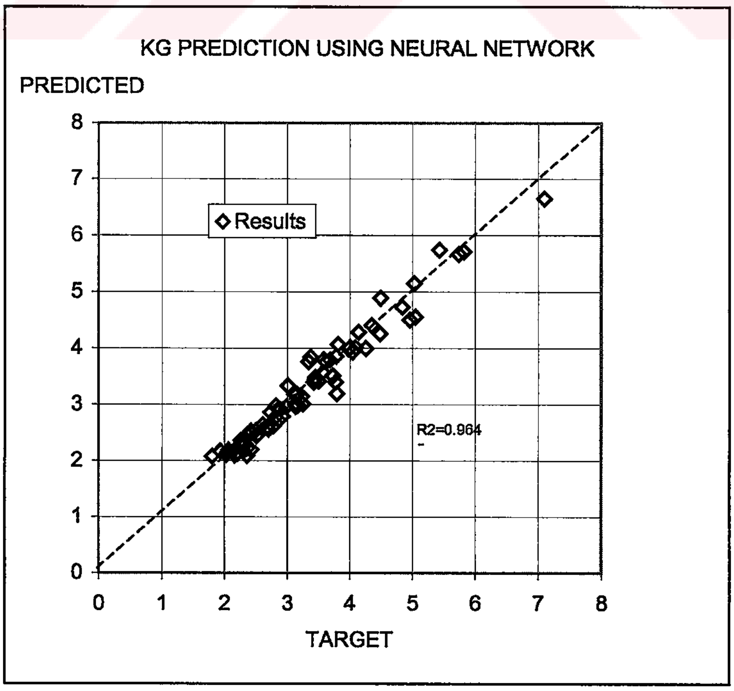


Figure 6. KG Prediction using a Neural Network

The resistance measurement made use of thin ship theory modified to accommodate a transom. This was tested using the ITU series if fishing boats. Figure 7 shows typical good agreement for the results as given by ITU 148/1B at light displacement up to a maximum speed represented by Froude number of 0.4.

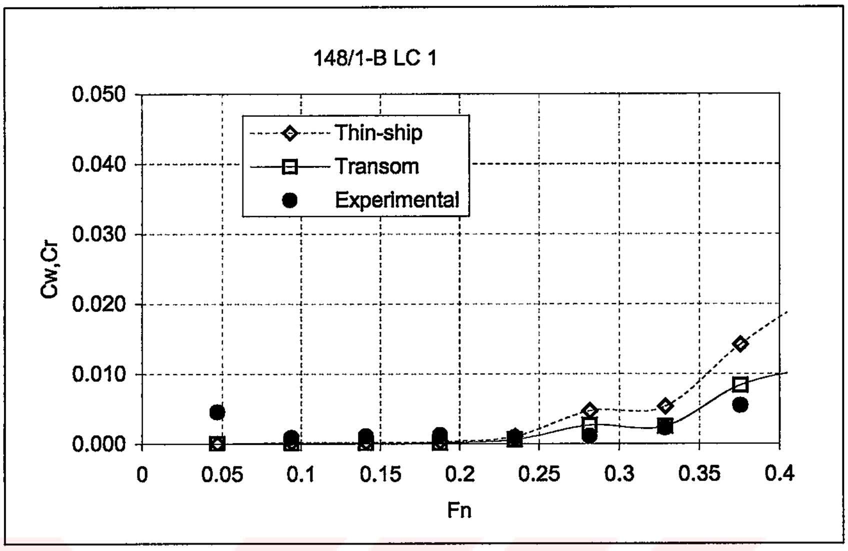


Figure 7. Modified Thin Ship Wave Resistance for ITU 1B Fishing Vessel

The thin ship calculation while not as accurate as 3-Dimensional modelling serves the purpose to be able to rank and distinguish similar vessels as shown in Table 1. It also has the distinct advantage of being quick to calculate. Since a 3-d calculation still takes minutes for each set of Froude numbers, the thin ship theory proved more useful in the general search for an optimum hull. However if only resistance was being optimized a GA solver could still be used with 3-D theory.

Although the seakeeping index is only representative of vertical motion, the actual performance of the index does tend to optimize the results and intuitively behaves in a manner appropriate to better seakeeping hulls. While there are no restriction or constraints added for slamming, accelerations o the deck and bridge or at other points on the vessel which are useful, it does allow the hulls that have better overall seakeeping to be optimized. Figure 8. Shows how the seakeeping index varies with length.

Beside the multi-objective problem, the issue of comparing dissimilar hulls was resolved by using the concept of multi-species. A multi species algorithm can compare different hulls by allowing them to compete in the same population but restricting the genetic operations to only members of the same species. By allowing them to compete the algorithm can eventually sort out which hulls are performing better at the same time as they are being optimized. Figure 9 shows 4 ITU fishing hulls that are optimized and indicates how Hull 4 wins out after only 10 generations.

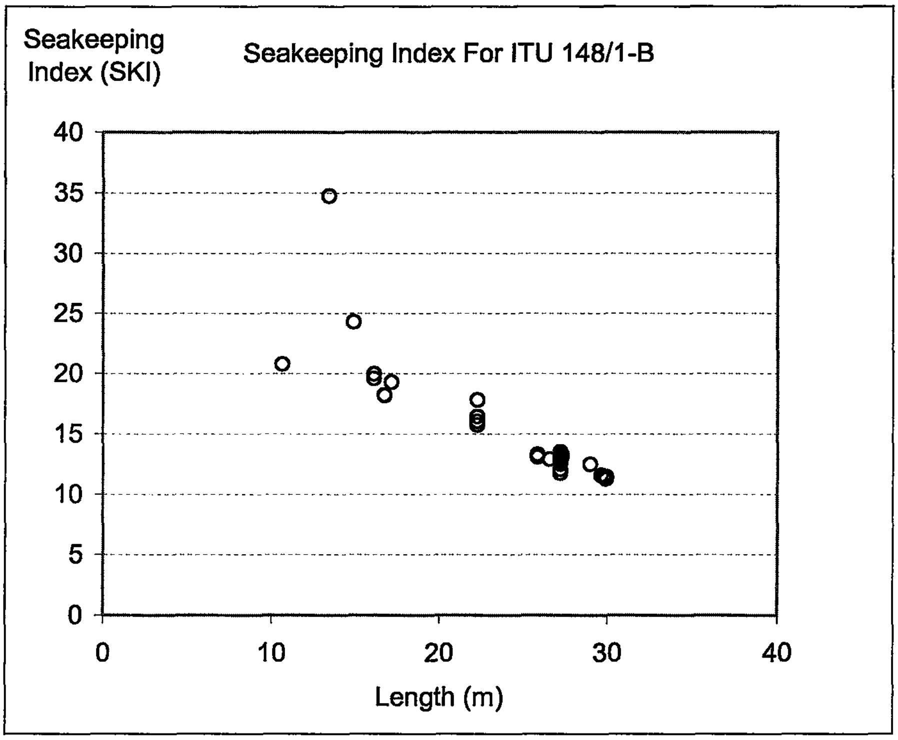


Figure 8. Vertical Seakeeping Index Variations with Length

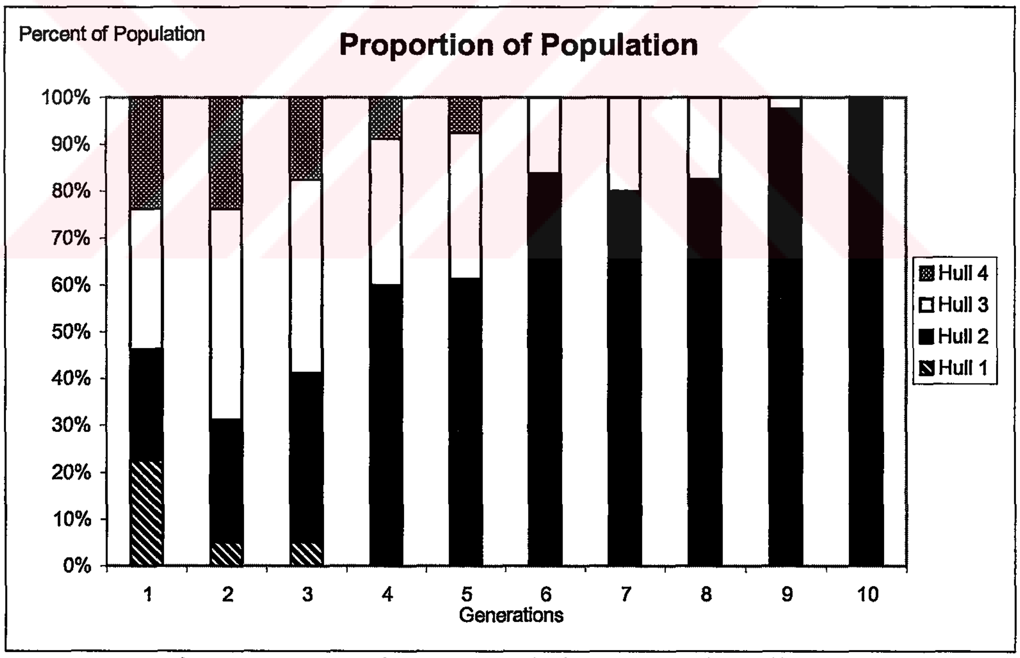


Figure 9. Proportion of Population for Each Hull Type

Initially the concern was to test the ITU fishing vessel series. Before optimizing the hull forms for a given concept set of design requirements, a hull was tested with fixed dimensions to determine if the hull form itself could be optimized. ITU 148/1-B fishing hull was optimized and the original and modified body plan is shown in Figure 10. The resistance, and seakeeping were largely improved upon but at a small cost to stability. The progress of the optimization over 100 generations is shown in Figure 11.

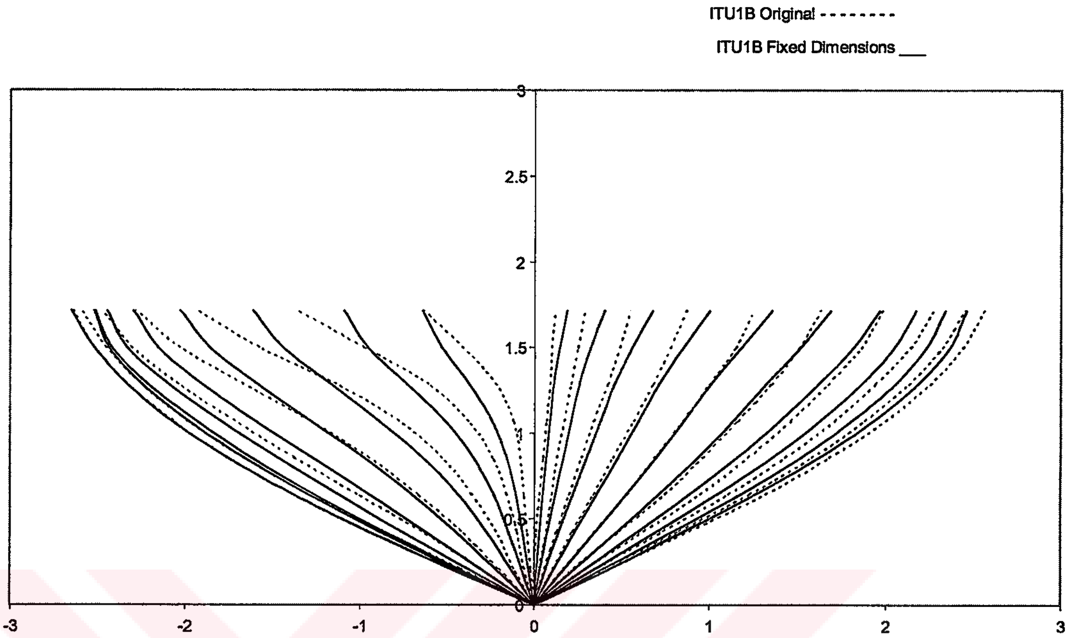


Figure 10. Original and Modified ITU 148/1-B Fishing Boat with Fixed Dimensions

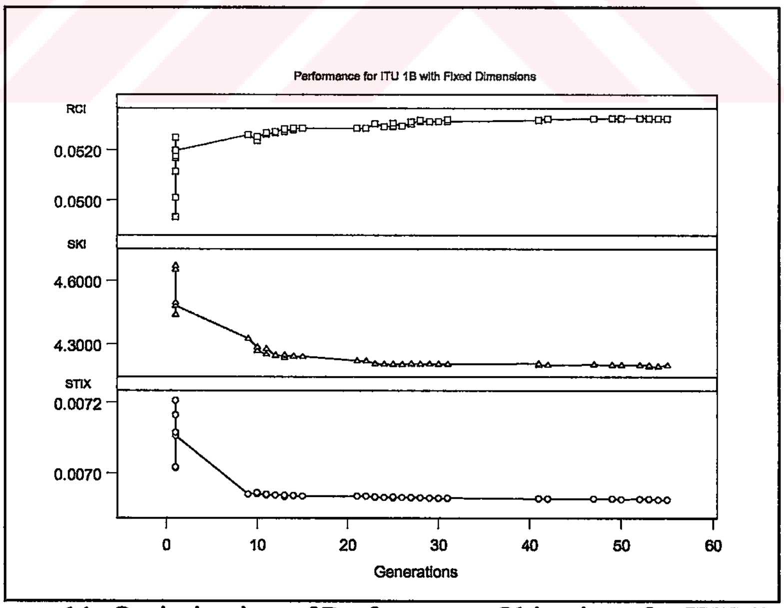


Figure 11. Optimization of Performance Objectives for ITU 1B

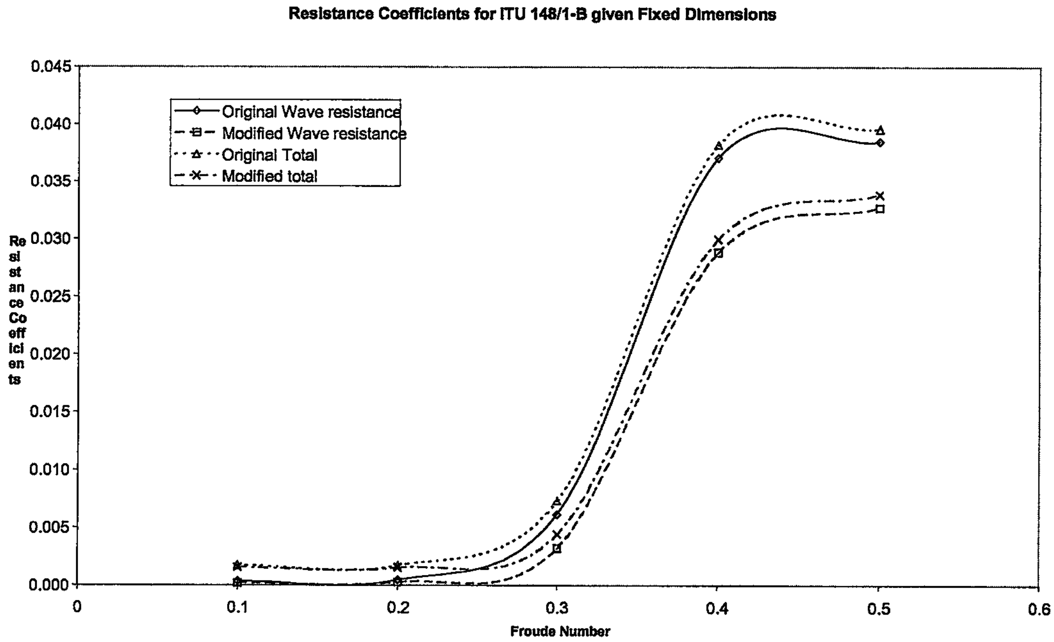


Figure 12. Optimization of Wave and Total Resistance Coefficients for ITU 148/1-B

Figure 13 shows the modified WIGLEY Hull while Figure 14 shows the reduction in resistance. Figure 15 shows the heave and pitch response.

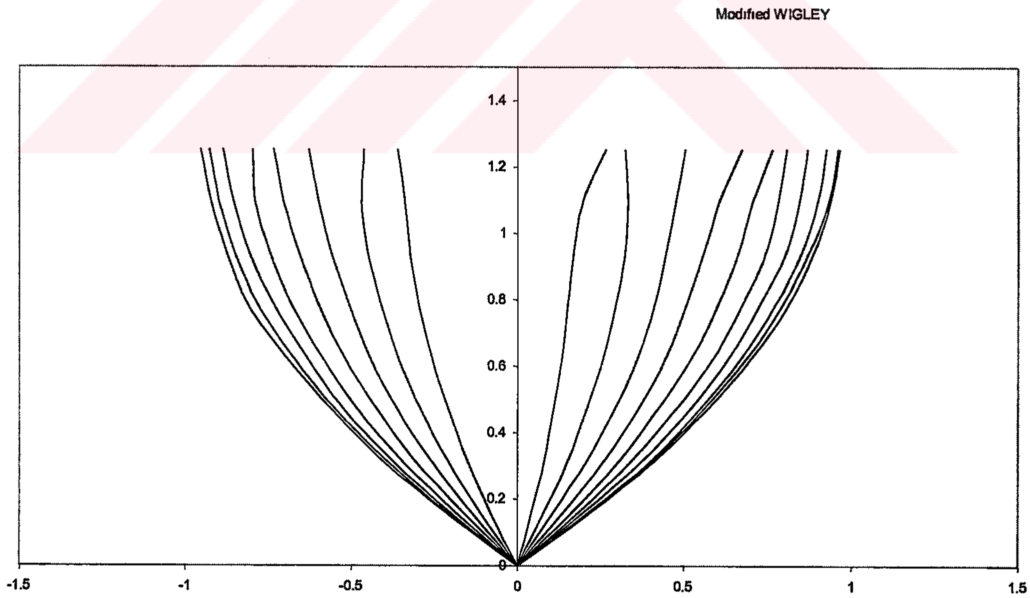


Figure 13. Modified WIGLEY Hull

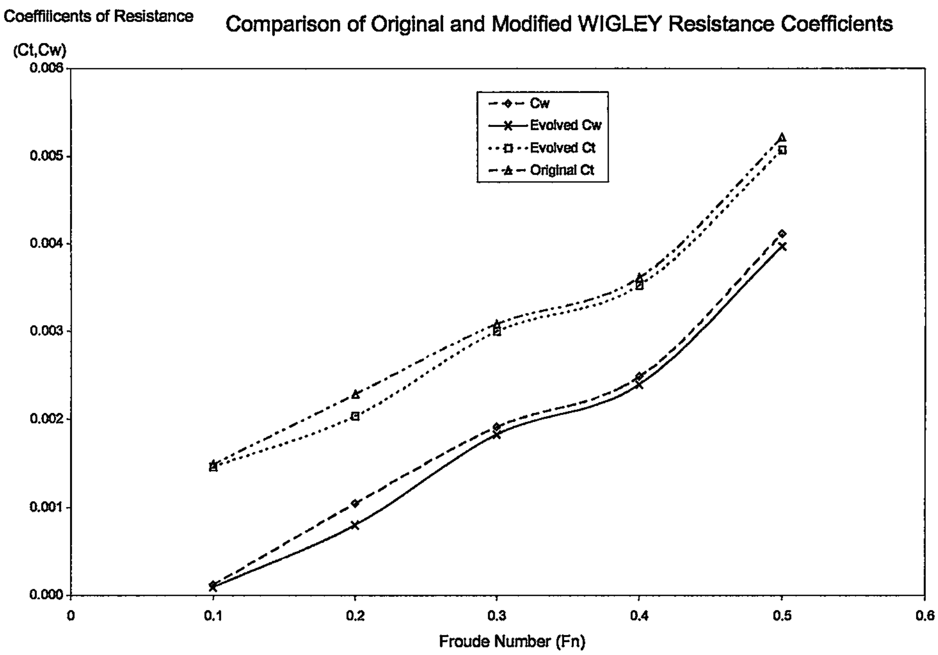
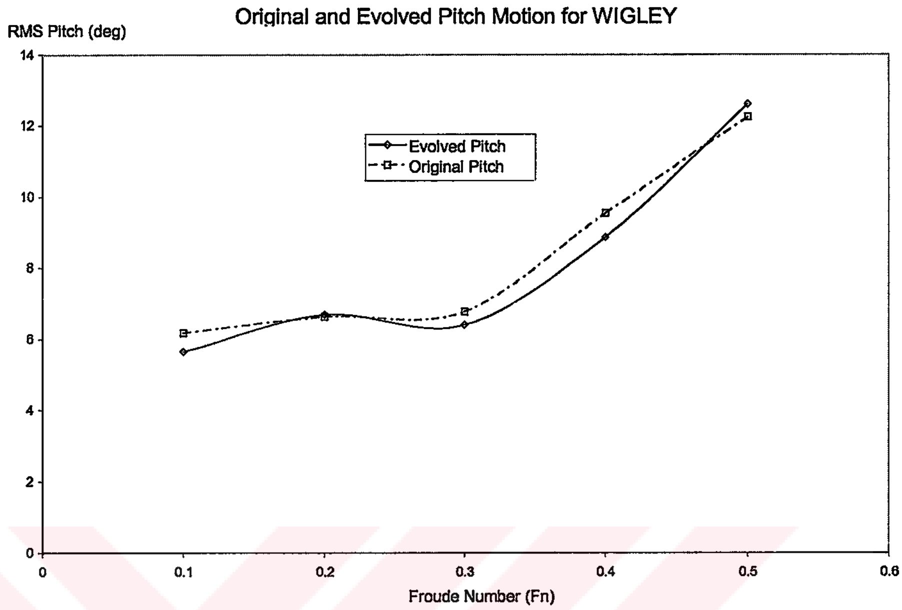


Figure 14. WIGLEY Optimization of Resistance

A number of other vessels are optimized in addition to fishing vessels ITU 148/1-B and ITU 1148/4-B. As shown the mathematical hull form WIGLEY was tested to compare with a known slender double-ended hull form. A fast patrol craft with a large transom known as ATHENA was optimized. In addition the ship hull Series 64 was selected because of known resistance data and the small transom that differs this form the Series 60 hull. Finally a typical Frigate hull as shown optimized in Figure 16 was tested.

A number of goals were introduced which are as follows; firstly actual hull forms should be considered. Most often in concept design parametric studies are conducted using a database of hull form parameters, sufficient to give the global parameters but insufficient to conduct more advanced analysis. This goal has been achieved by modeling of actual hull forms.

While hull form optimization is the focus the program should include global parameters to determine optimal general characteristics in terms of principal parameters. Hull ITU 148/1-B and Hull ITU 148/4-B were both changed from 18-meter vessels into 30-meter vessels and compared to the Grubisic Example Concept 23 meter fishing vessel. The program operates quickly in optimizing the length, which tends towards the upper limit of the design space unless further design requirements or constraints are placed on the length. Beam also tends to be maximized by stability requirements but is sometimes limited by minimum resistance, however, minimum resistance is achieved more often by limiting draft and optimizing wave resistance then by beam. Draft tends towards the minimum draft and displacement to satisfy the requirements.



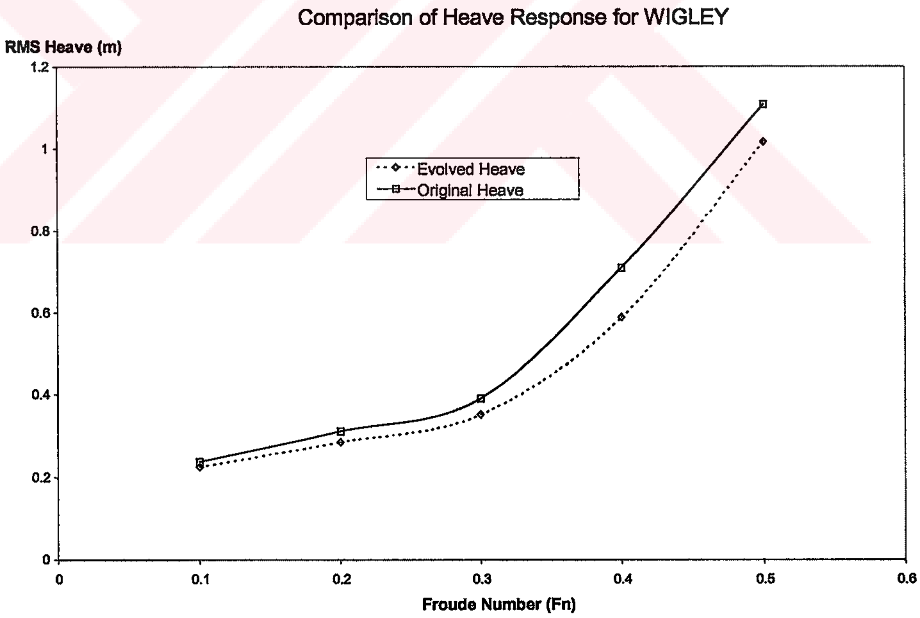


Figure 15. Heave and Pitch Response for Optimized WIGLEY Hull Form

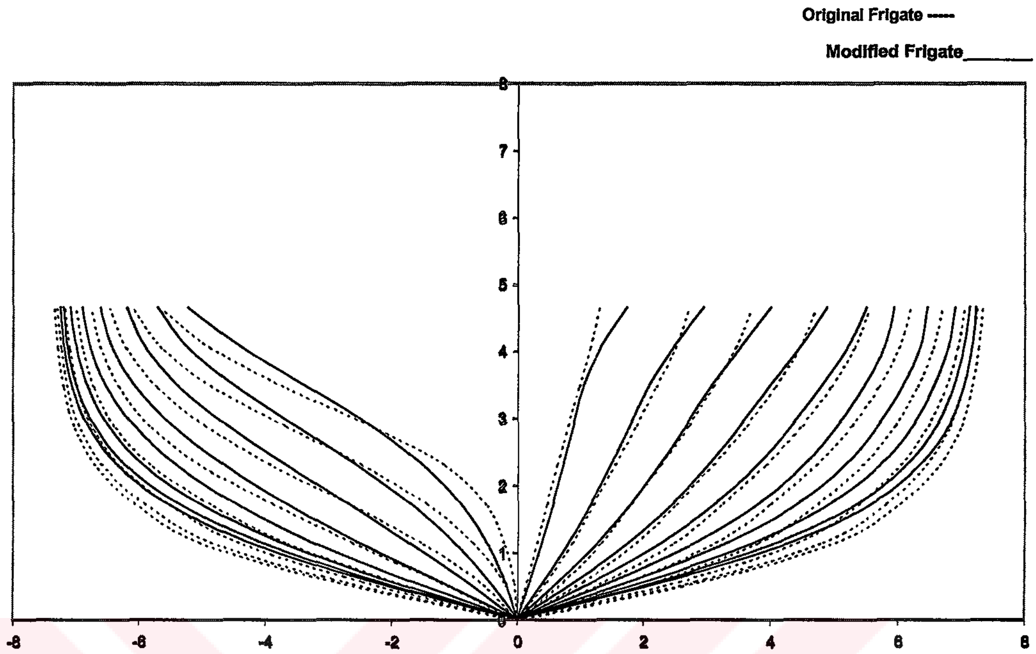


Figure 16. Original and Modified Frigate Hull

Hydrodynamic analysis should be conducted for local optimization of the hull form with respect to resistance and seakeeping. Stability should be maximized through hydrostatic analysis of the hull and by KG analysis using the neural network. In all cases these objectives are achieved.

Other objectives should be included in the optimization creating a multi-objective design methodology. As shown in Figure 17 resistance and seakeeping can be both minimized and while stability varies, it too can be selected for near-maximum stability exceeding IMO requirements.

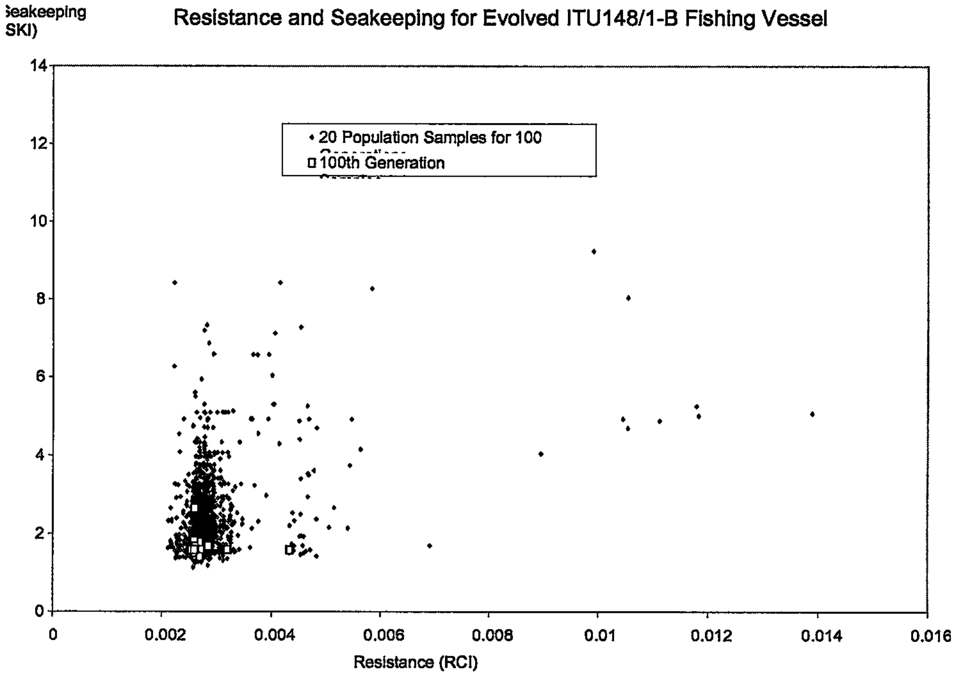


Figure 17. Optimization of Resistance and seakeeping of ITU 1B

Finally, a realistic hull form should be produced. The final fishing boat design body plan for ITU 1B is shown in Figure 18 represents a 30 meter vessel with minimum resistance and ship motion but near optimal (in second place) stability. ITU 4B had higher resistance and ship motion but better stability and is an alternative hull that has a fuller hull trawler form. The particulars for the hull Form are given in Table 1.

It should be noted that this thesis only represents the first step towards an integrated design tool. However all of the goals as set out by the thesis objective have been achieved. In the process, a practical tool has been developed along with a new method of dealing with multiple objective design problems as well as a new method of conducting hull form optimization on both a global principal parameter basis and a local hull form optimization basis using three basic principles of naval architecture. Further research will focus on strengthening the analysis methods including incorporation of advanced 3-D resistance analysis and more initial concept design requirements for a variety of more specialized hulls.

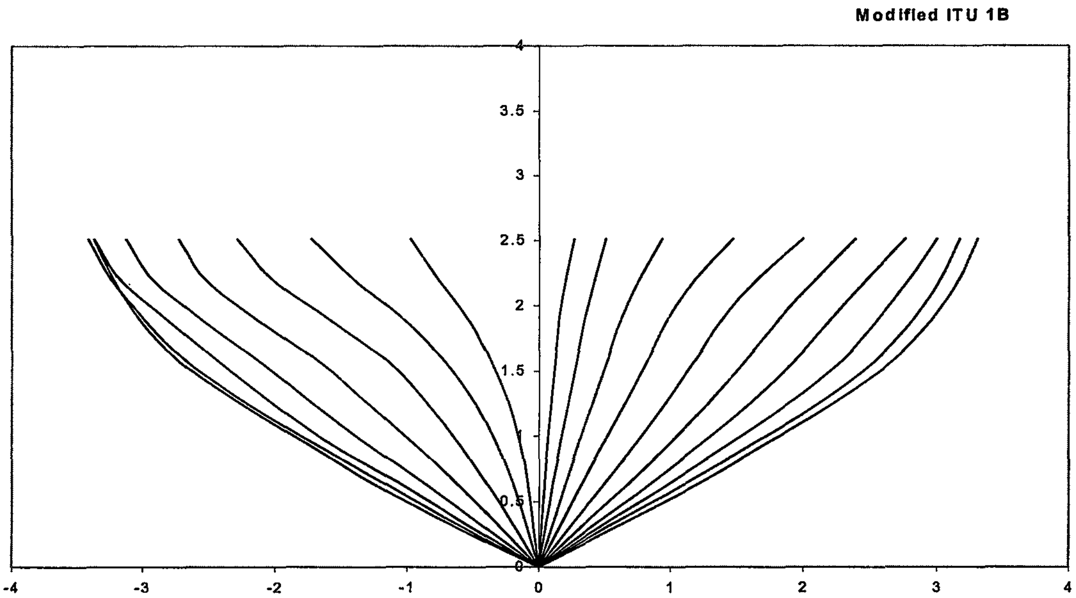


Figure 18. Evolved ITU 1B Fishing Hull form with Minimum Resistance and Ship Motion having Near-optimal Stability Matching Design Requirements

Table 1. Evolved ITU 1B Fishing Boat Design Parameters

Characteristic	Optimal Result	Characteristic	Optimal Result
LOA	29.24 m	KG (arrival)	2.411 m
LPP	29.24 m	GM (arrival)	1.218 m
LWL	29.24m	FHV	121.9 m^3
B	7.110m	C_p	0.53
T	2.510 m	C_b	0.309
Volume	161.4 m^3	C_{wp}	0.58
V_{max}*	13.55 knots	WS	202.706 m^2
AW	120.573 m^2	AM	10.421 m^2
KB	1.653 m	C_M	0.584
BMT	1.976 m	Xcb	0.437 m
BML	26.999 m	Xcf	0.875 m

* Based on Froude Number of 0.4

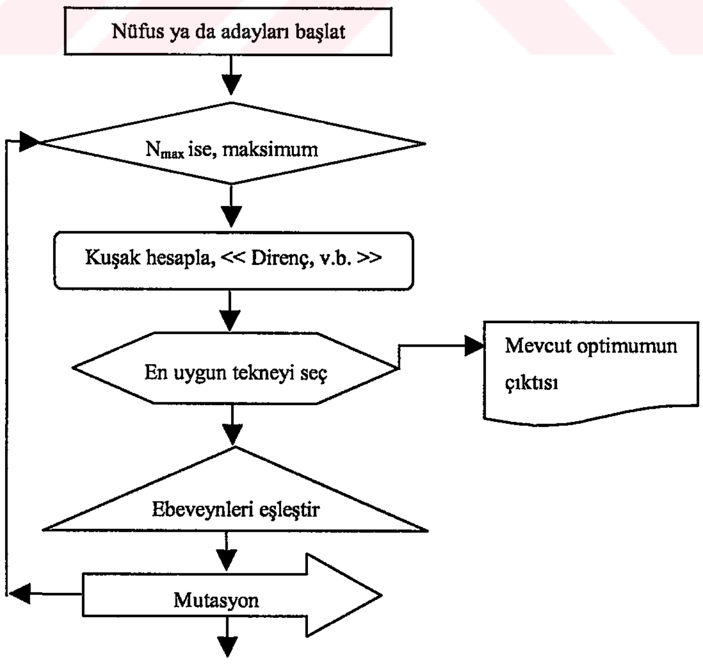
GENİŞLETİLMİŞ ÖZET

Bir geminin maliyeti, esas itibarı ile ön dizayn hesapları sonucunda belirlendiğinden bu aşamada gemi gövde formunun veya tekne geometrisinin optimizasyonu birçok fayda sağlamaktadır: Gemi gövdesinde yapılacak değişiklikler, inşa aşamasında önemli miktarda kazanç sağlarken, performanstaki iyileşme ise gemi ömrü boyunca daha kazançlı bir verim sağlamaktadır.

Tekne formunun alışılagelmiş biçimdeki bir optimizasyonu, yakıt tasarrufu için gemi direncinin iyileştirilmesi ya da güverte ıslanmasın karşı dalga oluşumunun azaltılması gibi tekli kısıtları kapsamaktadır. Daha iyi bir denizcilik kabiliyeti yüksek süratli yolcu gemileri gibi özel gemilerin işletiminde bir amaç oluşturabilmektedir. Stabilite ise, balıkçı teknesi gibi küçük gemilerin emniyeti açısından için önemli bir unsurdur.

Birçok tez çalışmasında, gemi formunun Genetik Algoritma (GA) ile optimizasyonu yapılmıştır. Bu tezde ise, gemi formunun çok amaçlı bir optimizasyonu amaçlanmaktadır. Bunun için, tekne formu, kavram dizayn aşaması sırasında ya da bu aşamanın başlangıcında ileri performans analizi yapabilecek düzeyde modellenir. Bu aşamada, ana parametreler ile birlikte tekne ofseti de kullanılarak gemi endazesi modelenir. Böylelikle, gövde farklı bakımlardan değiştirilip, bunların performans üzerindeki etkileri incelenerek optimizasyon yapılabilir.

Optimizasyonda GA veya Evrimsel Algoritmaların (EA) optimizasyon aracı olarak kullanımı kanıtlanmış ve optimizasyon işlemini yerine getirmede güçlülerdir. Söz konusu optimizasyon yönteminin kullanılabilmesi için teknenin GA'ya uygun bir biçime getirilmesi gerekmektedir: Tekne formunu tanımlayan elemanlara ait kodlar kromozomlar biçiminde yazılmakta, genetik işlemci yardımıyla bu kromozomların değişikliğe uğratılması sonucu gemi gövdesi farklı biçimlere getirilmektedir. Optimizasyon bu biçimde ilerlemektedir. Şekil 1'de basit GA yapısı görülmektedir.



Şekil 1. Basit Genetik Algoritmanın genel yapısı

Tekne elemanlarının tümünü modellemek için ana parametreler tek dizili bir kromozom kodunda yazılmaktadır: Esas olarak, teknenin boy, genişlik ve su-çekimi değerlerinin 'bit' cinsinden kodları bir boyutlu diziye yazılmaktadır. Ofsetin modellenmesinde matris kromozomunu kullanan özel bir yöntem gelişirilmişlir. Matris kromozomu oluşturulmasıyla, posta ve su hatlarındaki ofset değerleri olduğu gibi veya kullanıcıya bağlı olarak modellenmektedir. Tek dizili ve matris kromozomları birlikte gövdeyi temsil etmektedir. Böylelikle, tekne elemanlarının tümü elde edilip, değiştirilmektedir. Şekil 2'de, boy, genişlik ve su çekimi değerlerini taşıyan V tek dizili kromozomu görülmektedir. Şekil 3'de ise, tekne ofset değerlerini taşıyan W matris kromozomu görülmektedir.

$$\begin{aligned} V &= (150,30,15) \\ &= (2^7+2^4+2^2+2^1, 2^4+2^3+2^2+2^1, 2^3+2^2+2^1+2^0) \\ &= (10010110, 11110, 1111) \\ &= '10010110111101111' \end{aligned}$$

Şekil 2. Ana parametreleri taşıyan tek dizili kromozom

$$W = \begin{bmatrix} 1.posta, 1.suhattı & 2.posta, 1.suhattı & \cdots & m.posta, 1.suhattı \\ 1.posta, 2.suhattı & 2.posta, 2.suhattı & \cdots & m.posta, 2.suhattı \\ \vdots & & \cdots & \\ 1.posta, n.suhattı & 2.posta, n.suhattı & \cdots & m.posta, n.suhattı \end{bmatrix}$$

Şekil 3. Tekne ofset değerlerini taşıyan matris kromozomu

Bir nüfusa ait tekne adayının hesaplanması sırasında, tekne, tasarımcı tarafından önceden belirlenen sınırlar çerçevesinde rastgele değiştirilmekte, her bir gövde için hesap yapılmakta ve elverişlilik (fitness) ölçümü yapılarak performans değeri saptanmaktadır. Elverişli adaylar seçilerek, tekne evrimi sırasında iyi performans gösteren farklı teknelere ait elemanlar bir araya getirilmektedir.

Bu tezde izlenen yöntemin ele aldığı performans ölçütleri, temel gemi mühendisliği talepleri doğrultusunda stabilite, direnç ve denizcilik özellikleridir. Stabilite analizi kapsamında, her bir teknenin hidrostatik ve sakin-su stabilite karakteristiği hesaplanarak statik GZ doğrultucu moment kolu eğrisi oluşturulmaktadır. Direnç hesapları, eşdeğer yüzey sürtünme direnci eklenerek dalga direncini veren geliştirilmiş ince gemi teorisi kullanılarak yapılmıştır. Denizcilik performansı, tekne için öngörülen maksimum boy esas alınarak, belirli bir deniz şiddetinde gemi hareketlerini üreten şerit teorisi kullanılarak elde edilmiştir.

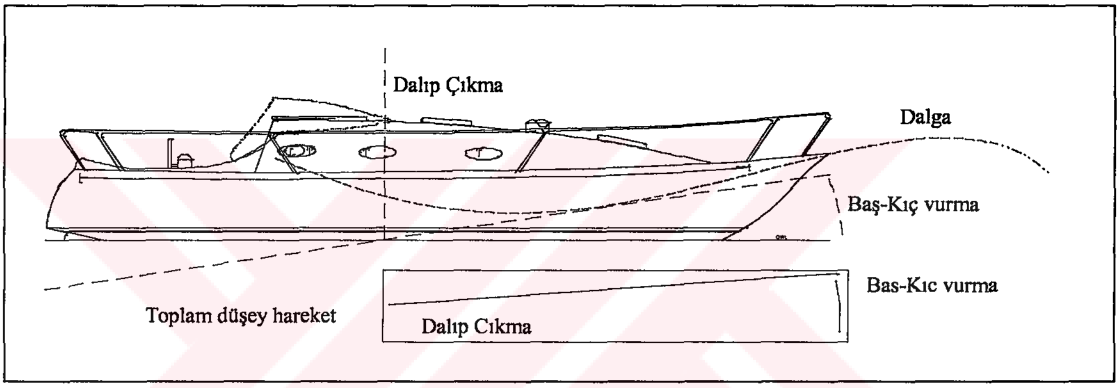
Kullanılan bu üç performans ölçütünün her birini tek bir parametre ile vermek için performans indeksi tanımlanmıştır. Kısıtlarda kullanılan bu parametreler, herbir kısıt için tekne adayına ait elverişlilik seviyesini göstermektedir. Bunlar açıklanacak olursa; stabilite indeksi (STIX), GZ eğrisi altındaki alan ile birlikte en yüksek GZ değerinin oluştuğu açıya bağlıdır (Eşitlik 1). Direnç indeksi (RCI), farklı hızlar veya Froude sayılarındaki toplam direnç katsayısı cinsinden tanımlanmıştır (Eşitlik 2). Güç yoğunluğu eğrisindekine benzer biçimde, eğri altındaki alan direnç indeksini belirlemekte kullanılmıştır. Denizcilik performansının belirlenmesinde, dalıp-çıkma ve baş-kıç vurma hareketleri ile sınırlı olan düşey hareketlerle birlikte, teknenin dalıp-çıkma ivmesi de kullanılmıştır (Şekil 4). Farklı hız değerlerine göre bu değerlerin oluşturduğu eğri altındaki alan dirençtekine benzer biçimde kullanılarak denizcilik indeksi (SKI) elde edilmektedir.

$$STIX = \phi_m \int_0^{\varphi_v} GZ(\phi)d\phi \qquad (1)$$

$$RCI = \sum_{i=1}^{N-1} \frac{1}{2} * \left(Ct(i)) + Ct(i+1)\right) * \left(Fn(i+1) - Fn(i)\right) \qquad (2)$$

$$SKI = \frac{1}{2} \sum_{i=1}^{N-1} \left(Vert(i) + Vert(i+1)\right) \times \left(V(i+1) - V(i)\right) \qquad (3)$$

$$Vert = H_{rms} \left(\frac{L}{2} \sin(\phi_{rms}) \right) \times \ddot{H}_{rms} \qquad (4)$$



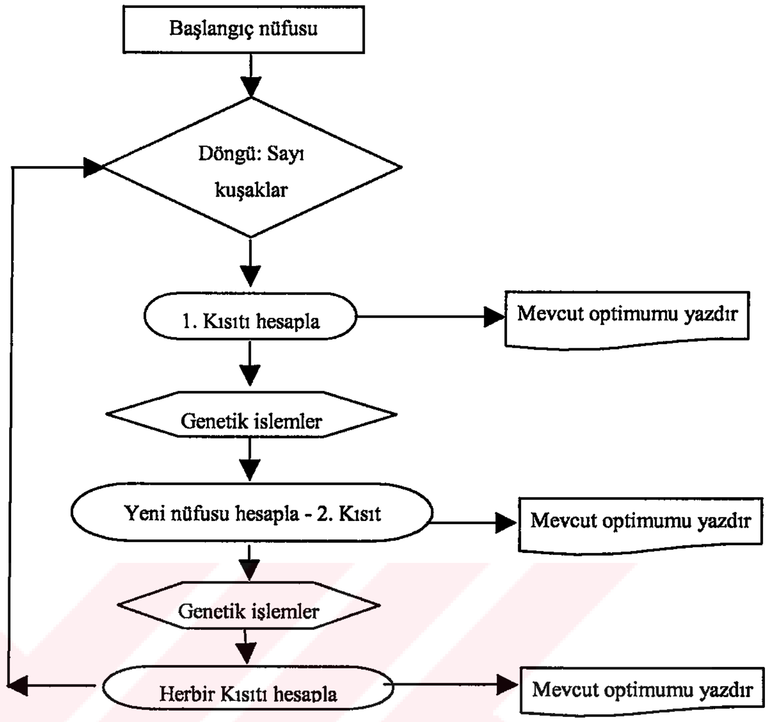
Şekil 4. Dalıp-çıkma ivmesi ile genişletilmiş dalıp-çıkma ve baş-kıç vurma düşey hareketleri

Teknelerin kodlanmasıyla birlikte herbir amaca yönelik performans değerleri hesaplanabilmekte, nesiller yinelenerek tekneler optimize edilebilmektedir. Ancak, çok-amaçlı problem çözümünde performans amaçlarını biraraya getirirken yanlış sonuçlar elde edilebileceğinden, çok-amaçlı optimizasyon metodolojisi izlemeyi gerekmiştir. Bu amaca yönelik, toplam fonksiyonlar ve Pareto öncü baskın olmayan sıralama algoritmaları bulunmasına karşılık, bunları içermeyen bir yöntem geliştirilmiştir. Bu yönteme, Sıralı-Amaçlı Evrimsel Algoritma (SKEA) adı verilmiştir. Birkaç problemde denenmiş ve iyi sonuçlar verdiği görülmüştür. Algoritması, Şekil 5'te görülmektedir.

Söz konusu yöntem, hesaplamalar ile birlikte en sonunda farklı gövde formlarının optimizasyonunda kullanılmıştır. Problemi daha gerçekçi bir hale getirmek üzere çok sayıda dizayn istekleri katılmıştır. Çalışmada İ.T.Ü. balıkçı gemi ailesinin yer aldığı değerlendirmede, Eşitlik 3 yardımıyla ticari hacim olan balık ambar hacmi ve I.M.O. stabilite kurallarının önerdiği GM talebi yer almıştır.

$$V_{FH} = 0.38 L_{FH} (B \times D)^{1.08} \qquad (5)$$

Söz konusu kısa ve öz koşullara ek olarak, modellerden çoğunun öngörülen deplasman değerlerinden uzaklaşması nedeniyle, deplasman da kısıt olarak alınmıştır. Söz konusu koşulların tümü, hata faktörü aracılığıyla performans hesaplamalarının elverişliliğini etkileyen kısıtlar olarak seçilmiştir. Hata faktörleri, balık ambar hacmi, GM (4a) ve bazı durumlarda deplasman hacmindeki (4b) ölçülen ile istenilen değerler arasındaki farktan türetilmiştir.

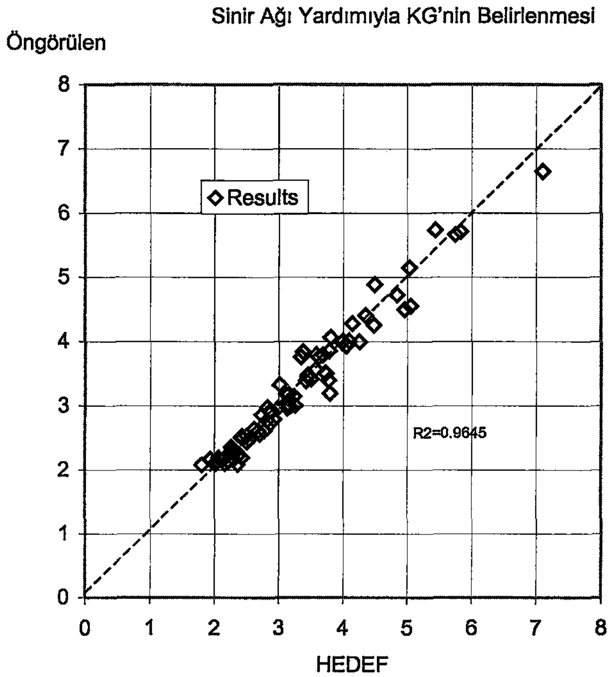


Şekil 5. Sıralı Kısıtlı Evrimsel Algoritmanın (SKEA) yapısı

$$penaltı = 1.0 - \frac{1}{2} * \left(\frac{D_{FHV}}{D_{FHV\,\max}} + \frac{D_{GM}}{D_{GM\,\max}} \right) \tag{6a}$$

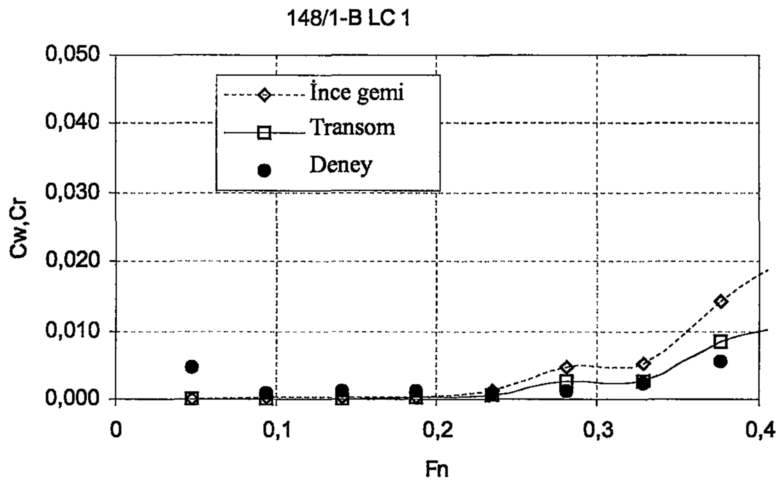
$$penaltı = \frac{D_{\nabla}}{D_{\nabla\max}} \left[1.0 - \frac{1}{2} * \left(\frac{D_{FHV}}{D_{FHV\,\max}} + \frac{D_{GM}}{D_{GM\,\max}} \right) \right] \tag{6b}$$

Optimizasyonda EA'ya ve balık ambar hacmini öngören regresyon denklemlerine ek olarak, Yapay Sinir Ağı (YSA) veri analizi için alternatif bir yöntemdir. Bu tezde, YSA'nın kullanımı, ağırlığa bağımlı, ancak tekne geometrisinden bağımsız olan KG'in tahmini ile sınırlıdır. Bu nedenle, GM'in belirlenmesi ve denizcilik programının bir girdisi olması nedeniyle KG'nin belirlenmesi gerekmiştir. Şekil 6'da YSA yardımıyla KG'nın belirlenmesi görülmektedir.



Şekil 6. Sinir ağı yardımıyla KG'nın belirlenmesi

Direnç performansı, ayna kıçı da kapsayacak biçimde geliştirilmiş ince gemi teorisi yardımıyla ölçülmüş ve İ.T.Ü. balıkçı gemisi serilerinin deney sonuçları ile karşılaştırılmıştır. Şekil 7'de, boş deplasmanda 0.4 Froude sayısına karşı gelen maksimum hıza kadar, yüksüz haldeki İ.T.Ü. 148/1B için verilenle iyi biçimde uyuşan sonuçlar görülmektedir.

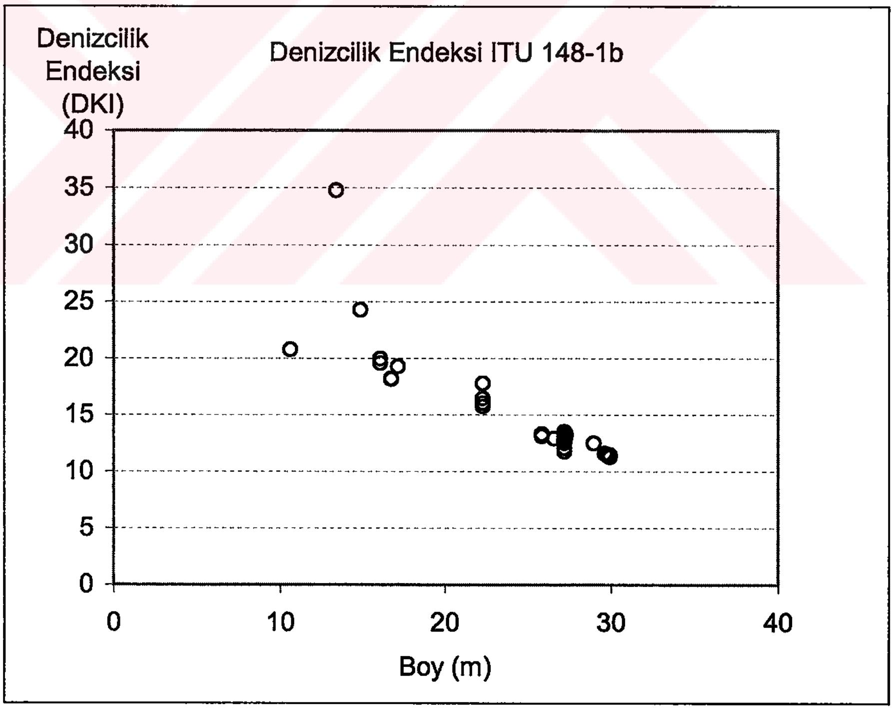


Şekil 7. İ.T.Ü. 148/1-B balıkçı gemisine ait iyileştirilmiş ince gemi dalga direnci

İnce gemi hesapları, 3 boyutlu model kadar hassas olmasa da, Çizelge 1'de verilen benzer gemilerin sıralanmasında ve ayrılmasında istenileni yerine getirmektedir. Aynı zamanda, belirgin biçimde daha hızlı sonuçlar verebilmektedir. Herbir :Froude sayısı grubunun hesaplarının yapılması dakikalar almakta iken, optimum teknenin genel anlamda aranmasında ince gemi teorisinin kullanımının daha yatkın olduğu kanıtlanmıştır. Ancak, yalnızca direnç optimize edilmek istenmesi durumunda, benzer biçimde 3 boyutlu teori ile de GA kullanılabilirdi.

Denizcilik endeksi, yalnızca düşey hareketleri temsil etmekteyse de, asıl yaptığı sonuçları optimize etmek ve kendiliğinden denizciliği daha iyi teknelere yönelik davranışta bulunmayı sağlamaktır. Suya çarpma (slamming), geminin güverte, köprü ya da gerekli başka bir konumdaki ivmelenmesine için, herhangibir sınırlama ya da kısıtlama olmamasına karşın, denizciliği daha iyi olan teknelerin optimizasyonuna olanak vermektedir. Şekil 8. 'de denizcilik indeksinin boya bağlı değişimi görülmektedir.

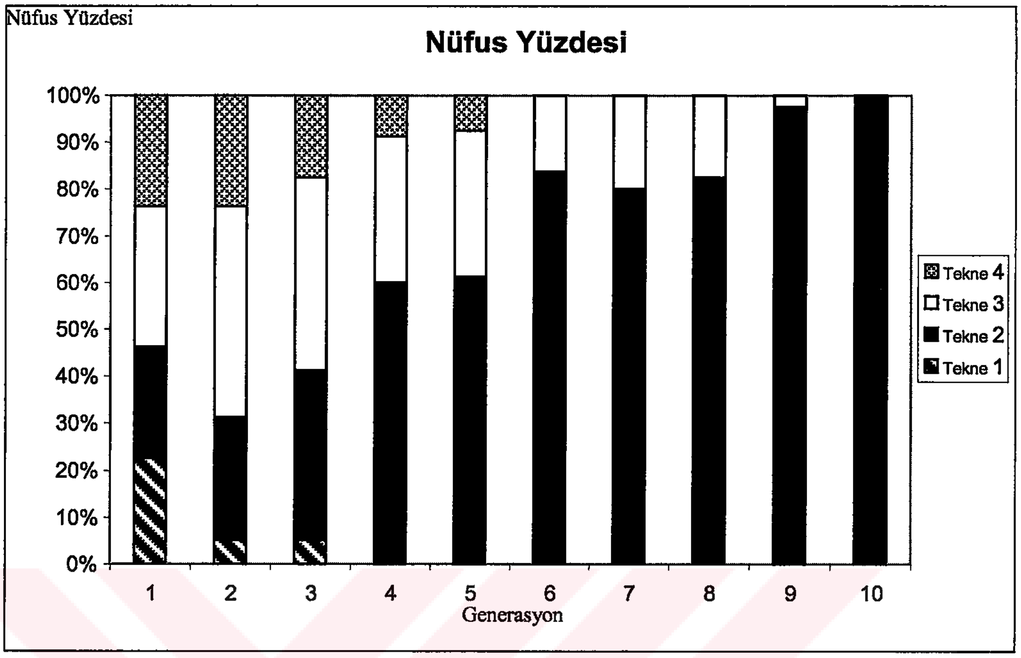
Çok kısıtlı problemin yanısıra, benzer olmayan teknelerin karşılaştırılması konusunda çok-tür kavramından yararlanılmıştır. Çok-türlü algoritmada, genetik işlemlerin sınırlandırılarak yalnızca aynı popülasyondaki aynı türün üyeleri arasında rekabetin gerçekleşmesi sağlanması ile farklı gövdeler karşılaştırılmaktadır. Rekabete imkan tanınması nedeni ile, algoritma son olarak optimizasyon sırasında daha iyi performans veren gövdeleri sıralamaktadır. Şekil 9'da, optimize edilmiş 4 adet İ.T.Ü. balıkçı gemisi görülmekte ve yalnızca 10 kuşak sonrasında Tekne 4'ün kazandığı belirtilmektedir.



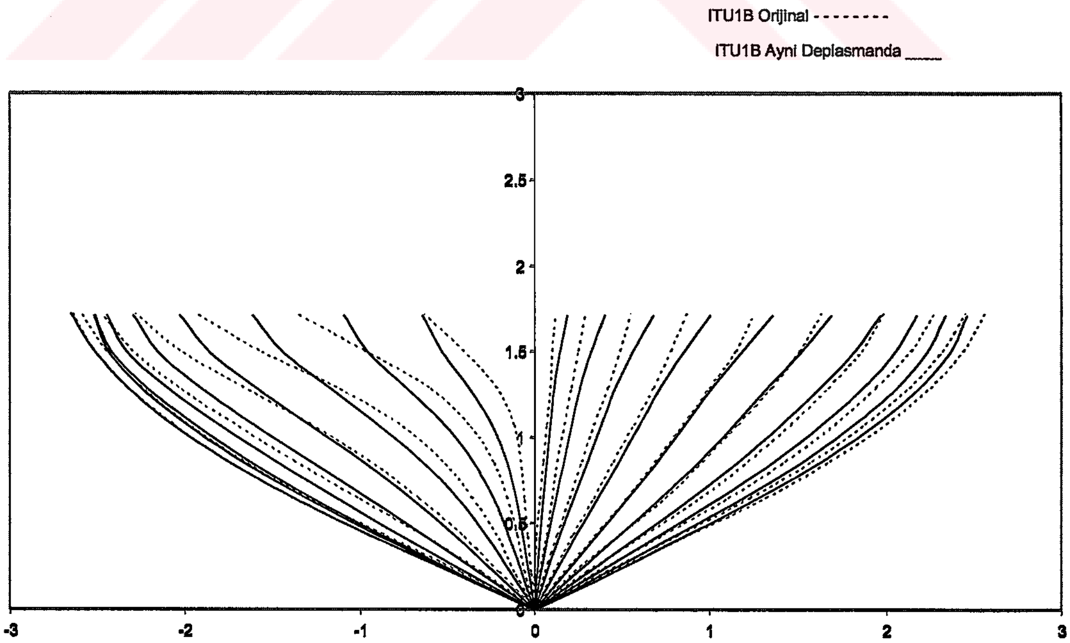
Şekil 8. Düşey denizcilik endeksinin boy ile değişimi

Başlangıçta, İ.T.Ü. balıkçı gemi ailesinin test edilmesi amaçlanmıştır. Gövde formlarının kavram dizayn taleplerine göre optimizasyonundan önce, gövde sabit boyutları ile test edilerek gövde formunun optimize edilip, edilemeyeceği belirlenmiştir. İ.T.Ü. 148/1-B balıkçı gemisi optimize edilerek, asıl ve iyileştirilmiş gövde geometrisi Şekil 10'da verilmiştir.

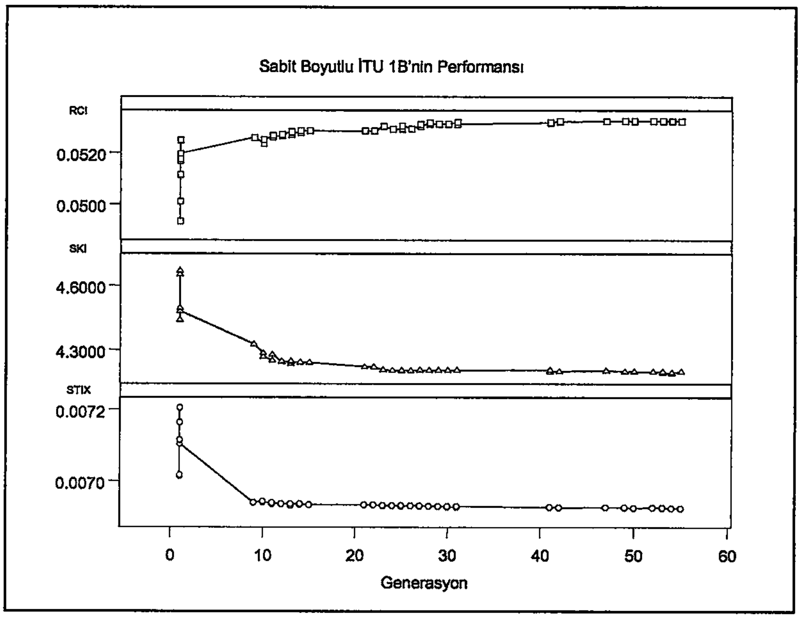
Direnç ve denizcilik, stabiliteden az bir miktar ödün verilmek kaydıyla, iyileştirilmiştir. Optimizasyonun 100 kuşak boyunca işleyişi Şekil 11'de görülmektedir. Dirençte sağlanan iyileştirme Şekil 12'de gösterilmiştir.



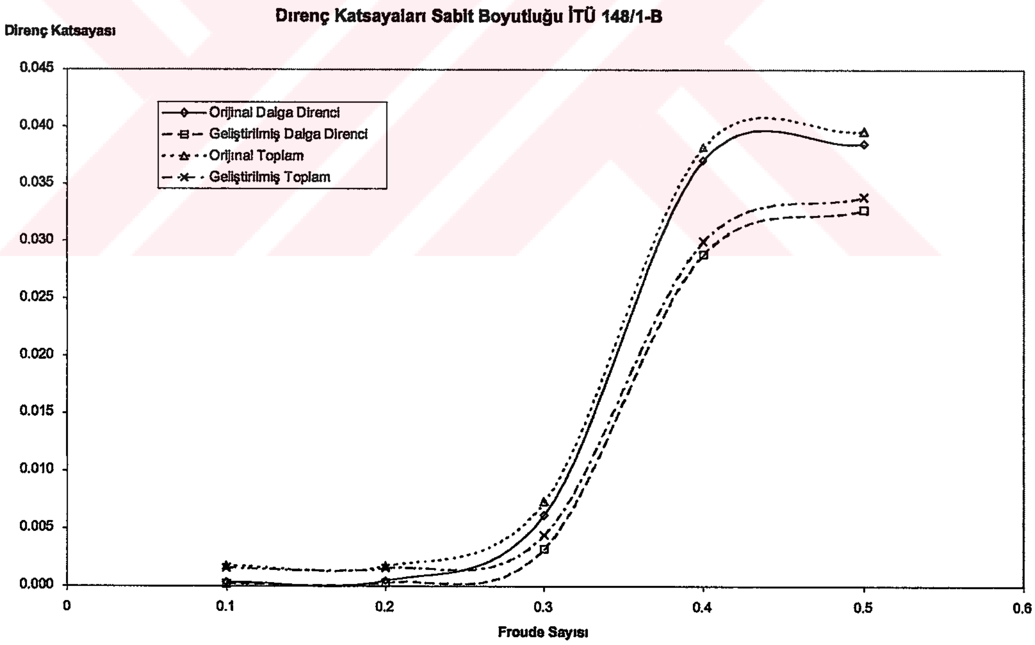
Şekil 9. Herbir gövde için popülasyon oranı



Şekil 10. Sabit boyutlarıyla, asıl ve iyileştirilmiş İ.T.Ü. 148/1-B balıkçı gemisi

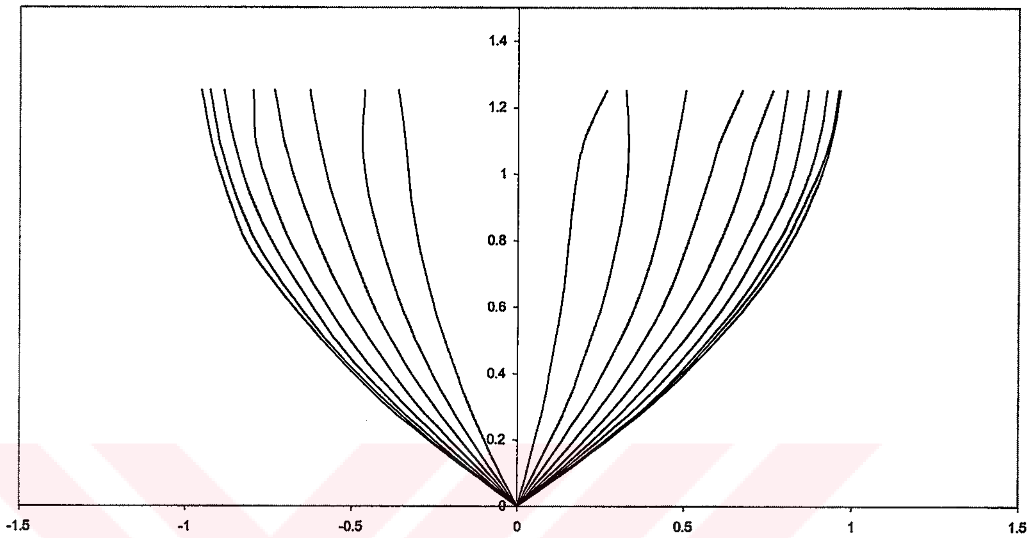


Şekil11. Performans Kısıtlarının İ.T.Ü. 148/1-B için Optimizasyonu.

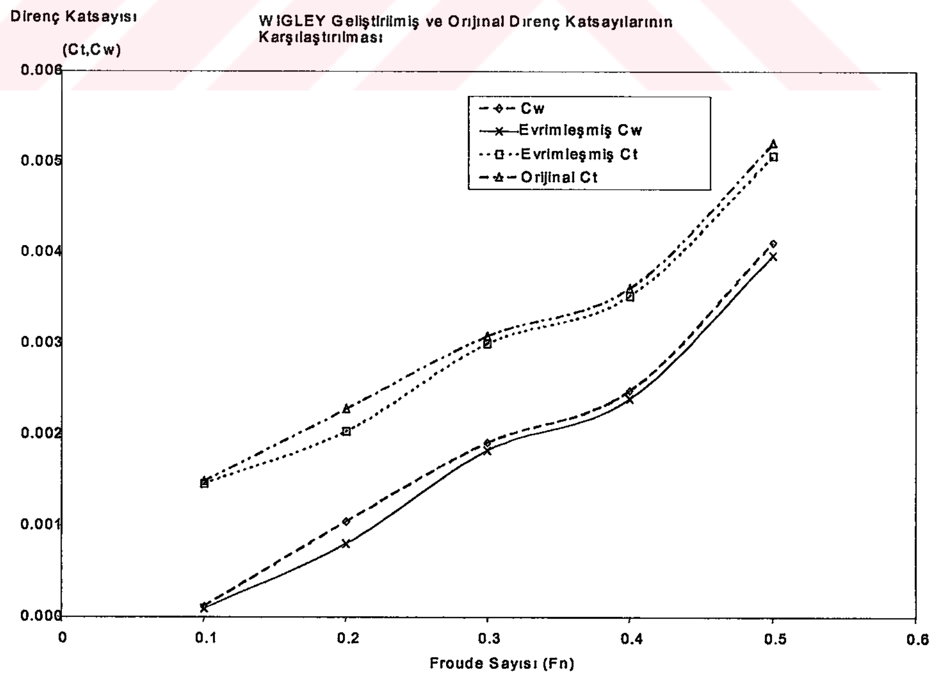


Şekil 12. Dalga direnci ve toplam direnç katsayılarının İ.T.Ü. 148/1-B için Optimizasyonu.

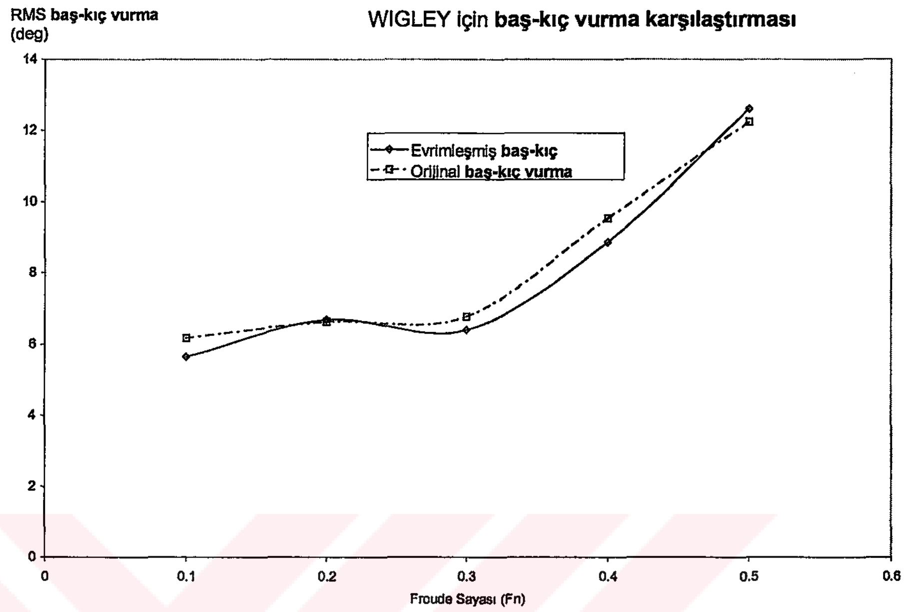
Şekil 13 'te, iyileştirilmiş WIGLEY gövdesi görülmektedir. Şekil 14'te ise, dirençteki azalma miktarı görülmektedir. Şekil 15'te, dalıp çıkma ve baş kıç vurmaya yanıtı görülmektedir.

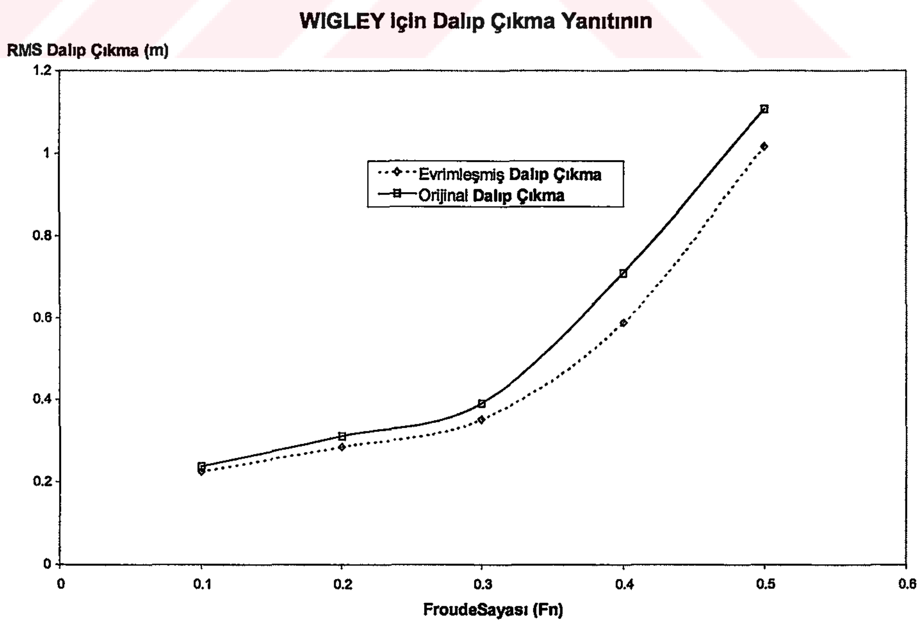


Şekil 13. İyileştirilmiş WIGLEY gövdesi.



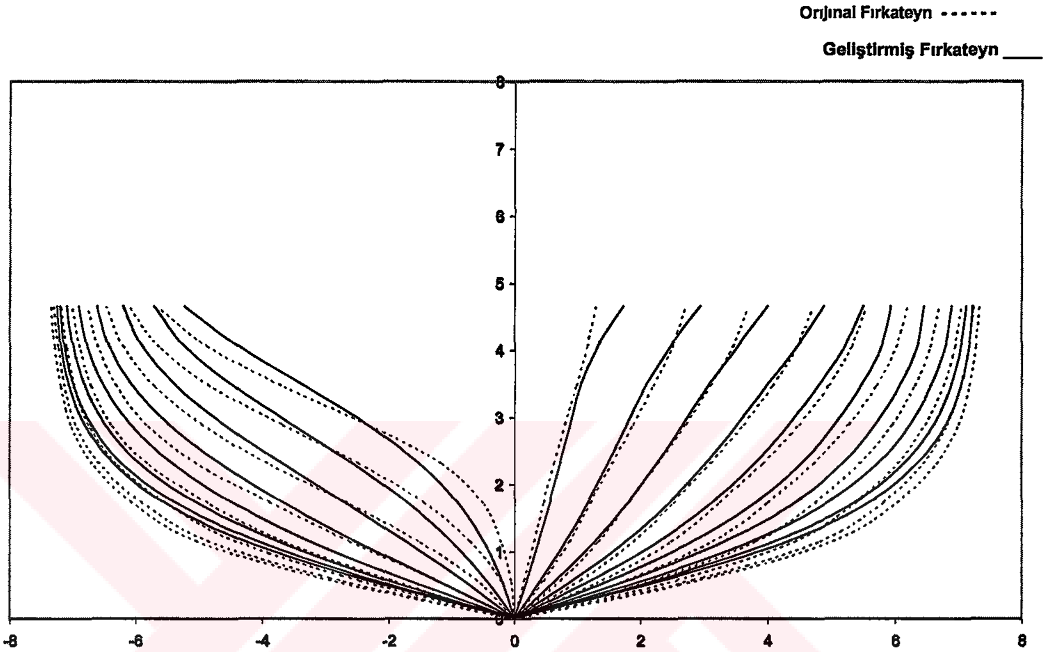
Şekil 14. Direncin optimizasyonu, WIGLEY





Şekil 15. Optimize edilmiş WIGLEY teknesinin dalıp-çıkma ve baş-kıç vurma danranışı

İTÜ 148/1-B ve İTÜ 148/4-B balıkçı gemilerinin yanısıra başka gemilerin de optimizasyonu gerçekleştirilmiştir. Sözü geçen matematiksel tekne formu WIGLEY, bilinen iki uçlu, narin bir gövde formu ile karşılaştırılarak test edilmiştir. Büyük ayna kıçlı hızlı bir sahil güvenlik botu olan ATHENA'nın optimizasyonu gerçekleştirilmiştir. Ayrıca, direnç verileri bilindiğinden ve küçük bir kıç düzeltmesi ile Seri 60'a geçilebildiğinden, Seri 64 gemi gövdeleri seçilmiştir. Son olarak, optimize edilmiş hali ile Şekil 16'da görülen tipik bir fırkateyn test edilmiştir.



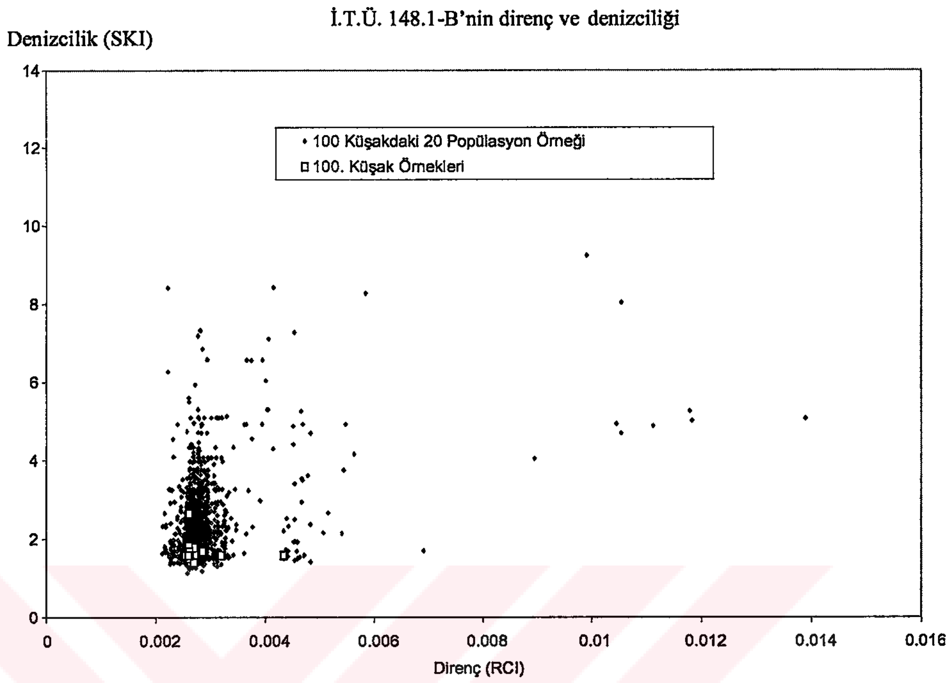
Şekil 16. Aslı ve iyileştirilmiş fırkateyn gövdesi

Ulaşılacak hedefler şu biçimde sıralanmaktadır: İlk olarak, tekne formları ele alınmalı. Çoğunlukla, kavram dizayn parametrik çalışmaları, tekne formu parametrelerini içeren bir veritabanı kullanılarak gerçekleştirilmektedir. Bu parametreler, global parametreleri elde etmeye yararken, daha kapsamlı analiz yapmaya imkan vermez. Bu hedefe gerçek tekne formları modellenerek ulaşılmıştır.

Asıl amaç, gövde formunun optimizasyonu olsa da, optimum geeneel karakteristiklerin ana parametreler cinsinden belirlenebilmesi için, program global parametreleri de içermelidir. Her iki İTÜ 148/1-B ve İTÜ 148/4-B teknesinin de boyları 18 m.'den 30 m.'ye değiştirilmiş ve Gubisic'in kavram tasarımını yaptığı 23 metrelik balıkçı gemisi ile karşılaştırılmıştır. Boyunun optimizasyonu sırasında program oldukça hızlı çalışmaktadır. Ancak, boya yönelik ilave dizayn koşulları ya da kısıtları konulmaması durumunda dizayn ortamının üst sınırlarına yönelmektedir. Stabilite koşulları ile genişlik de maksimuma yönelmektedir. Ancak, bazen minimum direnç ile sınırlanmaktadır. Çoğunlukla ise, su-çekiminin sınırlanması ve dalga direncinin optimize edilerek, ardından genişliğin optimize edilmesiyle, minimum direnç sağlanır. Su-çekimi, minimum su-çekimine yönelmekte ve deplasman ise, istenilen şartları sağlamaya yönelmektedir.

Hidrodinamik analiz tekne gövdesinin direnç ve denizciliğe göre yerel optimizasyonu sırasında gerçekleştirilmelidir. Stabilite ise, gövdenin hidroststik analiz ve sinir ağı ile KG analizi yardımıyla maksimize edilmelidir. Herbir durum için bu kısıtlar sağlanmalıdır.

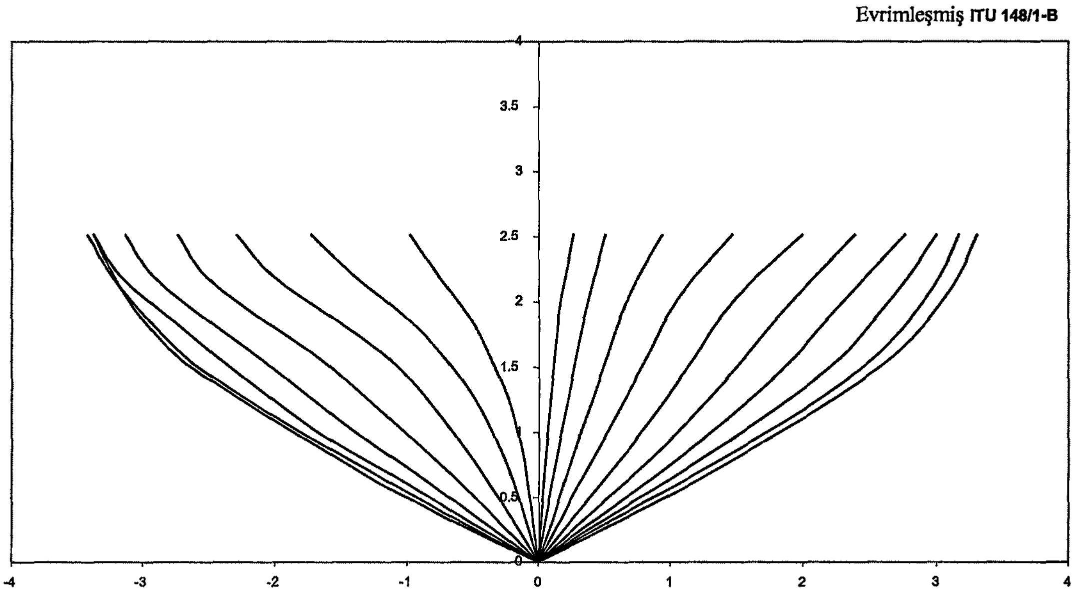
Çok-amaçlı dizayn metodolojisi kapsamında, optimizasyona diğer amaçlar da katılmalıdır. Şekil 16'da görüldüğü üzere, direnç ve denizciliğin her ikisi de minimize edilip stabilite değiştirilirken, I.M.O. kriterini aşan maksimum stabiliteye yakın seçilemektedir.



Şekil 17. İ.T.Ü. 148/1-B'nin direnç ve denizciliğinin optimizasyonu

Sonuç olarak, gerçek bir tekne formu elde edilmelidir. Şekil 18'de görülen İTÜ 148/1-B balıkçı gemisi dizayn planının son hali 30 metre, minimum direnç ve gemi hareketi, ancak optimale yakın (ikinci planda) stabiliteye sahiptir. İTÜ 148/4-B daha yüksek dirence ve gemi hareketine, ancak daha iyi stabiliteye sahiptir. Ve daha dolgun bir tekne formuna sahip alternatiftir. Tekne formunun ana büyüklükleri Çizelge 1'de verilmiştir.

Bu tezin, bir entegre dizayn aracının başlangıç aşaması olarak verildiği göz önünde bulundurulmalıdır. Buna karşın, tezde kısıt olarak alınan hedeflerin tümü sağlanmıştır. Hesap aşamasında, Pratik bir araç geliştirilmiştir: Çok kısıtlı dizayn problemlerinin çözümü için yeni bir yöntem geliştirilmiştir.Bunun yanısıra, hem global ana parametre bazında, hem de yerel tekne formu optimizasyonu bazında gemi inşatının 3 temel prensibi kullanılmıştır. Daha derin bir araştırma konusu, gelişmiş 3 boyutlu direnç analizi ve daha özel gövdeler için daha fazla başlangıç konsepti dizayn koşulunu içeren analiz yöntemlerinin geliştirilmesi olabilir.



Şekil 18. Evrimleşmiş İ.T.Ü. 148/1-B balıkçı gemisi. (dizayn koşullarını sağlayan optimal stabiliteye yakın maksimum direnç ve gemi hareketine sahip)

Çizelge 1. Evrimleşmiş İ.T.Ü. 148/1-B balıkçı gemisi dizayn parametreleri

Karakteristik	Optimal Sonuç	Karakteristik	Optimal Sonuç
LOA	29.24 m	KG (varış)	2.411 m
LPP	29.24 m	GM (varış)	1.218 m
LWL	29.24m	FHV	121.9 m^3
B	7.110m	C_p	0.503
T	2.510 m	C_b	0.306
Hacim	161.4 m^3	C_{wp}	0.598
V_{max}	13.55 kn	WS	202.706 m^2
AW	120.573 m^2	AM	10.421 m^2
KB	1.653 m	C_M	0.584
BMT	1.976 m	Xcb	0.669 m
BML	26.999 m	Xcf	0.875 m

1. INTRODUCTION TO HULL FORM OPTIMIZATION

1.1 Hull Form Optimization

Hull form optimization is a process that involves changing a given ship or boat hull in order to improve performance. The hull is a fundamental component of the vessel and this structure has the most significant influence on the performance and success of the design. The concept or initial design stage impacts the design such that first few weeks of designing the hull is responsible for the majority of the final cost of the vessel. Therefore optimization of the hull form can be of considerable benefit.

Usually hull form optimization consists of changing offsets of an already suitable hull in order to minimize hydrodynamic resistance. Other optimization problems for minimizing ship motion or maximizing ship stability can also be conducted. At the preliminary design stage the parameters of the vessel are the primary focus. These are more often determined through database analysis of known designs. This represents a search to find the principal parameters corresponding to the design requirements or owners' requirements.

For an optimization problem the purpose is to maximize or minimize an objective function, while satisfying constraints representing the design requirements. Using a function representing the cost function, which may not be the cost of the vessel, but instead is an objective function to be minimized, an optimal design can be obtained.

The cost function and the model are normally based on a functional representation of the ship. These are usually in the form of regression-based equations that describe the displacement, centre of gravity, form parameters, and other factors that describe the hull. They may also contain regression-based equations to evaluate the design. These may include regression equations for seakeeping, resistance, stability, and design requirements such as the hold volume or cargo deadweight.

Instead of using regression analysis, the focus in this thesis is to use hull forms directly for the computation of the performance factors and for evaluation of the design requirements. Further it is proposed that the principal parameters as well as the optimal hull form should be determined simultaneously. That is to say, the optimal hull form should also include the optimal length, beam, draft and displacement in order to create and optimal design. Regression analysis can still be utilized if convenient, as shown in Chapter 5 for the design requirements, but the focus is on the development of the hull form.

In order to conduct both optimization of the hull for minimization of ship resistance, which is a key factor for fuel cost, and to determine the preliminary design parameters to satisfy the design constraints given by the ship owner or client, it is necessary to develop a methodology that can conduct both facets of the design process simultaneously. The hull form provides both the performance characteristics of the hull and principal characteristics for evaluation of the preliminary design features of the vessel. Therefore the hull can be used directly during the concept design stage.

Once an appropriate optimization methodology is developed the performance characteristics of the vessel can be extended to include other cost objectives. For example seakeeping and stability characteristics as an evaluation of the operational performance of the vessel are included in the optimization. Then the optimization can be used for use increasingly advanced analysis that normally is performed only later in the design process. By including advanced analysis earlier during the concept and initial design process, the potential benefits of obtaining a near-optimal design earlier in the ship design process can be realized.

Evolutionary Algorithms (EA) and Artificial Neural Networks (ANN or NN) offer alternative methods for conducting optimization and for data analysis. The application of Genetic Algorithms (GA) in ship design is not without precedent. Lee and Roh (2000) developed a hybrid optimization method that uses a genetic algorithm. Yasukawa (2000) and Dejhalla et al (2001) have both conducted a resistance optimization analysis of a hull form using GA methods. These studies focus on existing hulls that are modified by varying the hull offsets slightly but keeping the principal characteristics of the hull the same.

Determining principal ship characteristics like length, beam, draft, volume and displacement utilizing GA methods means that parent hull forms would be significantly changed in a parametric fashion. Concept and initial design methods as presented by Lyon and Mistree (1986) describe three ship design methods that modify principal parameters. The first is a manual iterative method based on plots used to select principal dimensions. The second is a method of enumeration that increases the vessel length stepwise until a feasible design is found. All parameters are expressed as a function of length. The third is an optimization problem using linear programming.

The latter type of problem is formulated as a compromise Decision Support Problem (DSP), where a preliminary design is desired that satisfies design requirements while optimizing a set of objectives. Lyon and Mistree (1990) formulate the problem by using owner's requirements for cargo deadweight, speed and range to determine length, beam, draft, depth and form coefficients of the ship. Cargo deadweight is set as a goal in addition to metacentric height, a minimum displacement, and a shaft horsepower goal. These goals are allowed to deviate, while the objective is to minimize the deviations. Data on similar ships is required, and various constraints on block coefficient, period of heave and pitch, and other parameters need to be satisfied during the optimization.

In this method as in all classical optimization methods, the optimization begins at a position and proceeds to search in a direction according to the change in the objective. These methods are based on the gradient or rate of change of the objective from one position to the next. The techniques are classified as hill climbing techniques, since the objective landscape is represented as a series or a single hill in which the global optimum is the top of the hill for maximization or at the bottom of a valley for minimization. Difficulties occur when there are numerous local optimums such that the start position becomes important in order to find the global optimum.

An alternative method is to apply genetic or evolutionary algorithms for optimization. Evolutionary algorithms are stochastic in nature rather than deterministic as in classical optimization methods. The application of GA methods is based on the success of the survivors from a population of solutions or candidates. GA methods can be found in a wide variety of fields where the search for a particular solution may be difficult due to the presence of many local optimums or where the objective function is difficult to represent in mathematical terms for use in a traditional optimization problem.

For the ship design problem it is apparent that having a population of designs in which successful designs are used to derive the next generation has great appeal. The problem of how to structure the ship design problem in a manner conducive towards the application of GA techniques is considered in this thesis from the perspective of the hull. The goal is to obtain both optimal principal parameters of the ship such as length, beam, draft and displacement as well as to determine the optimal hull form based on offsets. Therefore it is necessary to develop a new methodology that is able to conduct both optimizations simultaneously.

Most of the thesis is devoted to the use of genetic and evolutionary algorithms, along with the evaluation of the objective function based on ship resistance, seakeeping and stability. In order to extend the ship design problem further the use of neural networks is incorporated for the evaluation of KG. Neural networks are used in many fields and provide an alternative approach to using regression.

1.2 Evolutionary Algorithms

Evolutionary algorithms or evolutionary computation methods are based on the principal of evolution, based on the survival of the fittest as described by Dasgupta and Michalewicz (2000). Optimization using genetic algorithms has reached significant maturity in the past decade both in industrial engineering and in other disciplines. A term describing this and other techniques such as evolution strategies, evolutionary programming and genetic programming is known as evolutionary computation. Gen and Cheng (2000) state that genetic algorithms are stochastic search and optimization techniques that have the following five basic components:

- A genetic representation of solutions to the problem;
- A way to create an initial population of solutions;
- An evaluation function rating solutions in terms of their fitness;
- Genetic operators that alter genetic composition of offspring during reproduction;
- Values for parameters of genetic algorithms.

The general structure for a genetic algorithm is shown in Figure 1.1. For concept and initial ship design problems genetic algorithms are suitable to use when the problem structure contains objective functions or constraints not easily modeled by classical optimization techniques, or when the search space becomes intractable. In this thesis the steps in the genetic algorithm, namely the parameterization of the problem, the evaluation of the candidate hulls and the recombination functions for generating a new population, are examined in the context of the hull form optimization problem.

As mentioned by Dasgupta and Michalewicz in their overview of EAs, there are several variants of evolutionary algorithms or paradigms such as genetic algorithms, evolution strategies, evolutionary programming and genetic programming as well as others. The general structure shown in Figure 1.1 is similar in all cases but differences in the application means the data structures and the methods used for operations of selection and recombination are different. Further in one technique there are many different methods. The example highlighted by them discussed the selection process that can be conducted through proportional selection where the probability of selection is proportional to the individual's fitness. The selection can also be made according to ranking of the individuals, or by tournament selection where individuals compete for the next generation. As pointed out in their overview there are differences within each of these methods as well.

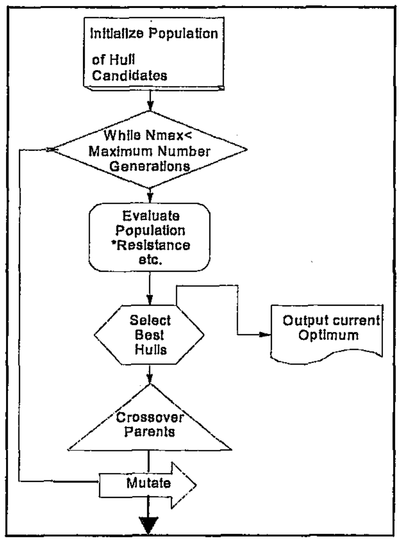


Figure 1.1 Simple Genetic Algorithm General Structure

Genetic algorithms trace their roots to the use of computers by biologists for simulating biological systems but were popularized by John Holland (1975) at the University of Michigan. A GA performs a search by maintaining a population of potential solutions and using recombination operators to share information between solutions. The population is usually modeled as a binary string of parameters for the solution. In addition a mutation operator alters a string randomly by flipping a bit in the string from 1 to 0 or vice versa to give greater variability in the population.

The use of GA for hull form optimization means that binary strings must model the hull form. Another method uses real value codes instead of binary strings, as some fidelity in values may be lost when using binary strings. The parameters for the hull form are discussed in Chapter 3 however to give an example let us assume the model consists solely of the length, beam and draft of the ship or boat. Given some constraints on how long or short the ship can be, how narrow or wide, and how deep or shallow, a binary representation of each number can be put into a string representing the chromosome describing the hull principal parameters.

For example if the length is 15 meters for a fishing vessel exploration somewhere between 10 and 30 meters, and the beam is 3 meters while the draft is 1.5 meters, then the numbers to be represented are [150, 30,15]. These are formed by a string where;

$V = (150,30,15)$
$= (2^7 + 2^4 + 2^2 + 2^1, 2^4 + 2^3 + 2^2 + 2^1, 2^3 + 2^2 + 2^1 + 2^0)$
$= (10010110, 11110, 1111)$
='100101101111101111'

This is typically how chromosomes are used to model a sequence of numbers in binary format. The operation to re-combine chromosomes is achieved by choosing a random point in the binary string and swapping each end of the chromosome for the next generation. If **V1** for example is a simple chromosome **V1**=1100 and **V2** =0011, randomly choosing the midpoint to cross chromosomes gives the new numbers **V1'**=1111, and **V2'**=0000. This crossover operation represents a single or 1-point crossover, but multi-point and other methods can be used.

GA uses strings by forming schemata. If subsections of the string are thought of as schema, and these are considered as shorter low-order building blocks for the string, then the more optimum solutions tend to have similar schemata. Consider the chromosome **V1**=1100 as an example. If the schema of having '11' in the first half of the chromosome leads to chromosomes having a higher fitness, then the following chromosomes with the schemata, **V1**=1100, **V2**=1101, **V3**=1110 and **V4**=1111 would have higher fitness values than those with zero in the first two bit positions.

The building block hypothesis states that genetic algorithm searches the space for better solutions using the juxtaposition of the lower order higher performance schemata. The schemata theorem states that short low-order, above average schemata receive exponentially increasing trials in subsequent generations of a genetic algorithm. The schemata theorem and the building block hypothesis are the underlying mechanisms for how the GA is able to search the space in a way in which combinatorial explosion is used to advantage.

In addition to modeling the problem and developing the method for the genetic operators, it is necessary to treat the problem of constraints. Constrained optimization using evolutionary algorithms has developed in a number of methods but the most common methodology is still probably the use of penalty functions. The evaluation of the candidate or individual would add or multiply a penalty to the objective function depending on the constraints. This aspect is an important consideration as both alternate methods to penalty functions can be used or different types of penalty functions can be devised. In any event this aspect must be considered in the hull form optimization problem.

1.3 Neural Networks

Neural networks or artificial neural networks are another type of artificial intelligence technique. The basic model is to use neurons along the lines of a biological neuron, in a computational parallel network that results in the ability of the network to model nonlinear systems. Given a set of N inputs, represented by an input vector $\mathbf{X}=[x_1,x_2,\ldots x_N]$, the network computes a set of P outputs $\mathbf{Z}=[z_1,z_2,\ldots z_P]$. Each neuron is an activation function that passes on a signal if the sum of the weights and inputs to each neuron reach the activation level. This is the feed-forward process.

A four-layered neural network for predicting the centre of gravity of a ship is represented in Figure 1.2. Besides the input layer and the output layer, there are two hidden layers. Often neural network applications only use one hidden layer but two hidden layers offer advantages. Connecting each neuron there are associated weights and this is the subject of the training algorithm for the neural network. By comparing the error in the outputs to known values in a training sample the error is propagated backwards through the network to change the weights. This represents the back-propagation process in training the network.

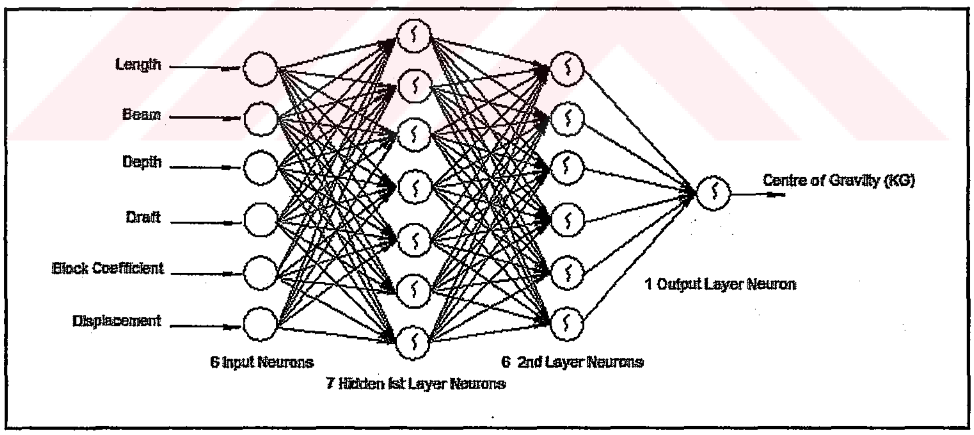


Figure 1.2 Neural Network Structure

The feed-forward/back-propagation neural network is now a classical method of using neural networks and other types exist. Particularly where the data has a considerable amount of scatter there maybe better methods of grouping data for use during the training phase. For the purpose of the hull form optimization the use of a classical method is adequate.

The application of neural networks can take at least two different forms. The first is to use the neural network to predict some outputs for a given series of inputs where the inputs and outputs are derived from a database. In this sense the neural network performs the same function as regression analysis, and prediction of the output is subject to how well the data is represented in the database, and how close a fit the neural network can achieve for the given data. Another aspect of the neural network is the ability to generalize, such that the test samples though different from the training samples are still predicted with reasonable accuracy. The trade-off between close fitness and generalization requires consideration.

As the example shows for database type of analysis, a prediction is made of the centre of gravity of a vessel. The centre of gravity is not just a function of the shape of the hull form as it is a function of the weights in the ship, and therefore cannot be calculated solely from hull form parameters. From a database of similar hull forms in which the centre of gravity is known the neural network can be trained to give an estimate of the centre of gravity for any test sample. The centre of gravity not only impacts the stability characteristic of the vessel but is also an important parameter in the seakeeping model.

Neural networks can also be used as a dynamic modeling tool as the networks can predict non-linear system behavior from a training set of data representing a dynamic system. Although the intent is to model seakeeping directly using the hull form, seakeeping data can also be used as a training set to train a neural network as a dynamic model of a hull in a seaway. The input to the network would represent the hull form parameters rather than the hull form directly. The output would be the predicted responses of heave, pitch, roll and accelerations as desirable for the seakeeping model.

Like evolutionary algorithms, the use of neural networks can yield better results for problems difficult to model or solve using classical techniques. In application both neural networks and evolutionary algorithms are not a panacea for problem solving. Haykin (1999) states that the lack of clear rules in application, the monitoring difficulty of the internal operation of the network, and difficulties training as well as the future performance ability to generalize, are among some of the problems in applying neural networks. These issues need to be considered in the actual application of the neural network in the hull form optimization program.

1.4 Thesis Approach to Hull Form Optimization

The approach to the thesis is first to set the overall objective that can be stated as follows;

***Thesis Objective;* To investigate the use of the evolutionary algorithms for hull form optimization.**

In order to facilitate this objective some key issues need to be resolved. Based on the foregoing, "genetic algorithms have proved to be a versatile and effective approach for solving optimization problems"- (Gen and Cheng, 1996). Therefore this approach is utilized for the search for an optimal hull. To use genetic algorithms, some steps need to be performed. The hull must be encoded into a solution space. To conduct the performance evaluation of each hull, some basic naval architecture properties need to be analyzed, namely, resistance, stability, and seakeeping. Each of these requires a program to provide the evaluations, and in addition must be incorporated into the optimization. Further, the design requirements and other design elements must be included. For these, regression and alternatively, the use of neural networks are utilized for the evaluation of these attributes.

The ability to generate a greater number of evaluations makes the exploration of the search space more likely to find a near-global optimal solution. A study by Gammon and Alkan (2001) using thin ship theory was conducted on fishing boat hulls and it was determined that this method, when incorporating a transom stern theory into the model, was sufficiently accurate to rank the individual candidate vessels. In addition a recent study by Percival et al (2002) has shown that a simpler CFD tool using zeroth order slender ship approximation for wave drag combined with the classical ITTC formulation for frictional drag estimation was able to rank a series of hull forms roughly in accordance with experimental measurements.

Hull form optimization generally concentrates on taking an already suitable form and optimizing it further. This optimization can be considered a local optimization of the hull surface rather than a global optimization of the hull general. On the other hand, most concept design methodologies focus on general parameters and usually rely on a database with some function approximations to determine the most applicable attributes of length beam, draft, and displacement.

1.5 Thesis Outline

The following represents the thesis outline. Chapter 1 presented an introduction of hull form optimization and AI methods to be examined. Chapter 2 conducts the literature survey of the topics under investigation. Hull form optimization studies are first examined in the general context of the ship design problem. Secondly some specific studies with regard to the use of evolutionary algorithms in hull form optimization are reviewed. Lastly neural network applications in the ship design area are examined.

Chapter 3 develops the representation of the hull form. The hull model is examined in the context of using evolutionary algorithms. A method to model the hull offsets using a matrix chromosome is introduced along with the genetic operators necessary for their manipulation. The combined single chromosome for principal hull parameters and the matrix chromosome for the hull offsets are described for the complete hull model. A B-spline surface is developed along with a method of fairing offsets.

Chapter 4 examines the evaluation of the design requirements. Design requirements are introduced into the model for a fishing boat. The design requirement looks at application from the context of a fish hold volume and a GM requirement, and how these requirements are translated into a constraint for the model. Displacement is also added as a requirement for cases where hull have fixed principal dimensions.

Chapter 5 looks at ship stability. Ship stability is examined for the specific application of a fishing vessel and in the context of the optimization model. A regression equation is examined for stability. A neural network model of the centre of gravity of the vessel is introduced. The development of the stability index for measuring the overall stability performance is introduced.

Chapter 6 investigates the evaluation of the resistance. The resistance model using thin-ship theory is introduced. Some studies are presented that examine the utility of thin ship theory in the context of a specific application of a fishing boat. A resistance index for comparing different candidates is developed.

Following resistance the seakeeping evaluation of the hull is developed in Chapter 7. A direct model using strip theory is proposed. The development of the seakeeping index for evaluation of the seakeeping performance is described.

Chapter 8 examines the problem of multiple objective optimizations. Multi-objective optimization can be utilized instead of a single objective with constraints. However the issue of the relative comparisons using weighting factors between objectives is addressed, and a methodology is introduced to conduct multi-objective optimization without weighting factors. It then applies the single and multi-objective formulations and compares the results from using a weighted Pareto optimal multi-objective methodology with an alternative Sequential Objective Evolutionary Algorithm (SOEA) using a number of test problems.

Chapter 9 develops the fishing boat application further and addresses the issues of multiple hull forms. A multi-species GA is developed to conduct simultaneous evaluation of alternate candidate hulls.

Chapter 10 applies the resulting methodology to a series of fishing boat hulls as well as a number of other example hull forms and demonstrates the capability of the system to optimize both the principal parameters of the hull while satisfying design requirements. In addition it shows how individual hull forms are optimized according to the different performance objectives, such that a parametric comparison of the resulting optimized hull form and the starting hull form shows more favorable resistance and seakeeping. Stability for fixed hull forms remains nearly the same.

Chapter 11 presents conclusions regarding the application of evolutionary algorithms for the hull form optimization problem. Further research areas and applications are proposed.

2. LITERATURE REVIEW

2.1 Hull Form Optimization using Genetic Algorithms

This section examines those studies that have a direct relevance to the use of genetic or evolutionary algorithms in the application of hull form optimization. Other studies on either genetic algorithms or on the subject of hull form optimization are referred to in chapters on the development of the optimization methodology and the evaluation of the hull's performance.

2.1.1 Resistance Optimization Based on Principal Parameters (Day and Doctors)

The first study reviewed that looks at hull forms and the use of genetic algorithms is by Day and Doctors (1997) in which the principal objective is to minimize resistance. The resistance evaluation uses thin-ship theory for the wave resistance calculations and combines it with the ITTC formulation for the wetted surface skin friction. The study varies a wide range of hull displacements and examines the optimization trends that occur on the basis of variation of the principal parameters

The study is interesting for its use of thin-ship theory for the hull optimization, and from the manner in which the hull was modeled. In fact a representation of the hull is used rather than an actual hull form in which key parameters for the hull shape are used in the optimization. That is a bearding line, bow, curve, and waterline curve are modeled as functional curves and as these functions are varied, the representation of a hull changes accordingly.

The study can be considered an investigation into principal parameters and the associated predictions for resistance rather than an actual hull form-modeling tool. It gives some firm foundations for the use of genetic algorithms. In their model, the genetic algorithm was combined with a hill-climbing algorithm in order to speed up the search in areas of local optimums. Hybrid genetic algorithms such as this may be used in situations when the simple genetic algorithm does not perform particularly well (Gen and Cheng, 1997).

2.1.2 Hull Form Optimization of Resistance using Dawson Panel Method

Yasukawa (2000) conducted a hull form optimization study around the same time as Dejhalla et al (2001 and 2002) where the objective was to minimize wave resistance. In both studies the Dawson panel method for the resistance calculation is used. The use of a three-dimensional panel methodology provides a more accurate prediction of the wave resistance.

The hull is modeled by panels in which the offsets given by the vertices of the panels are modeled such that variation of the offsets can be undertaken. In both studies the variation of the offsets is allowed by ± 10 percent of the original offset values. This is probably necessary in order to preserve some hull fairness as well as to limit the variation of the offsets to a manageable amount.

The limitation in the method of using a 3-dimensional panel method for calculating the resistance is in the computational time required for the calculation. Yasukawa reports that the calculation took approximately 48 hours on a DEC alpha workstation. Dejhalla et al report a similar time frame albeit on a Pentium II processor. More powerful desktop and laptop computers are now standard. In both studies the number of generations that were conducted was on the order of 100 that are minimal in terms of optimization using genetic algorithms.

In addition to the limitations imposed by the restriction on the hull offsets, the hull form optimization uses an already suitable hull. Optimization with regard to principal parameters is not considered. The purpose of these methodologies is to improve resistance of an already suitable hull form. For concept or initial ship design the process of hull form optimization should consider the principal parameters and a variety of hull forms in addition to allowing a larger variation of the hull offsets. In order to achieve these goals a new methodology is required that can provide a reasonable prediction of the resistance in addition to providing an optimization methodology of the hull form. Chapter 3 describes this methodology for a combined parameterization of the hull form that allows variation of the principal parameters as well as the hull offsets.

2.1.3 Hull Form Generation using Artificial Intelligence Techniques

Islam et al (2001) used artificial intelligence techniques including genetic algorithms and neural networks in a study to develop an automatic hull generation tool. The study used a neural network of a somewhat different form to analyze the characteristics of a group of ships. The inputs to the neural network are length, breadth, draft, and the type of ship that is necessary to determine which data set will be utilized. The outputs are the expected speed and displacement, as well as the breadth and draft. In addition, the hidden layer in the model is used to calculate the water-plane area, sectional area and mid-ship area.

This use of a neural network represents the first type of application for a database analysis of characteristics. The speed and displacement are used as design requirements for the hull form. The hull offsets are modeled by using a b-spline net and the vertices of the net are the parameters to be varied. The optimization using a genetic algorithm begins with a hull population of random or near values and evaluates the hull to how closely the hull characteristics match a target set of values for 6 hull form coefficients. The objective function is a summation of the average square error between the desired coefficients P_{dt} and the calculated values P_{ct} as;

$$Fitness(individual) = \frac{1}{6}\sum(P_{ct} - P_{dt})^2; for\ C_b, C_m, C_p, C_{wp}, C_{vp}, C_v \qquad (2.1)$$

The procedure then follows by using the neural network to determine the breadth and draft that gives an estimate for the desired speed and displacement. Then the GA is used to generate a hull that satisfies the target hull form coefficients using the length, and the breadth and draft generated from the neural network.

The performance of the hull relies on the database analysis provided by the neural network. Secondly the target hull form coefficients are required. As the target set of values or the desired coefficients are not necessarily know in advance this represents a limitation of using this methodology to perform hull form optimization. However the study does show that the hull offsets can be manipulated directly, and shows how a neural network approach can be used for database analysis. In addition, it mentions the use of a matrix or rather sub-matrices for the manipulation of the b-spline net. The use of a matrix for the hull offsets is considered in the next chapter.

2.1.4 Towards Optimal Design of Ship Hull Shapes

This is a three year European R&D project known as FANTASTIC consisting of a consortium of fourteen European partners and presented at the International Marine Design Conference by Maisonneuve et al. (2003). The recognition that information technologies and progress of numerical tools can be used for significant improvements in ship design prompted the project with the goal of improving the functional design of ship hull shapes. Key issues of parametric shape modeling, CFD tools and their interfaces along with the appropriate design space exploration and optimization techniques were investigated.

The principal objective is to be able to apply parametric shape modeling with state of the art CFD analysis tools to predict ship hull performance. The focus on the hydrodynamic prediction is on steady performance, using potential flow panels although further development may try to incorporate RANSE methods. Seakeeping was partially addressed. It was stated that other aspects like hydrostatics, maneuvering and structural resistance were not explicitly developed but kept as background during the optimization process for realism.

The hull models are restricted to sets of parameters so that wide ranges of variations can be investigate, in order to integrate the assessment tools easily and make searching for an optimal design more efficient. The approach involves the ship parametric modeling, the assessment process and the use of design criteria in an iterative design space exploration.

The assessment includes the use of three widely used codes for wave resistance computation, i.e. RAPID from MARIN, XPAN/SHIPFLOW from FLOWTECH, and SHALLO from HSVA. CAD mesh generation has been provided from the suppliers.

For the optimal design techniques, some key issues arise. First the fact that real optimization is basically multi-objective needs to be addressed. They use intuitive tools for the calculations, remote calculation, and modeling of response surface using neural networks as well as classical approximation functions.

For the optimization algorithms numerous techniques were utilized including method of moving asymptotes, and simplex. Some MOGA code was developed by Chalmers University. However the central optimization package is modeFRONTEIR that uses in addition to other methods a MOGA technique. Multiple criteria decision-making tools were also adopted to help the designer investigate Pareto fronts and outline trade-offs.

In their applications they optimized fast RO-RO vessels, frigates and fast ferries. For some ship types resistance and propulsion were optimized only while for the fast ferry seaworthiness is investigated early. For Phase I of one application, the fast ferry is optimized with respect to calm water resistance while maximizing the passenger comfort according to the Motion Sickness Index (MSI) evaluated at 4 locations. The target hull is defined only in terms of transport capacity. Speed is assessed only at one speed of 40 knots. The investigation used 100 hulls generated parametrically and evaluated separately with CFD and seakeeping codes.

In Phase II dimensions are fixed while displacement is allowed to vary by ± 1 percent. Here resistance, vertical acceleration at stern and bow, and bow slamming events arte used. The optimization used MOGA followed by a gradient search. In terms of optimal hulls, one in particular showed improved seakeeping by 6% for vertical accelerations and 10% for slamming but increased resistance by 3%, which was considered acceptable

These recent developments and significant funding for this project highlights the importance of hull form optimization in the initial stages of ship design. The approach used in this project is multidisciplinary and some of the solutions towards optimization are similar to the topics examined in this thesis. The use of MOGA particularly highlights the choice of this methodology for optimization, as well as the use of both mixed classical methods for optimization and data analysis and AI techniques such as the use of neural networks.

Marked differences in this approach and the topic of this thesis do occur. Since the optimization is done initially using a parametric approach, the parameters are varied in a parametric fashion for the evaluation of the initial designs. The advanced analysis is conducted with sophisticated hydrodynamics tools in an integrated design environment that proves advantageous for ease of use in the application. However some issues are resolved in an arbitrary manner. For example the hull is not initially modeled for use with the GA optimizer. Secondly the final optimization relies largely on the designer's preference and basically resolves the multiple objective problems into a single objective one by the addition of a preference matrix. However there is no doubt that the future of ship hull design will be at least largely in the manner described by the project.

2.1.5 Hull Form Optimization of High Speed Vessels

This is again another European R&D project known as FLOWMART (Fast Low Wash Maritime Transportation) conducted at the National Technical University of Athens by Zaraphonitis et al. (2003) and present at IMDC. The basic issue is to address the problem of minimum wash and total resistance. Some similar packages are used, namely NAPA for the design software and hull modeling tool to generate the series of hull forms, SHIPFLOW for the resistance evaluations, and modeFRONTEIR for the optimization using GA.

The form of the resistance is the wave resistance from the SHIPFLOW model added to the ITTC formulation for shin frictional resistance. For the wash, an objective function is utilized based on the form of the average wave height along a wave cut at a distance form the vessel centerline. The use of SHIPFLOW was validated with some tow tank models.

The optimization is conducted using the two objectives and the Pareto frontier established between resistance and wash. The designer then chooses the hulls that show the most favorable characteristics that can be made with the assistance of modeFRONTIER decision support tools.

2.2 Genetic Algorithms in Other Ship Applications

While the focus of the thesis is hull form optimization, it is useful to look at other ship related studies that use evolutionary algorithms, especially if they contain a significant aspect that can contribute towards the current investigation.

2.2.1 Multiple Criteria Genetic Algorithms in Engineering Design and Operation

This is a doctoral thesis by David Todd (1997) conducted at the University of Newcastle. Although one of the examples contained in the thesis and as a separate paper is a combinatorial problem regarding containership loading (Todd and Sen, 1997), a significant benefit provided by the thesis is the detailed discussion on multiple criteria genetic algorithms as well as the background provided on the use of GAs.

Multiple Criteria Decision Making (MCDM) as described by Todd in Chapter 4 are of two types; selection or synthesis. Selection as it suggests means choosing among different alternatives. Synthesis involves attaining a set of goals if feasible. Since ideal solutions may be infeasible, the search involves looking at the efficient boundary, where solutions are just feasible.

Todd goes on to discuss the various methods as also covered by Gen and Cheng (2000) but in a slightly more condensed form. He then begins to cover the use of Multiple Criteria Genetic Algorithms. Some of these areas are in more detail than discussed by Gen and Cheng as he implements four test functions. It should be noted that while Todd focuses on criteria, the test functions are mathematical and can be equally applied as objectives. In many cases the differences between criteria and objectives has become blurred.

In addition an interactive neural network was used in one case along with the multi-criteria GA that was used to generate a preference surface between criteria. Preference data is collected from the user and used to re-introduce members into the population at regular intervals of the GA process. The purpose was to accommodate the user preferences in an interactive methodology and focus the search on those areas that are preferred by the decision maker. Although this methodology is not implemented in this thesis, as preferences from the designer are not utilized, the use of an interactive neural network is interesting and may be the subject of future work.

2.2.2 Submarines via Genetic Algorithm

This is a doctoral thesis conducted by Mark Thomas (1998) at MIT on the stern design aspects of a submersible. The use of genetic algorithms along with a hydrodynamic evaluation of the boundary layer to predict the separation and wake characteristics allowed for an optimization of the hull volume and propulsive efficiency. Besides using a three-objective Pareto-optimal surface that was found to be superior to a scalarized multi-objective procedure, the work demonstrated fully the use of a hydrodynamic model within the genetic algorithm.

As a further consequence it introduced a concept in evolutionary computation of using non-interbreeding competitive species that enabled simultaneous optimization of four incompatible propulsor configurations. This idea holds promise for the development of a multi-species hull form model. For example the offsets of a catamaran and monohull cannot be exchanged as these represent two different types of hulls. Even within the same type of hull such as two different fishing boat hulls, the optimization may create inconsistencies if part of the hull from one hull form is exchanged with part form a second hull form. In this case the use of a multi-species genetic algorithm may be the best recourse.

2.2.3 MOGA and Fleet Optimization

It is apparent that it is not necessary to focus only on hydrodynamic analysis and MOGA techniques can be applied to other ship related problems such as fleet optimization. Chen et al. (2003) presented one such study at the IMDC conference where the objective is to minimize average annual cost (ACC) and a factor for maximizing the management of the fleet. The management of the fleet is modeled through a management factor. Other factors are assessed through regression equations for Maximum Continuous Rating (MCR). Factors and constraints are modeled for the number of barges, and presumably the number of tugs.

2.2.4 Enhanced Survivability of Naval Ships

This study was conducted by Boulougouris and Papanikolaou (2003) and also presented at IMDC. Though the issues of survivability were already defined the use of MOGA techniques to further the preliminary design characteristics of a naval ship using the optimization package modeFRONTIER was investigated. The problem formulation consists of maximization of the Survivability Index, while minimizing probabilities of both engine room failures, minimization of transverse bulkhead area, minimization of the length of shaft lines, and satisfying constraints for the minimum engine room requirements.

Naturally the focus in this case is survivability. Thus factors such as stability, resistance and structural weight, even though may be included in the optimization as previous stated, are not really part of the full optimization. In particular, estimation of ship structural weight through simple transverse bullhead areas, as given in the study, may not be wholly realistic and probably require further refinement of the optimal hull.

2.3 Evolutionary Techniques for Multi-Objective Optimization

Since consideration is given towards the aspect of multi-objective optimization, the background on this topic is a suitable area for review. This is a very broad topic and special emphasis is given towards those techniques that use genetic algorithms for multi-objective genetic algorithms (MOGA) used for optimization. Other areas include multiple criteria genetic algorithms as mentioned previously and multiple attribute genetic algorithms.

2.3.1 Multiobjective Optimization Problems

This topic is extensively discussed in Chapter of 3 of Gen and Cheng (2000) book entitled "Genetic Algorithms and Engineering Optimization". This chapter deal with the basic concepts of multiobjective optimization the concept of non-dominated or Pareto optimal solutions. They further discuss the use of preference structure to resolve the best-compromised solution form a set of non-dominated solutions.

In the discussion on the basic solution approaches to a multiobjective problem, the section outlines how in traditional approaches most multiple objectives a reduced to a single objective using a weighted sum approach, utility functions, or a compromise approach. Lexicographic ordering is also described.

Finally the Pareto approach is described in which no information on the preferences is available or assumed. They point out that for Pareto problems the use of genetic algorithms are useful as the search technique does not require specific knowledge of the problem and therefore can hopefully solve more complex problems than using the traditional approaches.

The biggest issue in using genetic algorithms for a multiobjective problem is how to assign the fitness. Vector evaluation that is similar to the method used later in this thesis, with some changes to how it is applied. There are two types of Pareto approaches, Pareto ranking and Pareto tournaments. Finally the weighted sum approach can be used as an extension of traditional methods.

2.3.2 Empirical Study of Evolutionary Techniques for Multi-objective Optimization

Among the numerous papers published is a doctoral thesis by Carlos A. Coello Coello (1996). He conducts an empirical but exhaustive study on the use of GAs for multi-objective optimization techniques.

While any or possible all of the techniques described may used in a multi-objective engineering optimization problem, one of the items that is highlighted after reviewing the subject area is that in most every case a method to distinguish the objectives is required. It also mentioned a technique of using Evolutionary Strategies that is a key leading idea towards development of a multi-objective technique.

2.3.3 A Non-Generational Genetic Algorithm for Multi-objective Optimization

This study (Valenzuela-Rendon and Uresti-Charre, 1997) examines different techniques for conducting multiobjective optimization with the intent of developing a non-generational genetic algorithm. The difference between a normal genetic algorithm and a non-generational algorithm is that in the typical GA, the entire population is replaced with a new generation, while in the non-generational algorithm only selected few individuals in the population are replaced.

The justification for replacing only a few individuals is that maintaining good members in the population can enhance the search by not having to re-discover fit members during each generation. In the study this technique is compared to a Niched Pareto GA and appears to perform better for three increasingly difficult mathematical example optimization problems.

2.4 Neural Network Ship Applications

There are numerous studies concerning ships that use neural networks, particularly in the control system area. Some relevant studies are mentioned that concern the two different approaches for using a neural network. Only one is directly concerned with hull optimization but the other studies may be of use for other evaluation of the candidates.

2.4.1 Metallic Hull Weight Estimation

One such study conducted by Wu et al (1998) first studied the problem of estimating the metallic hull weight of transport ships. The neural networks model consists of a back propagation model having seven parameters as the input including one derived parameter; the length, breadth, depth, draft, and the block coefficient, length to depth ratio and the breadth to depth ratio. The final derived parameter is the draft to depth. The output neuron consists of a single neuron for the metallic hull weight. The interest in the hull metallic weight is of interest as it makes up 75-80 percent of the light-ship weight and as such is a major factor in capital cost.

This study was used later to design and calibrate a neural network as the authors provided both the input data for the training samples used and some results. Although the same type of network was attempted in fact a more developed model is utilized as the neural network implemented in the study only had one hidden layer, which proved to be somewhat insufficient with regard to accuracy. However the study and the model provided a good example of the type of database analysis that was possible using a neural network.

2.4.2 Ship Motion Using Neural Networks

Haddara and Wishahy (2000) examined the roll motion of ships using actual measurements from two Canadian Coast Guard vessels. The techniques involved were able to identify the roll characteristics of each of the vessels without having to use wave measurements. In the inputs the mean value of roll angle and mean value of roll velocity are used as inputs to the neural network model, along with a bias which is normal in a neural network model. The output is a nonlinear function G that is used in a roll equation of the form

$$\ddot{\mu}_1 + \omega^2 \mu_1 + G = 0 \qquad (2.1)$$

where G = function of the mean values of roll angle and roll velocity;
μ_1 = roll angle
ω = periodic roll

G includes the damping moment and nonlinear part of the restoring moment. By using training samples from the collected data, the function G can be predicted which gives accurate roll predications.

This method of using the neural network to model the dynamic behavior of a system such as ship roll provides an example of how a neural network may be used in this context. In addition to roll, Haddara and Xu (1997) used a neural network to examine coupled pitch and heave motions. In this earlier work the pitch and heave parameters in the heave-pitch ship motion Fokker-Planck equation are identified using the neural network. In both cases it is apparent that insight and accuracy are gained by using the mathematical model in conjunction with the neural networks.

2.4.3 Hull Form Resistance Optimization using a Neural Network

In this study by Damışman et al (2000) the use of a neural network is utilized as a dynamic model for the hull of a catamaran. In the study the aft part of a catamaran is altered through the aft hull offsets and resistance characteristics and wave heights are calculated using a 3-dimensional Dawson panel method. Since optimization using a 3-dimensional method directly is time consuming as mentioned in the earlier hull form optimization studies, the results from each set of Dawson panel runs were used as part of a database to train a neural network. The inputs to the network are then the hull coefficients. The output is the wave resistance and wave height characteristics. A total of 350 samples were developed for 300 training samples and 50 test samples. Finally the optimization was conducted and compared to a thin-ship optimization methodology. The advantages of using the neural network are that the neural network can be used inside the optimization process rather than the flow solver directly. The use of the neural network for modeling ship flow shows the potential of the methodology.

3. SOLUTION DEVELOPMENT: HULL MODEL

3.1 Hull Model

As previously seen in Chapter 2, a review of the literature shows alternative methods of modeling the hull are used. For off the shelf programs the use of NAPA or another hull modeling software offers considerable advantages to the user in application. Also different types of hull models are utilized. Besides a full representation of a hull using B-spline control nets to produce a hull, parametric models specifying only the chief characteristics of the hull are often part of the initial hull model. These have the advantage of being simpler to manipulate during the search for an initial "optimal" concept design.

On the other hand for full hull form optimization to be conducted, and not just the search for the principal parameters, the hull has to be modeled in greater detail. As seen the use of regression formulas using only characteristics of the hull can be one method. Another is to use a neural network to model the same properties. But generally in order to get a more advanced analysis of the hull form, a detailed depiction of the hull is necessary.

For most naval architects, the use of standard CAD program is essential for development of a hull model. But the basic measurements of a hull are still in the form of the tried and true table of offsets. The offsets, along with various other features of the hull, especially stern, keels, and bow profiles, form the basic hull parameters. All other features of the hull such as the centre of buoyancy, centre of flotation, volume and consequently displacement, hull coefficients such as the block coefficient, prismatic coefficient, water-plane coefficient, and mid-ship area coefficient are derived from these as a basic representation of the hull. Therefore the table of offsets and principal dimensions constitute the primary elements of the hull model.

As seen for hull form optimization studies, genetic algorithms have been used to minimize resistance, as well as more recent applications to include seakeeping. The study by Day and Doctors (1997) used a GA technique combined with a hill climbing technique and applied the algorithm to a wide range of hull displacements. Their model successfully used Michell thin ship theory for the evaluations.

The difficulty with their hull model is that in order to keep the hull simple it is modeled using various key lines in a functional form. By using a functional form for the hull instead of an actual hull using offsets, the number of parameters to be varied can be kept to a minimum.

When encoding the hull as discussed in the next section, the number of parameters to be varied affects the size of the chromosome used in the genetic algorithm.

The disadvantage is that the hull being modeled is not an actual hull form. Whereas Yasukawa (2000) and Dejhalla et al (2001,2002) used well known ship hulls (Series 60 and a container ship hull form) to validate their optimizations, these hulls were constrained to small variations in the hull offsets, as the resistance is evaluated using a three dimensional Dawson panel method.

These studies perform a local optimization of the ship hull, where the objective is to minimize the resistance of a single hull form through small variations in the hull. This is the typical application of hull form optimization. As an alternative in the first study by Day and Doctors the parametric variation in hull forms allows a global optimization of the ship principal parameters, namely length, beam and draught.

As mentioned the three-dimensional methods of resistance evaluation for an actual hull form takes a considerable amount of time. The study by Yasukawa reported and evaluation of 100 hulls in 100 generations took approximately 48 hours to complete. In our evaluations using a program developed by Barbaros Okan et al. (2001), a typical 3-D computation of a single hull takes in the order one minute. As the objective is to ideally evaluate up to 100 candidates per generation over 1000 generations clearly the evaluation can take no more than a few seconds. This forced Day and Doctors to use thin ship theory as well as use a hill climbing technique for a hybrid GA optimization in order to consider a larger number of hull variants.

The aim in this study is to be able to determine the principal parameters that would achieve a global design but additionally to optimize a hull form. As the hull form has a large impact on the performance attributes and subsequently the mission capability the focus is to provide a suitable methodology to provide detailed evaluations that can be carried out concurrently with the determination of the principal parameters.

A number of goals are introduced which are as follows;

- Actual hull forms should be considered. Most often in concept design parametric studies are conducted using a database of hull form parameters, sufficient to give the global parameters but insufficient to conduct more advanced analysis.

- While hull form optimization is the focus the program should include global parameters to determine optimal general characteristics in terms of principal parameters.
- Hydrodynamic analysis should be conducted for local optimization of the hull form with respect to resistance.
- Other objectives should be included in the optimization such as stability.
- Finally, a realistic hull form should be produced.

In order to achieve these objectives some initial candidate hull forms are initially required. While the research conducted on the automatic generation of a hull form by Islam et al (2001) using both neural networks and GA techniques is interesting, the problem of using desired target hull coefficients as the objective means that the desired coefficients have to be assumed in advance.

For this thesis one or more hulls is known in advance but are utilized only to provide an initial start point for the optimization. The hull is modeled using a data file containing the principal parameters and the hull offsets, as well as the station spacing and Froude numbers to be tested. Other data files are produced from these as necessary to calculate hydrostatics and to run seakeeping.

In order to be able to conduct simultaneous optimization of the hull form and the principal dimension of the hull, the variants produced are allowed to vary by changing the offsets and the principal dimensions. For these to be used in the genetic algorithm, it is necessary to encode the hull into a chromosome that represents a solution for the optimization. This problem is addressed in the next section.

3.2 Encoding Hull Form Solution into Chromosomes

In order to be able to use evolutionary algorithms for hull form optimization, it is necessary to develop a scheme to map the problem into a format that can be utilized by the algorithm. The parameters of the problem need to be defined. In every application of an EA, the problem of mapping the parameters for candidate solutions follow from the development of the genetic algorithm. As stated by Gen and Cheng (2000), encoding the solutions may require further development of heuristics to manage the solution properties.

There are several ways to implement the encoding. Gen and Cheng list the 4 methods or classification of encodings that are available;

- Binary encoding using chromosomes made from binary representation
- Real number encoding which uses real numbers instead of binary to enable infinite (at least to the computer code level) variation of the solution parameters and are best suited for function optimization
- Integer or literal permutation encoding which are useful for combinatorial optimization problems
- General data structure encoding which may use complex or other data structure.

In most cases the encoding is also one-dimensional but multi-dimensional structures are also used for real-world problems. For the hull form encoding, both single dimensional and multi-dimensional structure in the form of a matrix are used.

For the current application binary chromosomes are used. While it is equally possible to use a real value rather than binary equivalents, the binary format is sufficient to find near optimal values as long as the accuracy of the binary equivalent is sufficiently high. In our model the desired accuracy can be changed according to the number of decimal places. The number of decimal places affects the length of the chromosome.

It is necessary to consider the encoding from the perspective of the solutions for possible candidates. If the problem is constrained then the constraints limit the solutions to feasible solutions. In most cases the constraints can be handled by use of penalty methods. However in addition to infeasible solutions, the possibility of illegal solutions can occur in which the resulting genetic operator yields a chromosome that does not represent a solution to the problem. In this case either the nature of the encoding or a repair strategy must be utilized to "repair" the chromosome.

For the first part of the hull form model the principal parameters are considered. Given the length, beam and draft the basic dimensions of the hull are defined. Gen and Cheng (2000) show how the accuracy and the upper and lower limits are defined for a single chromosome. Using the following representation for the domain $[a_j,b_j]$ for each variable x_j;

$$2^{m_j - 1} < (b_j - a_j) \times 10^3 \le 2^{m_j} - 1 \tag{3.1}$$

where the accuracy of 0.001 represented by the range from a_j to b_j multiplied by 10^3 gives the decimal number required. The power m_j then represents the number of bits in the chromosome. The mapping of each variable is obtained by

$$x_j = a_j + decimal(substring_j) \times \frac{b_j - a_j}{2^{m_j} - 1} \tag{3.2}$$

where the decimal is the decimal equivalent of the binary substring in the chromosome.

3.3 Design Variables

Each vessel is modeled using a number of attributes that may vary for the intended type of vessel. For the supply ship concept design where GA was used to examine the main attributes of supply vessels (Sommersel, 1997), the dimensions of various compartments of the ship are the major concern. Developing a measure of effectiveness related to each compartment size was necessary and a rule-based method based on design experience was implemented. Each vessel is modeled using basic geometric characteristics as;

1. Length (waterline or characteristic length)
2. Breadth
3. Draft
4. Hull offsets (at least to the Design Waterline)
5. Transom parameters - average breadth and depth (not required for optimization)
6. Waterline positions and station positions (derived from principal parameters).

The resistance calculation is conducted at several Froude numbers and a "power density" curve constructed. This gives an effective Resistance Coefficient Index (RCI), which reduces the effect of the significant change in resistance at different speeds (Doctors and Day, 2000). This will be discussed further in the next chapter.

Besides resistance, the need to satisfy or at least maximize the stability constraint is a basic requirement. In addition, the optimization should explore those designs with better qualities. Together with some form of mission requirement or owner's requirements, these constitute the basic objectives for the optimization problem. In most cases these objectives can be modeled in the form of constraints. Alternatively these can be left as objectives with the idea of maximizing the performance of each objective. For the optimization of the fishing boat example, a fish hold volume is used (Grubisic 2001 and Papanikolaou et al 2000) which is given as the owner's requirement. In addition there is a stability requirement given for a minimum GM. These performance attributes will also be discussed in following chapters.

As these performance attributes can be modeled as constraints, a penalty is added to the RCI to penalize the factor if the GM and stability constraints are not met. The penalty function is determined according to Gen and Cheng (2000) using a multiplication factor.

Hard constraints can be used to define the boundaries of the design space. These may be referred to as the designer input and are naturally flexible to a degree. An example is to limit the length to be explored between 10 and 30 meters for a fishing trawler. For the example of a fishing vessel the following (rather arbitrary) conditions are imposed;

$10.0 \leqq L \leqq 30.0$ meters
$3.0 \leqq B \leqq 5.0$ meters
$1.0 \leqq T \leqq 3.0$ meters

The parameters for the principal parameters of the hull are put into a format for the genetic algorithm. The length, beam and draft can be described by a binary representation where the limits above are used to determine binary values. Using equation 2.1 to determine the number of bits required for the ranges assumed for the length, beam and draft and a decimal accuracy of 10^3 gives the following;

Length:	$2^{m_1-1} < (30.0-10.0)*10^3 \leq 2^{m_1}-1;$	$m_1=8$
Beam:	$2^{m_2-1} < (5.0-3.0)*10^3 \leq 2^{m_2}-1;$	$m_2=5$
Draft:	$2^{m_3-1} < (3.0-1.0)*10^3 \leq 2^{m_3}-1;$	$m_3=4$

The total binary string or chromosome required to describe the length, beam and draft is now 17 bits. Each binary equivalent of a number is put into the string and this represents the chromosome describing the hull principal parameters. If the length for example is 15 meters (between our limits of 10 and 30 meters), and the beam is 3 meters, while the draft is 1.5 meters, then using only one decimal accuracy (10^1), the numbers need to be represented are [150, 30,15]. These are formed by a string where;

$$V = (150,30,15)$$
$$= (2^7 + 2^4 + 2^2 + 2^1, 2^4 + 2^3 + 2^2 + 2^1, 2^3 + 2^2 + 2^1 + 2^0)$$
$$= (10010110, 11110, 1111)$$
thus, $V =$'1001011011110111 1'

This is the typical use of chromosomes to model a particular sequence of numbers. Choosing a random point and swapping each end of the chromosome result in a new generation. If **V1** for example is a simple chromosome **V1**=1100 and **V2** =0011, randomly choosing the midpoint to cross chromosomes gives the new numbers **V1'**=1111, and **V2'**=0000.

In treating the hull offsets, an alternative representation is used. All hull form optimizations using GA as the optimization methodology apparently take each offset as a variable, then create a string as long as the number of elements for single chromosome. For example if a hull has ***m*** stations and ***n*** waterlines, the string produced would contain each offset as follows;

V= [(station 1, waterline 1); (station 2,waterline 1).....(station 1, waterline 2) ....station ***m***, waterline ***n***]

This treatment stems from the fact that two chromosomes must be recombined at some point for a new hull to be created for the next generation of hull candidates. The procedure would include the other parameters of the hull and the hull offsets into one chromosome.

In our methodology, a matrix is formed from the stations and waterline such that a matrix chromosome, which would appear as follows for ***m*** stations and ***n*** waterlines; represents each hull;

$$W = \begin{bmatrix} station1, waterline1 & station2, waterline1 & \cdots & station\ m, waterline1 \\ station1, waterline2 & station2, waterline2 & \cdots & station\ m, waterline2 \\ \vdots & & \cdots & \\ station1, waterline\ n & station2, waterline\ n & \cdots & station\ m, waterline\ n \end{bmatrix}$$

Recombination is approached by choosing a random point in the matrix and in the string representing only the hull offset at that position. The recombination can be done ins several ways, however in keeping with the GA methodology, the matrices are recombined following the point in the offset, by swapping remaining row after the offset point, and the remaining column below the offset point.

To illustrate this idea further, Table 3.1 shows two hulls offset matrices. In the first methodology, swapping a chromosome at the random point of the 8th station and 3rd waterline yields Hull A, where the string of offsets are swapped for each station and waterline following the random point chosen. The matrix chromosome representation would yield Hull B. In hull A the new hull generated has a dramatic change in hull offsets, which degrades the idea of using evolution as genes from successful candidates in recombination. In Hull B, a significant portion of the hull remains largely untouched and the process of evolution is the underlying method for hull development.

Table 3.1 Hull Offsets for Chromosome Representation Example

HULL A	10	9	8	7	6	5	4	3	2	1
WL2	0.000	0.000	0.002	0.048	0.088	0.122	0.108	0.026	0.000	0.000
WL3	0.000	0.050	0.095	0.140	0.198	0.218	0.212	0.135	0.000	0.000
WL4	0.000	0.07	0.137	0.180	0.320	0.280	0.257	0.2	0.1	0.000
WL5	0.000	0.073	0.140	0.193	0.231	0.25	0.2	0.2	0.2	0.01

HULL B	10	9	8	7	6	5	4	3	2	1
WL2	0.000	0.000	0.002	0.048	0.088	0.122	0.108	0.026	0.000	0.000
WL3	0.000	0.050	0.095	0.140	0.198	0.218	0.212	0.135	0.000	0.000
WL4	0.000	0.065	0.127	0.180	0.220	0.240	0.237	0.215	0.105	0.000
WL5	0.000	0.073	0.140	0.193	0.231	0.242	0.243	0.239	0.206	0.013

The matrix method allows the use of a broader range for constraints of the offsets. Hull optimization methods using the single chromosome method constrain the offsets to ranges of 90 to 110 percent of the original hull offsets. In the matrix methodology, the range of offsets that was first used was 50 to 150 percent, though larger ranges could be used. At each station the offsets are modified by starting at the keel and adding each increment to obtain the next offset at the next waterline. By modifying each increment rather than the offset directly some relation to the original hull form is retained. Figure 3.1 shows how each hull is affected by swapping offsets from a single chromosome for Hull A and by using the matrix methodology for Hull B.

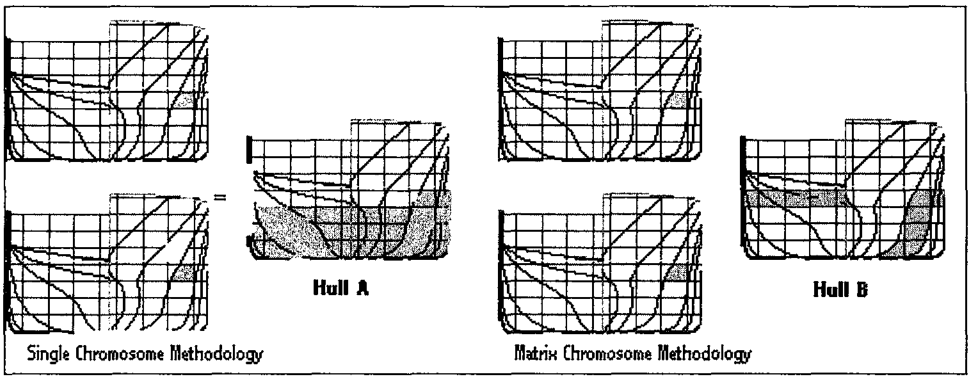


Figure 3.1 Representation of Hull Offsets Swapped from a Selection Point

The hull is now modelled in a form that allows both the solutions to the variants in the form of dual chromosomes, the single chromosome representing the principal dimensions and the matrix chromosome for the hull offsets. This model now provides for most of the objective as stated earlier for using actual hull forms. However a methodology is required to produce hulls that can be used as realistic hulls. This problem is addressed next.

3.4 Drafting the Hull

Each vessel is now modeled in both principal parameters and in hull form that can be encoded for use with the genetic algorithm; however this does not generally mean that a realistic hull will be produced. By using a parametric functional hull, Doctors and Day avoid the problem of encountering and unfair hull form. Yasukawa and Dejhalla et al. constrain the hull offsets to small variations in the hull to avoid major changes in the hull or in displacement, and in most optimizations restrictions concerning variation in displacement, hull offsets or other parameters are used to avoid unrealistic hulls being produced.

Even so, most of the resulting optimizations require some form of fairing afterwards to generate a feasible hull, or alternatively, it is required to sort through optimal variants to choose the design that satisfies the judgment of the designer. Therefore it is expected that some fairing or sorting will be required at the end of the optimization process.

Given this fact, it may not be fully necessary to restrict the design or optimization, and neither is it fully necessary to produce a fair hull at the end of the process. Nevertheless it is required to produce hulls that have some relation to the parent form, and have some form that can be utilized to produce a fair, realistic hull form. Otherwise by final fairing the form may be changed so much as to void the previous optimization process.

This problem was repeatedly tackled during the course of the thesis and may yet still find further solutions. The first technique basically resorts to a drafting of the hull using an algorithm. That is, the sections and waterlines are manipulated one at a time, and these are done in sequence so that some relation to each other is maintained.

The second technique is in the waterline or section is constructed form the differences in the offsets. That is, each section starts at one point and proceeds to the next using the difference between it and the next offset. In order to do this, the offsets are not changed directly, but the differences between the offsets are used in the genetic algorithm.

To illustrate this technique, and to show the difference between manipulating offsets directly as opposed to the differences, Figure 3.2 shows a body plan of a faired hull of a sailboat. Beginning at the keel, each section is developed by adding the previous waterline's offset with the difference between it and the next offset in the section.

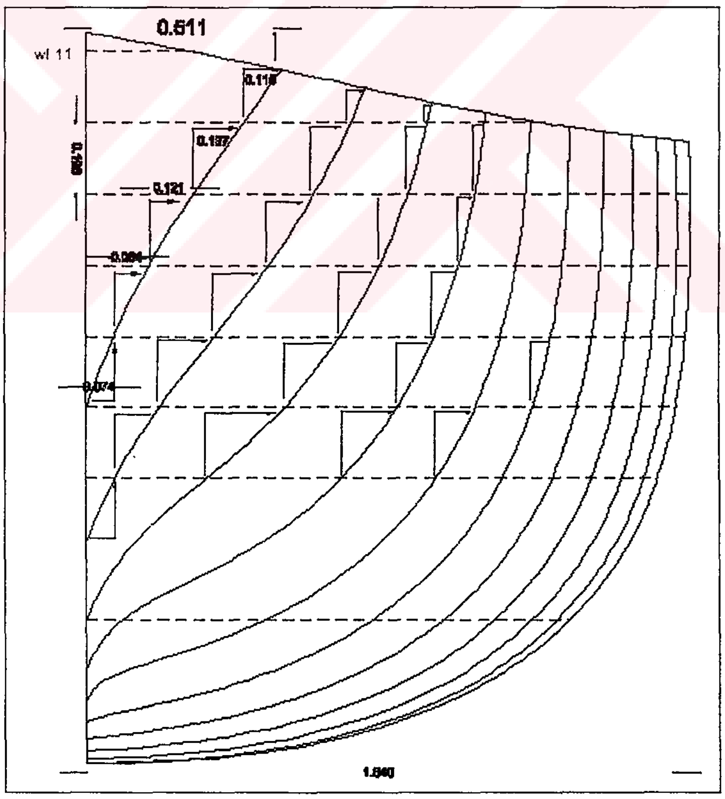


Figure 3.2 Body Plan showing sections with Offset Differences

If each offset were used directly, the value of 0.511 as shown for the first offset would be used in the matrix for the hull offsets. Instead, this offset is represented by the difference it and the offset below, that is the value of 0.115. By adding each of the differences, from the keel outwards the actual offset value of 0.511 is obtained.

What this allows is a variation in offsets greater than 10 percent as used in other hull models as the offsets are built from one another. Otherwise one offset may increase while another may decrease such that an offset may be less than the one below. Although bumps can still be produced in the hull, this greatly increases the flexibility in the hull model.

In addition it was found that using offsets directly or the offset produced form the offsets tend to create numerous bumps because of the previous discussion. Therefore to reduce to unfairness a b-spline was introduced between offsets. While the initial hull offsets are utilized for the initial control points of the hull b-spline, this is not critical as the initial hull is only used as a starting point.

Finally, the hull as mentioned is 'drafted' i.e. beginning with one section, the sections and waterlines are constructed in sequence. Where the section points have already determined form a previous section or waterline, these are kept fixed. Figure 3.3 indicates how the drafting is conducted by keeping drawing intermediate sections and waterlines.

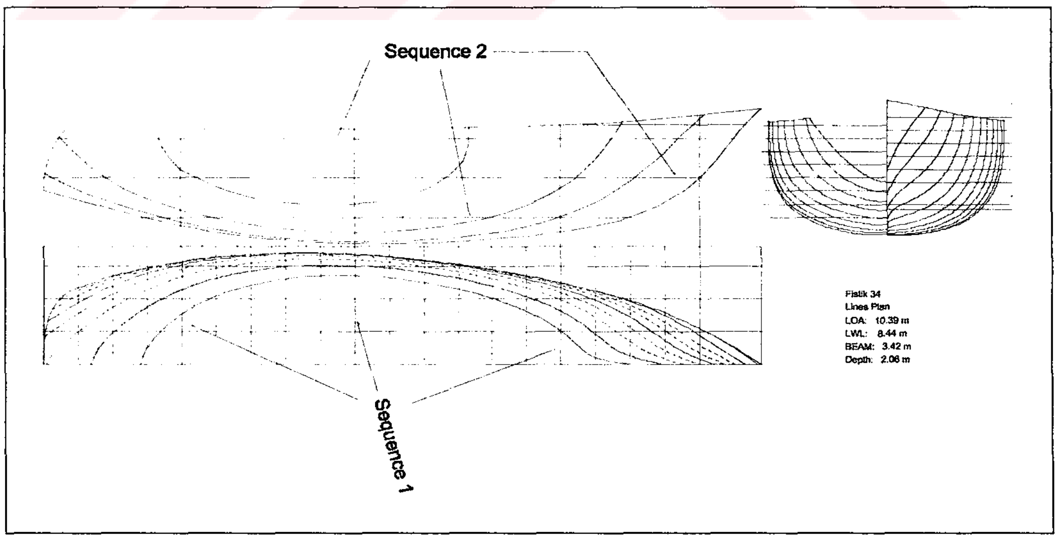


Figure 3.3 Drafting of the Lines by Sequence of Sections and Waterlines.

The result of using these techniques is that some relevant hull forms that only require minimal fairing as a result are produced. In addition, flexibility in shape and changing of offsets can be carried out under the optimization. However additional fairing of the hull has to be made as shown next.

Different hull forms were examined using the previous techniques. A narrow deep hull was developed from ITU 148/1-B as shown in Figure 3.4 given the previous limitations on the beam and draft. Obviously this hull is too narrow to provide the deck space required to work comfortably. A wide and shallow hull form shown in Figure 3.4 provides the deck space, but is very unconventional. Neither of these hulls is satisfactory from the naval architect's design perspective, and both would be abandoned in favour of a more conventional hull.

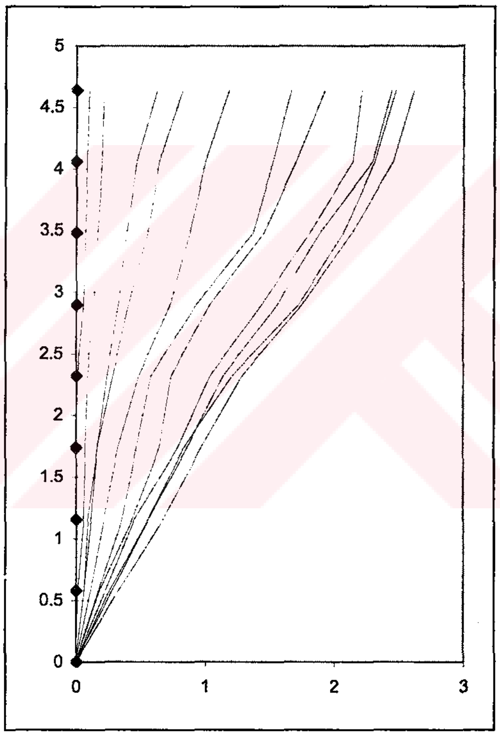


Figure 3.4 Forebody of Narrow and Deep Evolved ITU 148/1-B Hull

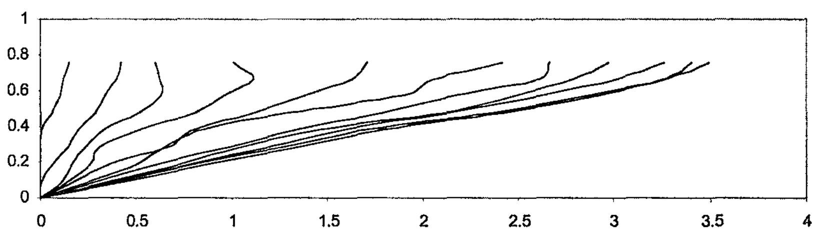


Figure 3.5 Forebody of Wide and Shallow Evolved ITU 148/6-B Hull

Based on the foregoing, a trial run was attempted shown in Figure 3.6 in which the restrictions on beam and draft were made tighter, allowing less variation in these two parameters. The beam was restricted to 6.0 metres while the draft was limited to 3.0 metres. The minimum beam was set at 3.0 metres while the minimum draft was set at 1.0 metre to limit extremely shallow hulls.

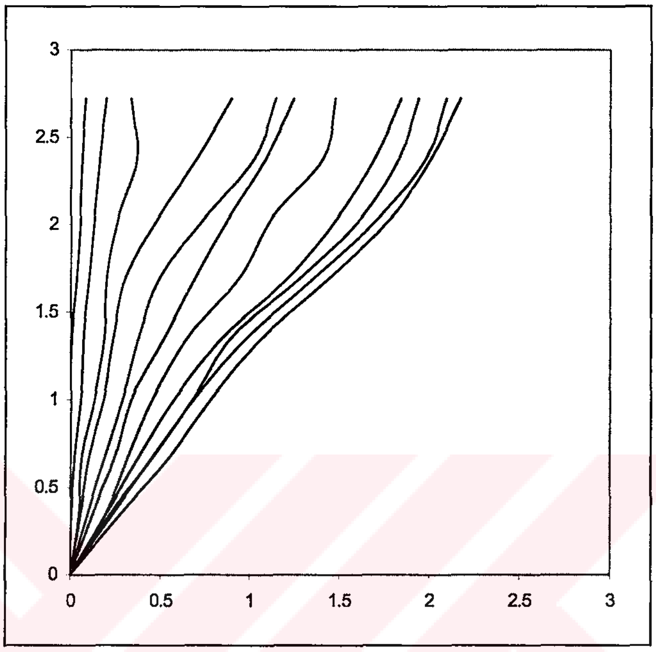


Figure 3.6 Forebody of Evolved ITU 148/1-B using More Restricted Beam and Draft

While the results from a performance perspective may be a satisfactory improvement in the size of the vessel, the hull offsets still show marked deviations and a general unfairness that is unpleasing to the eye. Therefore some additional techniques must be incorporated to render a fairer hull. This issue is addresses next.

3.5 Development for a Fairing Routine using B-Spline Surfaces

As seen in the previous section, the use of some members of the ITU fishing hull series resulted in hulls that provided improved performance but lacked in not producing a fair hull. The reasons for this can be seen from the method used to produce the initial populations for the evaluation and in subsequent generations. An offset is derived from the previous offset given the chromosome and the lower and upper limits for the variation on the offsets. As was shown in Figure 3.2, each offset is derived from the previous offset by adding the difference between offsets. For each offset, a chromosome in the ***W*** matrix for the hull is used to represent the change in the offset.

For example, if $y(i, j)$ represents the hull offset, then the next offset in a section or waterline is obtained by the following;

$$y(i, j+1) = y(i, j) + \Delta y \times w_{ij} \qquad (3.3)$$

where Δy = difference between the adjacent offsets
w_{ij} = chromosome representation of next change in offset.

The allowable change for the offsets is specified in the program. For example, if the allowable change is from 0.5 to 1.0, then the range in which the chromosome can change is from 50 to 100 percent of the full difference between the offsets. This is given simply by,

$$w_{ij} = w_{lower} + (w_{upper} - w_{lower}) \times chr_{dec} \qquad (3.4)$$

where chr_{dec} = decimal value between 0.0 and 1.0 from the binary chromosome.

However, what this means is that for a large variation of for example, between 0.0 and 1.0, the next offset could in fact have the same value as the previous offset in the section. Some of the FORTRAN statements are shown as follows, where *bint* represents the binary integer value of the chromosome and mm is the chromosome length;

```
yy(p,i,j)=loweroffset+ bint * (upperoffset-loweroffset)/(2**mm-1)     (3.5)
ydiff=ymax-ymin                                                        (3.6)
y(i,j)=yoffset(i,j,s)+ydiff *(yy(p,i,j)-0.5)                           (3.7)
```

As can be seen, if the upper offset is greater than 1.0 a larger offset can occur that may be larger than the next offset. Similarly a value less than 0.5 would result in a smaller value.

Because there is no fairing procedure in this method, it was prudent to adopt B-spline (Gerald and Wheatley, 1999) to smooth the offsets. Offsets are given in a matrix to the hull spline routine and used as control points. Using these, intermediary hull offsets as part of a B-spline for each section or waterline is produced. However a single pass through the B-Spline may not results in a fair hull, as the control points may still produce unfair B-Spline sections as shown in Figure 3.7.

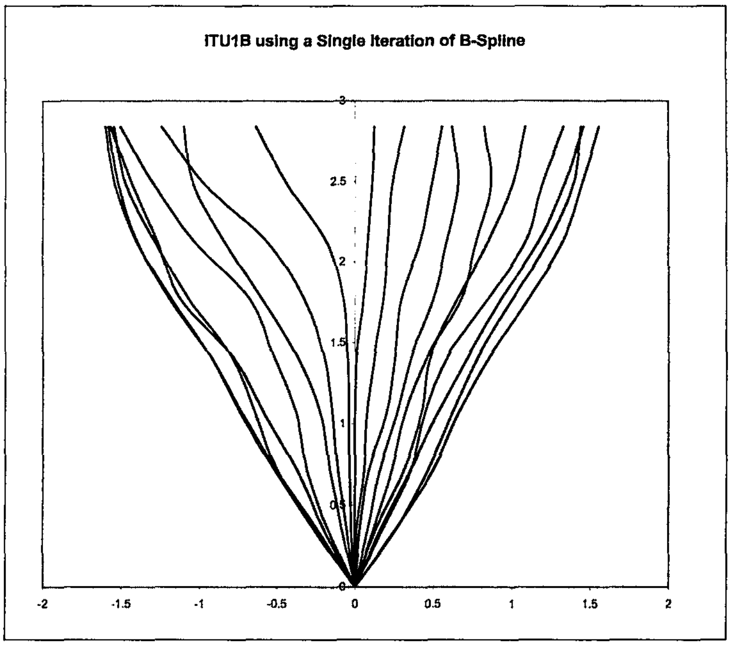


Figure 3.7 ITU 148/1-B Evolution using B-Spline with Single Iteration of Offsets

However, if the number of iterations using the B-Spline is increased, a fairer hull results. This is achieved by using the results from each pass or sweep of the B-spline as the next set of control points. As seen in Figure 3.8, using two iterations results in a fairer hull, however deviations still exist in some of the sections.

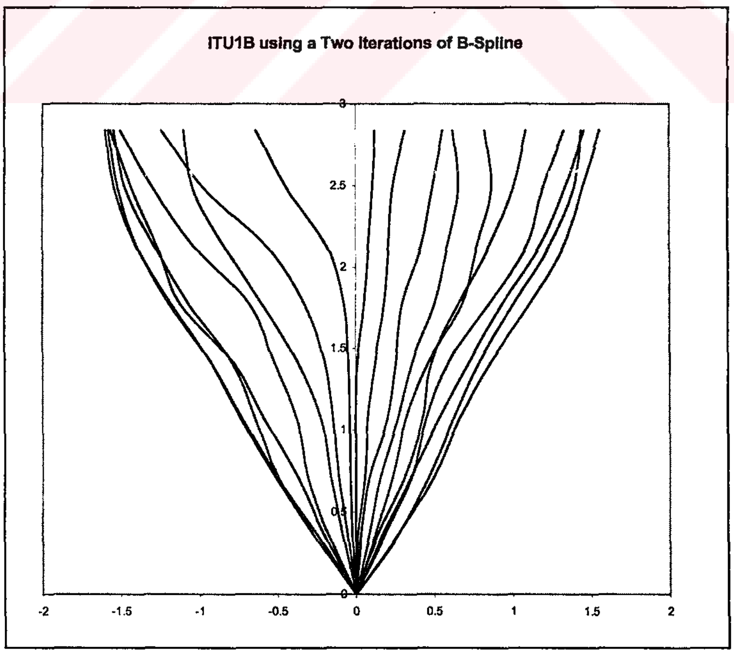


Figure 3.8 Two Iterations using B-Spline for Evolved ITU 148/1-B

If the number of iterations is increased, a fairer hull results. In Figure 3.9, the same hull optimization is carried out but with four iterations instead of two. In this case, as each set of smoother offsets is re-used as the next set of control points and these in each iteration results in a smoother, after four iterations a smooth hull results. This is the case even when the allowable range in the offsets is set from 0 to 100 percent as described previously.

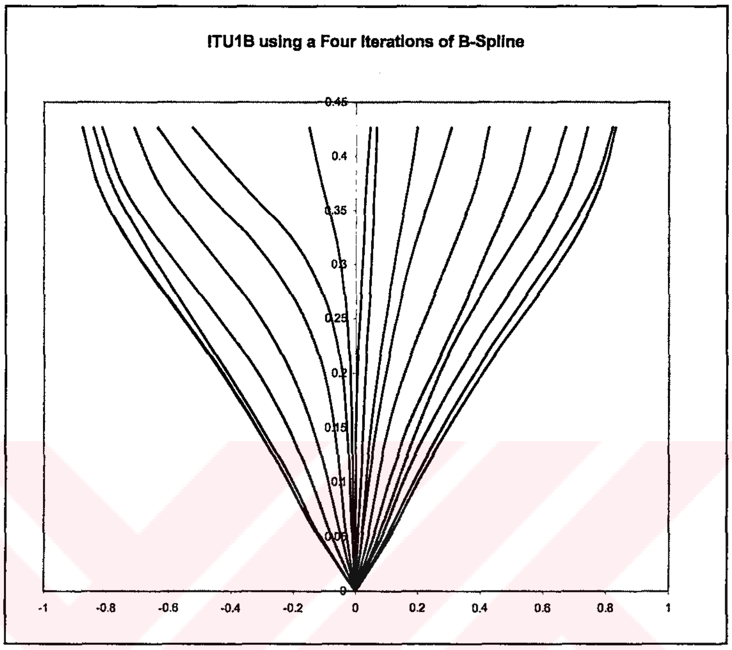


Figure 3.9 Four Iterations using B-Spline for Evolved ITU 148/1-B

Though the sections may be of good fair quality, the use of a B-spline does not guaranteed a completely fair hull as the waterlines may remain unaffected and the fairness of the hull may not be complete. However, as shown in Figure 3.10, the fairness of the sections combined with the "drafting" routine as described in section 3.3, means that the waterlines are also quite fair. For a full fairing routine, a B-spline surface generation would be required.

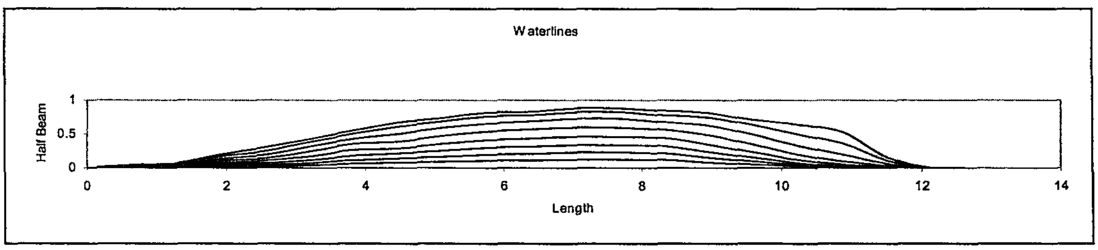


Figure 3.10 Waterlines from Evolved ITU 148/1-B using Four Iterations of a B-Spline

An alternative method to using a B-Spline and 'drafting' the hull by keeping some waterlines or sections constant while drawing other using a B-spline is to use a surface generated by the same control points. A B-spline surface can be generated where the offsets are given as a function of two variables. This means that each of the pints on the surface is a function now of 16 control points to create a surface patch. The patch is a natural function of the control points and therefore is already fair to some extent. Nevertheless as shown in Figure 3.11, a single iteration using a B-surface may be insufficient to generate a full fair hull.

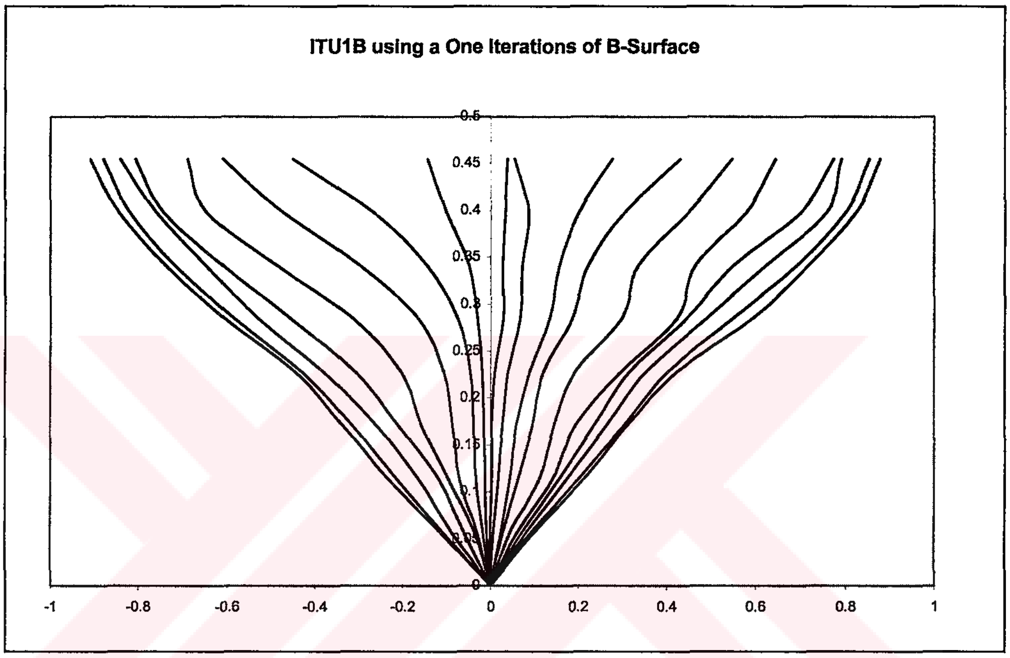


Figure 3.11 An Evolved ITU 148/1-B using a B-spline Surface after One Iteration

As in the previous example using a B-spline, subsequent iterations of re-applying the B-surface (Gerald and Wheatley, 1999) yields a fairer hull as shown in Figure 3.12. The waterlines in Figure 10.17 show some small improvements in fairing as well when compared to the waterlines shown in Figure 10.14 using a B-Spline, though a bump in the stern is still prominent.

Among the remaining issues in the hull model is how many iterations and what range the offsets are allowed to vary. These can be left as a matter of input and experience to determine how smooth and to what variation the hull forms are allowed to vary. One other issue that needed a solution was the development of a method to determine the required number of stations and waterlines for use with the evaluation programs. However, using a B-Surface, intermittent points are generated for any number of stations and waterlines given any number of input stations and waterlines.

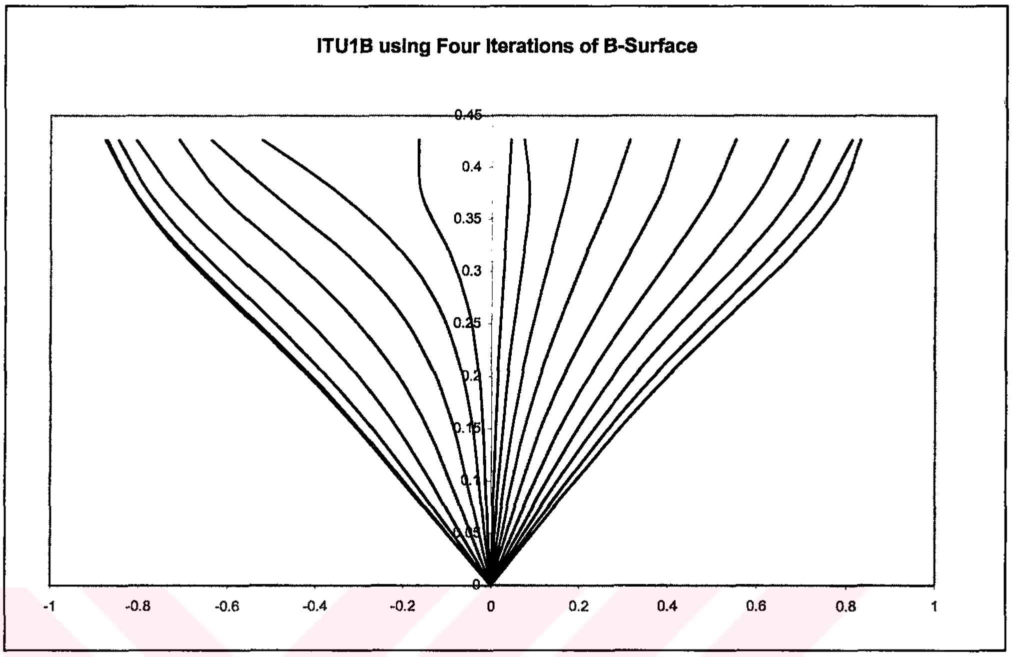


Figure 3.12 Body Plan of Evolved ITU 148/1-B after Four Iterations of a B-Surface

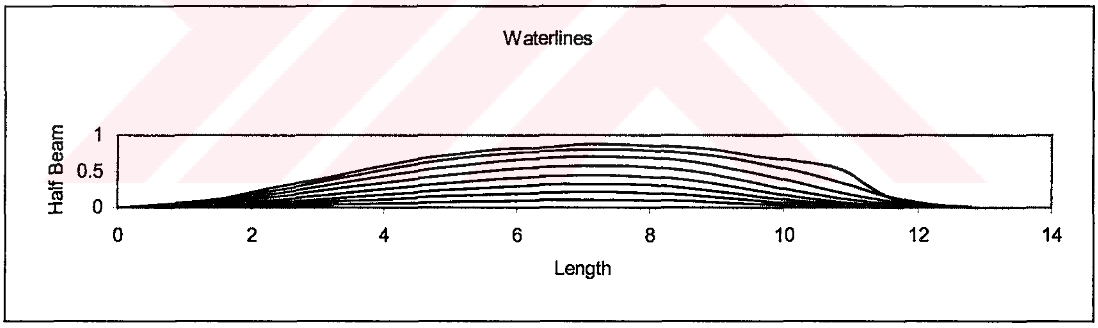


Figure 3.13 Waterlines from Evolved ITU 148/1-B using Four Iterations of a B-Surface

For example in Figure 3.14, a Wigley Hull is modelled using only 13 stations and 6 waterlines. The required number of stations for the ship motion and hydrostatic programs are 21 stations and 9 waterlines. Therefore in Figure 3.15 the same hull is modelled using the B-Surface algorithm to predict the surface using the original offsets as control points. As mentioned previously, this does not reproduce the hull exactly as the control points as derived from original offsets produces a slightly smaller hull, but since the optimization program is changing the hull in a radical fashion in any case, this is not materially important.

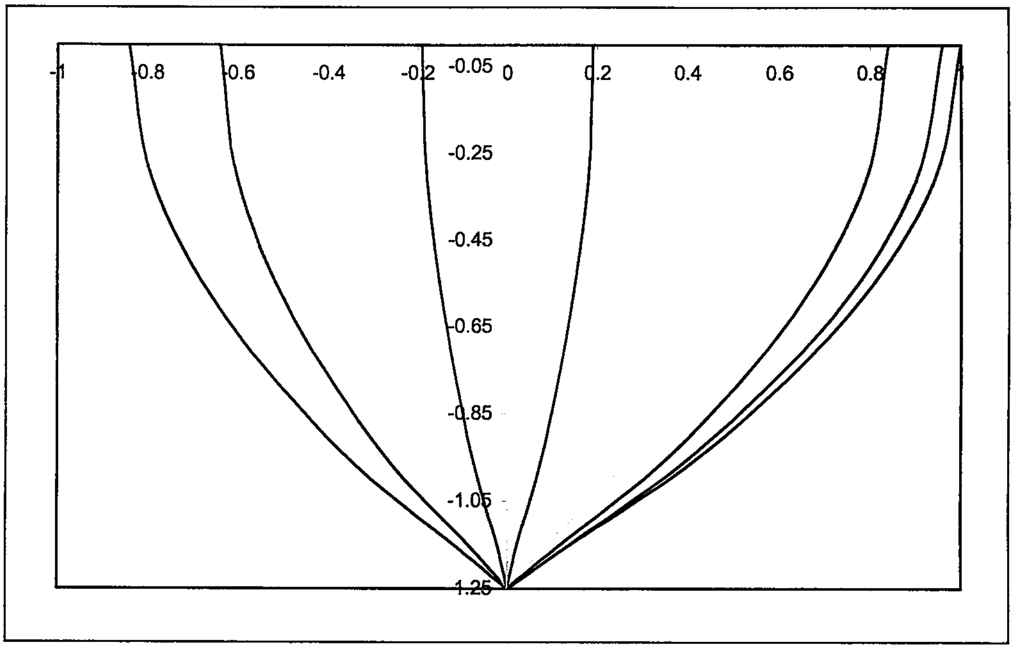


Figure 3.14 Wigley Hull Form with 13 Stations and 6 Waterlines

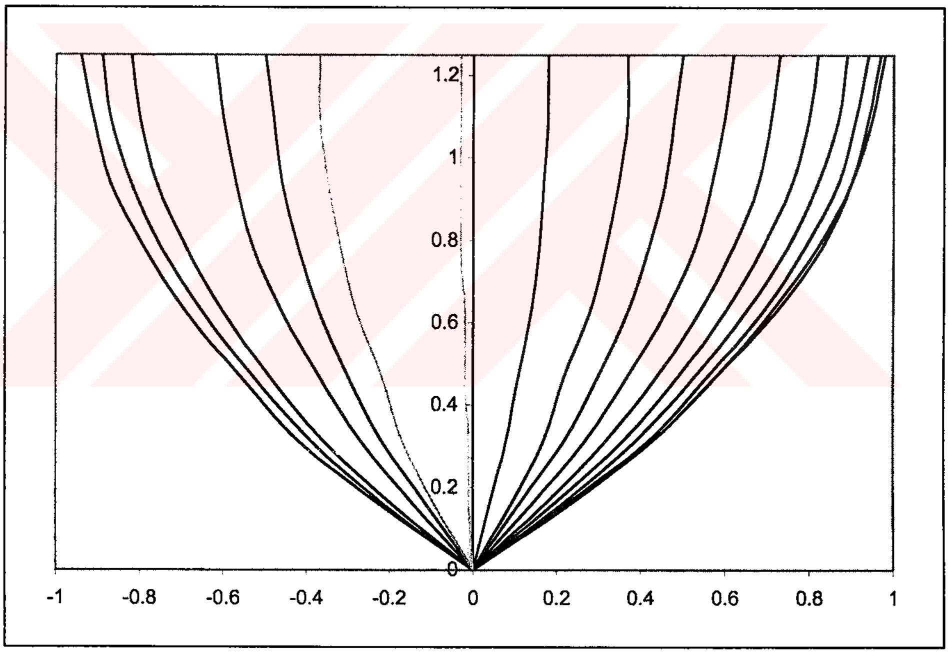


Figure 3.15 Wigley Hull Form with 21 Stations and 9 Waterlines

The use of the Wigley hull form is useful for comparisons but as the hull form is mathematical, and range of offsets can be determined without using a B-surface. Another hull form that is particularly difficult to model with few offsets is the Series 64 hull form, as it contains a transom. In Figure 3.16 the sections are shown for 13 stations. In Figure 3.17, the interpolated B-surface sections are shown using 21 stations.

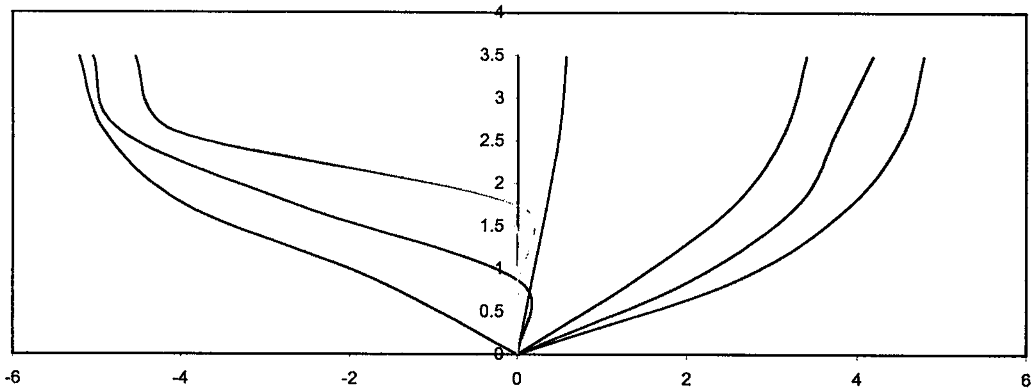


Figure 3.16 Series 64 Hull Form Modelled with 13 Stations and 5 Waterlines

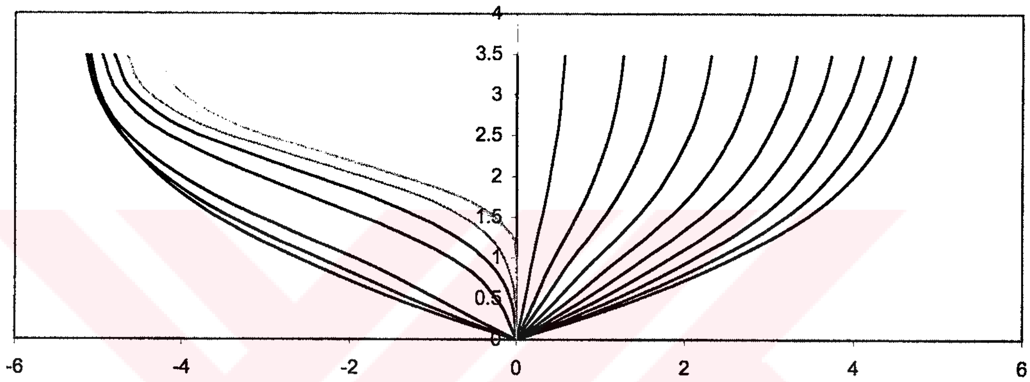


Figure 3.17 Series 64 Hull Form Modelled with 21 Stations and 9 Waterlines

3.6 Development of B-Spline End Conditions

Both Dejhalla et al (2002) and Yasukawa (2000) used an application of the GA method to optimization of a Series 60 hull form as mentioned in the literature review. In this example we will use the Series 60 hull form but have changed it into a different round-bilged huil form entirely and will refer to it as the Series 60 Round Bilge (S60RB) hull. The requirement is to maintain the same required volumetric displacement, minimizing resistance while maximizing seakeeping performance as well as stability. This is achieved by using the volume form the original Series 60 hull form as a constraint.

As the methodology allows variation in both principal parameters as well as hull offsets, variation in the length beam and draft is allowed. However in order to restrict the search space and to keep the resulting ship hull near the original for comparison, the length, beam and draft are restricted to a $\pm$ 10 percent variation in the principal parameters.

The hull form that has evolved is shown in figure 3.18. There are a number of features that should be noted, foremost being the accentuated turn at the bilge. Since the draft was allowed to vary, the draft is now 7.23 metres. The beam is 16.3 metres and the length is 134.1 metres. The volumetric displacement is also smaller at 10357 cubic metres. It is apparent in all the different examples that if the length of the vessel is not restricted, then the maximum length is usually one of the optimal results since increased length allows increased volume, while decreasing wave resistance. This may not be true for beam, as the beam affects stability and a minimum beam may not be the best solution. The minimum beam corresponds to 14.7 metres.

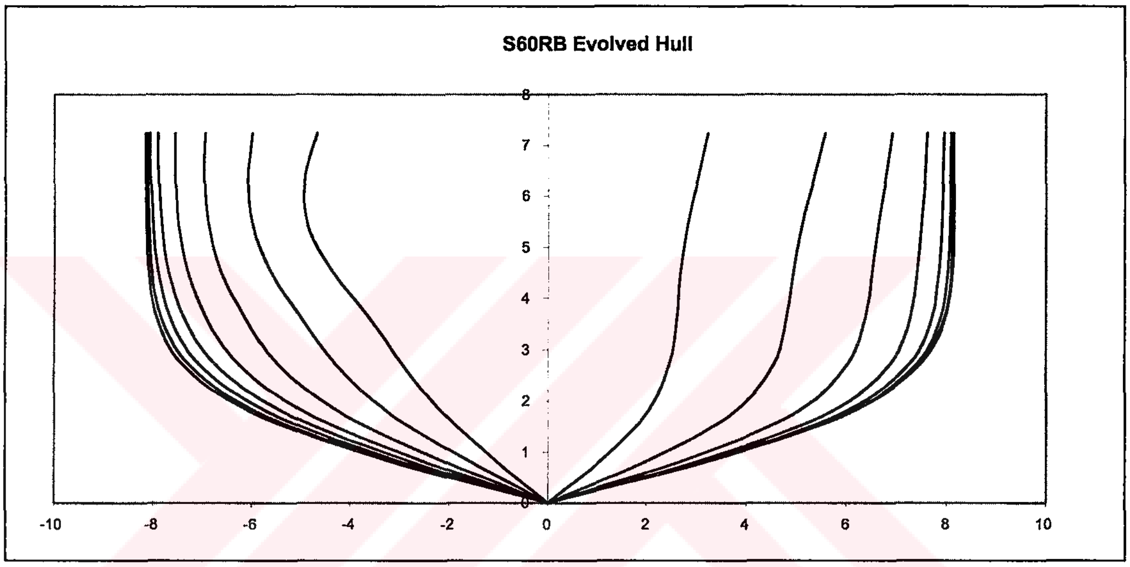


Figure 3.18 Modified Body Plan Evolved from S60RB Hull Form

The problem with the sections at the bilge radius stems from the fact that the algorithm is currently using equidistant control points at each waterline. Therefore the spline naturally interpolates between the control points and creates a curved bottom rather than flat bottom sections. This problem will occur for all flat bottom hull forms and can be corrected by adding additional control points at the same waterline as the keel.

The problem that needs to be addressed for any type of hull whether flat bottomed or not is seen in Figure 3.19 showing the result of using a B-spline surface in which the end conditions are derived by setting a number of control points to have the same offset. This creates basically a moment induced on the spline. Though this guarantees that the last control point will be the offset as stated in Gerald and Wheatley (2002), it also creates a spline surface that has uncharacteristic shapes.

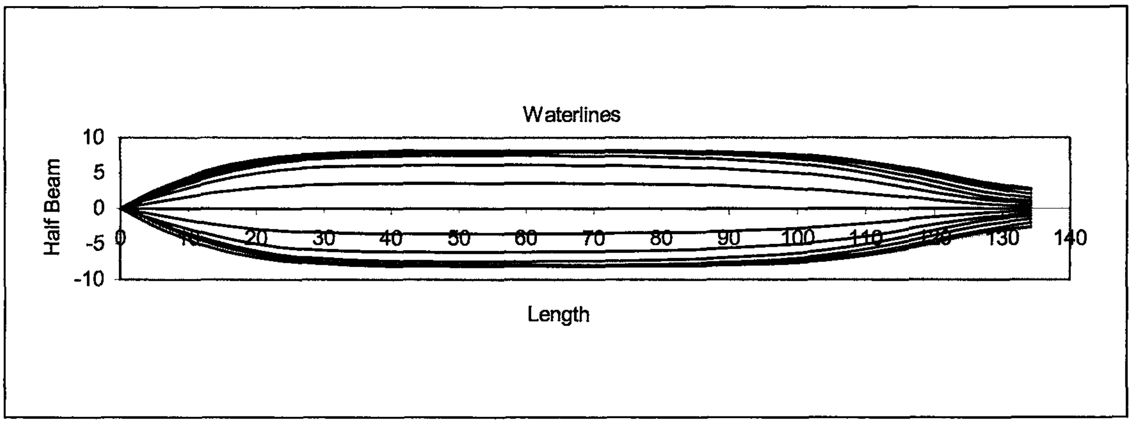


Figure 3.19 Waterlines of Evolved S60RB Hull Form with Open End Conditions

An alternate technique is to use the tangents to the offsets in order to create a series of artificial points past the stern that can be used to keep the spline surface with the same tangent in the offsets as the stern control points. The simplest method to do that in this case is to use the negative values of the proceeding offsets and creates artificial points as shown in Figure 3.20. The artificial points work well for the waterlines that don not have a transom as shown in Figure 3.21 but the sections at the stern still show some unusual shapes.

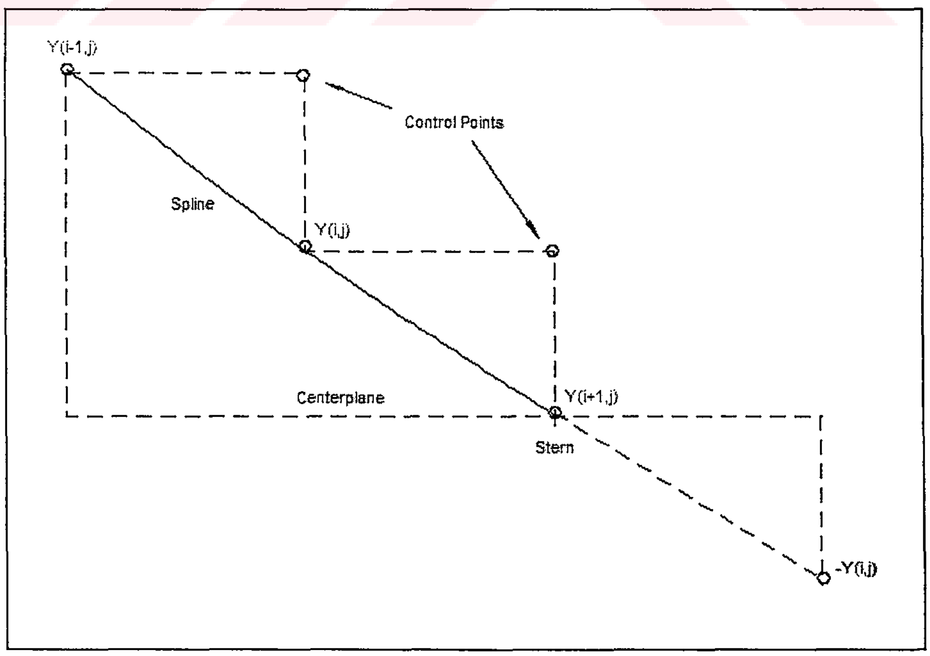


Figure 3.20 Modeling Control Points at Stern

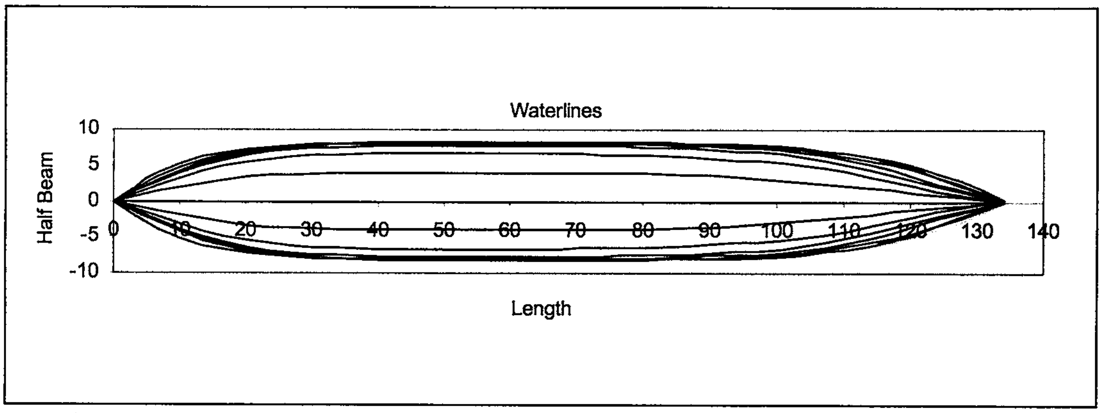


Figure 3.21 Waterlines of Evolved S60RB Hull Form using Tangent Control Points

The reason that the routine shown by result in Figure 3.21 does not always work is that this method does not actually account for cases when the stern has a transom. The assumption for that algorithm was that the last control point would be on the centerline, which is not the case if the vessel has a transom stern. A more general method is to use the following for the next control point as an end condition;

$$\begin{aligned} y(i+2,j) &= y(i+1,j) - (y(i,j) - y(i+1,j)) \\ &= 2 \times y(i+1,j) - y(i,j) \end{aligned} \tag{3.8}$$

This ensures that when the end control point is not zero, as in the case of an immersed transom, then the next control point is at a position at the same slope as the previous two control points.

The algorithm for the hull model is complete except for the issue of equidistant waterlines as pertaining to the Series 60 hull or other flat bottom hull forms. The S60RB hull resulted from using equidistant waterlines. As the examples used here do not have a flat bottom, this issue is not addressed further. However for most of the modern ship hull forms with high block coefficients including tankers, ferries, and cargo vessels, a flat bottom and parallel mid-body are features which must be accounted for in any further geometric development and modeling of practical hull forms.

4. HULL DESIGN REQUIREMENTS

4.1 Design Requirements

Different vessels have different design requirements. For much of the work conducted during this thesis, the focus has been centred around fishing boats, given previous work conducted in that area and a ready source of information. However other types of vessels are considered by various authors. Kupras (1976) studied optimisation by parametric study for pre-contracted ship design. This used a computer oriented methodology for conducting optimisation, and models which vary different sequences of parameters while holding others constant or as constraints. The variables consist of length, beam, draft, volume, depth, block coefficient and GM. The requirements consist of the deadweight, stowage factor, and minimum freeboard. The objective for the cargo ship being considered is required freight rate.

The design example given by Pal and Peacock (2001) optimise a high speed mono-hull ferry. The model is designed to find principal design parameters at the preliminary design stage. The objectives are to minimize the total resistance, minimize the lightweight, and maximize the next present value index for the life of the ferry. The objectives are constrained by numerous coefficients or hull parameters. The hull is modelled by a series of regression based equations for prediction of LCB, displacement, and so forth while keeping within the bounds of the database using restrictions on L/B, B/T, and numerous other factors.

In both of these examples the system variables and constraints are given in terms of simplified equations for restricting the principal dimensions, and for various factors concerning the vessel design requirements. The design requirements for the fast ferry are not in fact that great, utilizing only passenger seating area based on number of passengers, the area per vehicle for the number of vehicles, and the weight regression formula for the ship. Variables required for some prediction formulas like half angle of entrance at the bow are utilized for resistance. This makes these optimisation problems particularly easy to solve using normal optimisation. The fast ferry solution using LINGO is given below.

Table 4.1 Summary of Fast Ferry Characteristics using LINGO

PARAMETER	Symbol	Value	Ref.
Number of Vehicles	NOV	100	100
Number of Passengers	NOP	500	500
Speed (knots)	V	46	46
Deadweight (tonnes)	DWT	219.9664	221.38
Length over all (m)	LOA	97.37865	103.64
Beam (at main deck) (m)	BEAM	17.19087	17.49
Depth (m)	DP	5.132805	5.21
Length of Waterline (m)	LL	84.86038	90.39
Length between Perpendiculars	LP	84.86038	90.39
Beam at the waterline (m)	BEAMMW	15.62806	16.66
Draught at Midship (m)	TM	2.450469	2.24
Displacement (tonnes)	DISPLT	1133.342	1217.69
Weight (of the ship) (tonnes)	WEIGHT	1133.342	1208.10
Area for Vehicles (sq. m)	AREAVH	1240	
Area for Seating (sq. m)	AREAST	400	
Gross Area for Passengers (sq. m)	AREAPG	520	
Waterplane Coefficient	CWP	0.83	
Area of waterplane (sq. m)	AWP	1100.749	
Metacentric Height (m)	BM	2.15E-02	
Displaced Volume (cubic m)	VOL	1137.437	
Initial GM	GMINI	1.719087	
Block Coefficient	CB	0.35	0.35
Midship Area Coefficient	CM	0.597883	
Prismatic Coefficient	CP	0.585399	0.611
Midship Area (sq. m)	AREAMX	22.89657	
(given) Freeboard	FBC	2	
Lightship Weight (tonnes	WLT	913.376	986.72
Target Lightship Weight (Given)	TRWLT	500	
Target Resistance (kN)	TRRESD	1000	
Calculated Resistance (kN)	RESD	1196.532	1408.5

Comparison with the round bilge hull table in the reference, shows deck beam, waterline beam, draught, and lengths are similar, though in fact closer to the reference results obtained at 44 knots. This implies a better model of resistance would lead to more accurate results. This model should be of use to anyone doing preliminary design. As mentioned initially, some user supplied formulas or subroutines (tables can also be accessed by LINGO are required in order to make valid results.

4.2 Hull Form Optimisation Requirements

For the hull form optimisation problem, the evaluations are less easily resolved. In changing one factor such as length, the previous problem structure automatically defines the search space and impact of numerous other factors and principal dimensions. For the hull form, changing an offset is not immediately apparent on the impact without conducting a full evaluation of the hull form.

Given the basic precept in this thesis that the hull can be used initially during the preliminary design phase of the vessel, the use of many of the formulas given in studies that are parametric in nature are no longer either required or valid. While there may be rational reasons to constrain the length, or beam or draft, the use of variable such as length/beam ration that are restricted accordingly makes sense only if there are rational requirements for their restriction. Otherwise these are restrictions in the design space that limit the exploration of the optimal vessel hull form.

On the other hand, use of regression equations may be fully justified where the hull form cannot provide the necessary factors governing the design. For example, in the fast monohull ferry, the total (gross) area for passenger seating is given as a function of the individual passenger seats, and these are in turn a function of the number of passengers. These regression equations are based on data that is independent of the hull form and should still be relied on for use during the optimisation process.

For the rest of the thesis, design requirements will be considered if they satisfy the criterion as stated as follows;

Design Requirement Criteria; **Owner's requirements or designer requirements based on a given rationale; restrictions based on hull dimensions if they are supportable. Constraints such as L/B, B/T are not utilized unless a rational other than database related can be given.**

What this does is exclude all of the constraints used in preliminary design programs to fit designs within the regression based equations derived from a database or past designs. Because of this technique, it is hypothesized that it is equally likely to miss a global optimal solution as it is to satisfy the given constraints which or may not be arbitrarily set. Therefore only those constraints that can be rationalized are utilized.

For the hull form optimisation, there are number of evaluation factors for the design which should be included. These will be covered more exclusively in the chapters on stability, resistance and seakeeping.

4.3 Fishing Boat Design Requirements

Much of this thesis focuses on the fishing boat example. The fishing boat is typically a difficult problem because it is a relatively small craft relative to ordinary cargo vessels; and requirements such as working conditions on deck are critical for safety concerns. The resistance, seakeeping and stability evaluations all have a large impact on the design. Further the owner's requirements are often difficult to satisfy. The fishing boat example uses a number of factors for the design and owner's requirements.

One significant design requirement is given by regulations concerning stability. The GM requirement is 0.40 meters. For stability an empirically derived formula for fishing boat models is used (Grubisic, 2001). The GM formula is given as follows;

$$\text{Maximum}\, GM = 0.163e^{0.742\times B/D} \tag{4.4}$$

where the minimum Depth is also given as,

$$D\min = 0.266L^{0.77} \tag{4.5}$$

In addition to the stability requirement, the owner's requirement is to obtain a fish hold volume of 95.2 cubic meters as in the example of Grubisic (1997). In that model the fish hold is obtained by the following relation by first obtaining a fish hold length;

$$L_{FH} = 0.157Lwl^{1.26} \tag{4.6}$$

Fish hold volume is then obtained by;

$$V_{FH} = 0.38L_{FH}(B\times D)^{1.08} \tag{4.7}$$

One parameter that is not included specifically is the depth of the model. For our purpose as we are mostly concerned with the underwater portion of the hull, the depth is simply modelled as a function of draft according to the following relation;

$$D = 1.27\times T \tag{4.8}$$

It should be noted that in addition to these constraints Grubisic uses numerous other relations that are not included in the current model. As the objective in this thesis is to investigate the methodology for using GA as an optimization tool and the impact of requirements on the methodology rather than investigating a fishing boat model, some of the design requirements are not included. Additionally the constraints concerning hull dimension, except for the gross dimension of length, beam and draft, are not utilized as they pertain to the databases used for the fishing boat hulls. Nevertheless, further constraints and relations could be easily included.

In order to include the constraints in the optimisation process, the penalty method is utilized. The penalty is found per candidate using a method by Gen and Cheng (2000) according to the two design requirements of fish hold volume and GM;

$$penalty = 1.0 - \frac{1}{2} * \left(\frac{D_{FHV}}{D_{FHV\max}} + \frac{D_{GM}}{D_{GM\max}} \right) \tag{4.9}$$

where D_{FHV} is the deviation of the fish hold from the required and D_{GM} is the deviation of GM from the required. For example for the fish hold volume;

$$D_{FHV} = \begin{Bmatrix} (\text{Required FHV} - \text{Achieved FHV}) \text{ if} > 0 \\ 0 \text{ if (Required FHV - achieved FHV)} < 0 \end{Bmatrix} \tag{4.10}$$

The maximum and minimum are from among the population in each generation. The penalty times the ratio of RCI for this one objective is given by the fitness function;

$$\text{fitness} = \left(1 - \frac{\text{RCI - RCI}_{\min}}{\text{RCI}_{\max} - \text{RCI}_{\min}} \right) * penalty \tag{4.11}$$

As the previous outline shows, each objective can be tested accordingly with each of the design requirements included as a constraint. Alternatively if there is the possibility of maximizing or minimizing a particular design requirement, then these can be included as objectives. However additional objectives take additional computation time whereas using constraints take almost no additional time at all, therefore, where possible, the use of constraints should be considered rather than objectives.

This does not preclude the fact that design requirements should not be modelled as objectives. For the fast ferry example given previously, the design requirements included the following; minimize the total resistance, minimize the lightweight, and maximize the next present value index for the life of the ferry. In this case each of these can be modelled as an objective rather than constraining the weight or achieving a minimum present value index.

In some cases the displacement was considered as a requirement. It is modelled in a similar way as the previous constraints, but because of the importance of displacement, it was given a larger priority. Taking it as a separate term rather than averaging it together with other constraints achieved this result as shown;

$$penalty = \left(\frac{D_{\nabla}}{D_{\nabla \max}} \right) \times \left[1.0 - \frac{1}{2} * \left(\frac{D_{FHV}}{D_{FHV \max}} + \frac{D_{GM}}{D_{GM \max}} \right) \right] \tag{4.12}$$

The deviation is calculated in a similar manner as shown by (4.10), and the penalty is again used in the same way as multiplication factor as shown by (4.11) for each objective.

5. SHIP STABILITY

5.1 Ship Stability for Design

Stability is an area of ship research that is by itself too large to treat in detail. It is a fundamental performance criterion that must be given first priority in the evaluation of the design. Gammon and Yilmaz (2003) have developed a stability performance index to be used in the hull form optimization program. Design model parameters such as stability have been previously modelled using regression-based formulae (Grubisic 1999) and Yilmaz (1999). These parameters take the form of stability constraints defined for the particular ship design problem, given requirements from IMO regulations or other sources.

In this research, stability characteristics based on hydrostatics are calculated directly from the hull form. The calculation is used to develop an appropriate indication of the stability ranking for each hull candidate. Further, a method for evaluation of the stability index is derived. The desire for a flexible method has been incentive for using a Neural Network (NN) to model stability characteristics from a fishing hull database previously used for regression analysis by Yilmaz (1999). The NN method is compared to the stability regression models of Grubisic.

5.2 Stability for Fishing Boats

Stability for fishing vessels is an area of ongoing research as these vessels are often subject to extreme conditions for their size. Safety concerns continue to be an issue (Yilmaz, 1999) and accidents continue to take a toll on human life as well as impacting the environment. The study of stability characteristics of fishing vessels has provided designers with a number of methods for the prediction of stability (Yilmaz and Kükner, 1999) that have been utilized to predict stability issues.

Recent effort has gone into development of a NN model for the evaluation of stability characteristics such as KG, as this vessel characteristic is independent on the hull form though dependent on other hull characteristics. For the purpose of hull form optimization the use of KG is useful for both the constraints that may be applied directly to restricting maximum KG or indirectly. Indirectly KG can be used as input to a hydrostatic program for prediction of GZ, as GZ is directly proportional to KG as shown in Figure 5.1. The GZ stability curve is a very useful for indication of the stability characteristics. For this reason the prediction of KG is a required element in the evaluation of stability.

For hull optimization the comparison of different hulls means that the comparison of stability between different hull forms is necessary. Previously the use of a regression based formula for fishing boats was utilized as a constraint for GM. In addition KG was also determined through the use of regression formula (Grubisic, 2001) and applied as a constraint. While these are useful and informative measurements it is also necessary to develop a general stability index, as two vessels with different hull forms may have the same GM and KG since KG is independent of hull form. However different hull form swill have different GZ stability curve characteristics in which one hull may be better than the other.

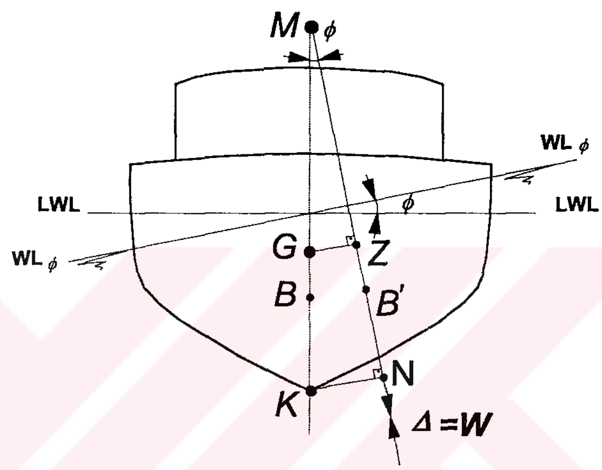


Figure 5.1 Geometric representation of a heeled vessel.

For both fishing boats and other types of vessels for the purpose of comparing different hull forms a stability index is required. Since in the optimization a number of other objectives are being evaluated in addition to stability such as resistance and seakeeping, it is convenient if a single index can be developed for comparing stability rather than using multiple objectives solely in the area of ship stability. Therefore the stability evaluation is more useful in the optimization program if it is a single value for merit rather than a number of disparate values.

Besides developing a stability index that can be useful for different disparate hulls with different displacements, hull forms and different principal dimensions, an additional goal is then to combine stability characteristics into one value. However this does not preclude the use of single characteristics such as a minimum GM as a constraint in the optimization.

For the fishing boat model used in this thesis, the GM requirement was given by Grubisic to be 0.36 metres, whereas we adopt a slightly more conservative GM requirement of 0.40 metres.

Both the regression equation for GM by Grubisic and a NN estimate of KG and GM are used. The KG estimate is used in a hydrostatic program to develop the GZ curve and determine GM.

5.3 Some Basic Stability Concepts

The second moment of area or moment of inertia about the centerline for each half of a vessel can be given by (Rawson and Tupper, 1984);

$$I_T = \frac{1}{3}\int y_1^3 dx \quad (5.1)$$

This becomes useful later in the discussion on stability. The longitudinal and vertical moments of the volume divided by the volumetric displacement can be used to give the center of buoyancy for the displaced volume.

$$LCB = \frac{1}{\nabla}\int A(x) * xdx \quad (5.2)$$

$$VCB = \frac{1}{\nabla}\int Aw(z) * zdz \quad (5.3)$$

Although by no means complete, this brief introduction provides some background on often used parameters describing vessel hull geometry. An important geometrical property of a floating body refers the movement around an axis parallel to the waterplane. The metacenter refers to an imaginary point that can be determined if a body is titled or heeled as known about the waterplane's longitudinal axis. Referring to Figure 5.2, a floating block (for example a square barge) is rotated on an axis while keeping the displacement the same. In this case the wedges for the immersed volume and immersed volume must be the same in order for the volumetric displacement to remain the same. The moments of each wedge and their transfer are equal to the change in moment of the floating body.

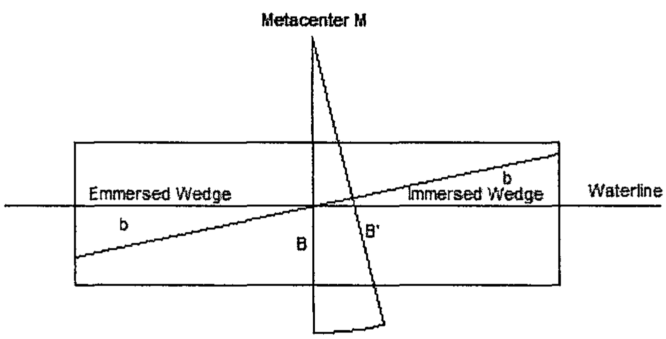


Figure 5.2 Floating Block

If the waterline width is measured in the y axis direction then;

$$Vb = \int y * \frac{1}{2} y\phi \;\; dx \tag{5.4}$$

where *Vb* is the volume of the wedge, ϕ is the angle of rotation.

The moment of the volume is;

$$M_{Vb} = \int (y * \frac{1}{2} y\phi) * \frac{2}{3} \mathrm{y}\, dx \tag{5.5}$$

The transfer of moment is twice the moment of one wedge;

$$Mb{=}2{*}\,M_{Vb} = 2 * \int (y * \frac{1}{2} y\phi) * \frac{2}{3} \mathrm{y}\, dx = \frac{2}{3}\phi \int y^3 dx \tag{5.6}$$

The transfer of moment of the body from B to B1 is

$$M_{Vb} = \nabla * \overline{BB_1} = \nabla * \overline{BM} * \phi \tag{5.7}$$

Actually the sine of ϕ is required but for small angles, or even up 20 degrees the sin is 98.5%.

Equating each moment gives;

$$M_{Vb} = \nabla * \overline{BM} * \phi = \frac{2}{3}\phi \int y^3 dx \tag{5.8}$$

We saw previously that the is moment about one half the waterplane was given by I_T, so that for both halves of the waterplane;

$$M_{Vb} = \nabla * \overline{BM} * \phi = \phi * 2 * \frac{1}{3} \int y^3 dx = \phi * I_T \tag{5.9}$$

Thus we have;

$$\begin{aligned} \nabla * \overline{BM} &= 2 * I_T \\ \overline{BM} &= \frac{I}{\nabla} \end{aligned} \tag{5.10}$$

where *I* is the total second moment of area for both halves of the waterplane.

We now have a reasonably accurate method of obtaining the metacentric height given small angles of inclination. This becomes highly useful in the next section.

5.4 Stability Index Model

In general the slope of the GZ curve that yields GM as shown in Figure 5.3 can characterize the stability. In addition the angle of heel (ϕ_m) corresponding to maximum GZ (GZ_{max}) is an important characteristic as in practice capsizing occurs shortly after this point. Finally, but not exclusively, other stability characteristics are important such as the area under the GZ curve, which indicates the energy in terms of the moment that the vessel can absorb from a disturbing moment of wind and wave. This factor should also be included in the stability index.

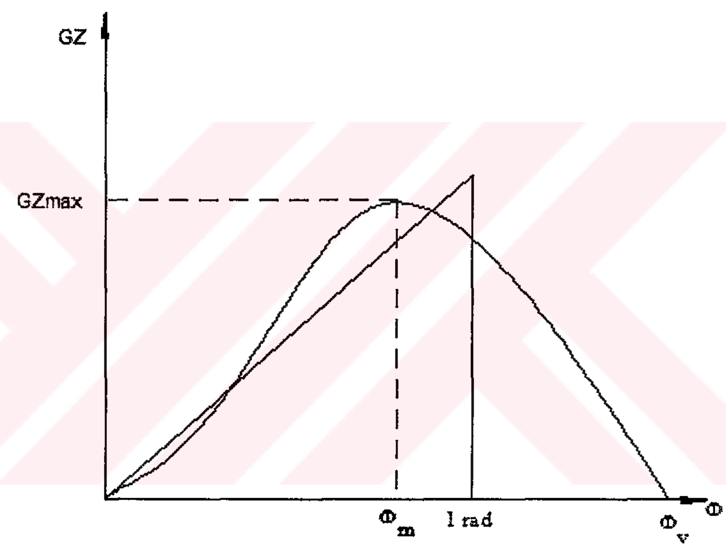


Figure 5.3 Righting Arm Curve

In order to model the stability index, the area under the GZ curve is calculated up to the vanishing angle or a maximum angle of 120 degrees. The area under the curve is then multiplied by ϕ_m corresponding to GZ_{max} in order to combine these two important stability characteristics into one index. This gives one important indication of the stability for the hull. The other characteristic GM is used as a constraint in the hull form optimization model. The Stability Index (STIX) is derived as follows;

$$STIX = \phi_m \int_0^{\varphi_v} GZ(\phi)\,d\phi \qquad (5.11)$$

A typical GZ curve is shown in Figure 5.4. As can be noted, the vanishing angle (ϕ_v) occurs for the fishing boat hull around 60 degrees. Therefore the area under the GZ curve is calculated as mentioned previously up to wherever ϕ_v occurs less than or equal to 120 degrees.

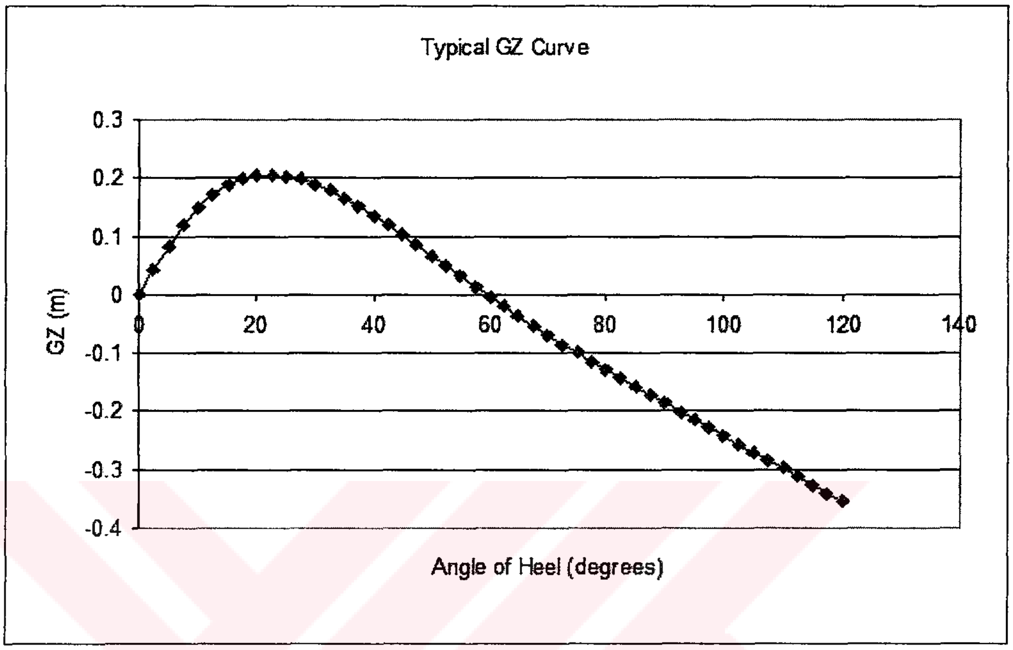


Figure 5.4 Typical GZ Curve

In comparing GM as calculated using hydrostatics from the hull form and that using regression from Grubisic, it can be seen as in Figure 5.5 that due to the minimum KG determined from the NN as used in the hydrostatic program, GM calculated by hydrostatics differs significantly from that predicted by regression.

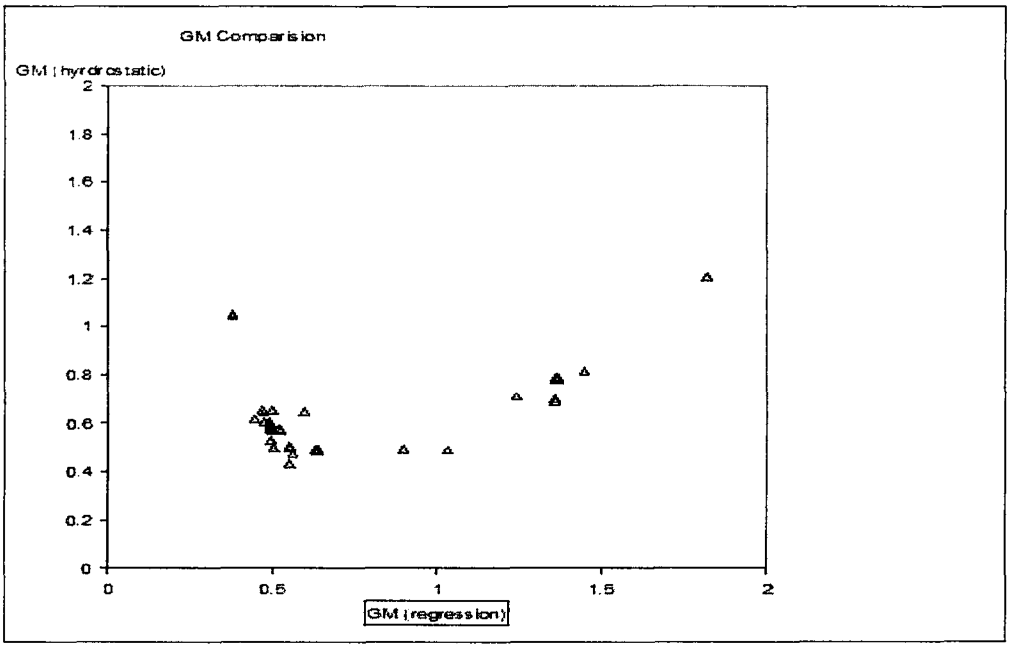


Figure 5.5 Comparison of GM as calculated from Hydrostatics and using Regression

In Figure 5.6 variation of the stability index with GZ_{max} shows that the highest stability does occur with increasing GZ_{max}. However this may not always be the case, as high GZ_{max} may signify a high initial stability, but the GZ curve may have a smaller area under the curve. Also two vessels having the same area may have different ϕ_m. In general the Stability Index also does increase proportionally with the area under the GZ curve although not linearly. Further any given area there will be some difference in the stability index as shown by the variance in the data again as a result of different hull forms yielding the same area under the curve but different ϕ_m. Also for the same maximum righting angle different areas are obtained. An interesting trend indicated that after a maximum of near 45 degrees the area becomes less and thus the stability index would be less.

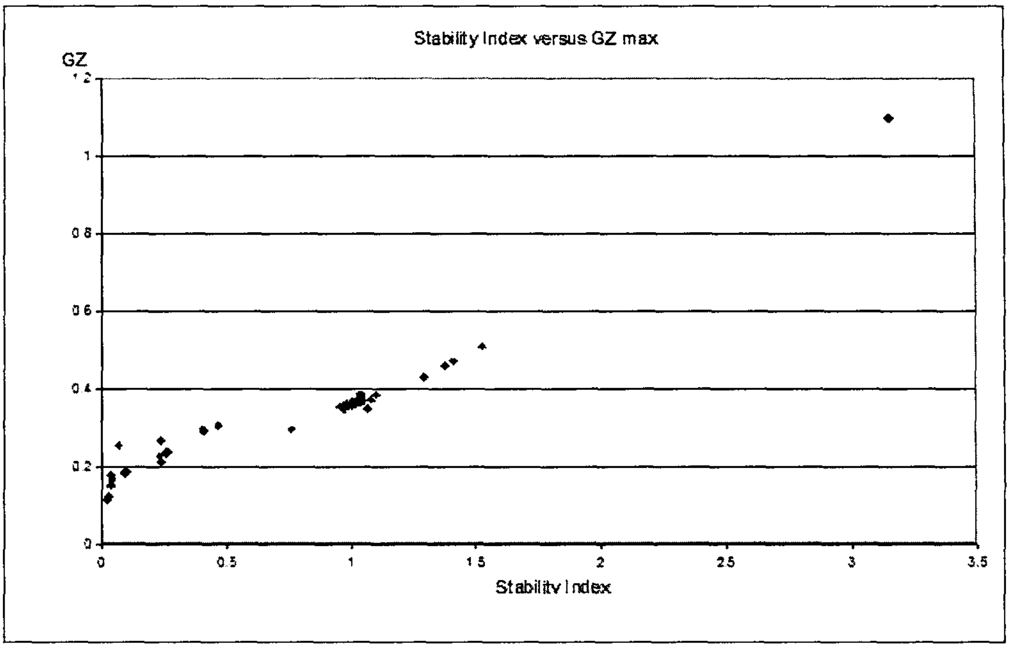


Figure 5.6 Stability Index versus maximum GZ

5.5 Neural Network Estimation of KG

In the estimation of KG previously, reliance on regression formulations provided by Grubisic (2001) for KG was made in the case of a fishing boat. The regression formulation approach is valid for the databases where the formulations are applied and but consideration was given to novel hull forms that may be evaluated during the optimization process. Therefore alternate methodologies are used for the KG estimation.

In Figure 5.7 the results of using an artificial NN are presented. A full description of NN and their application can be found in a number of textbooks (Haykin, 1999) such that a detailed explanation is not required here. The details of the network are that the network is a two hidden layered model with 6 inputs, 7 hidden neuron in the first layer and 6 in the second hidden layer; there is only one output for the KG estimation.

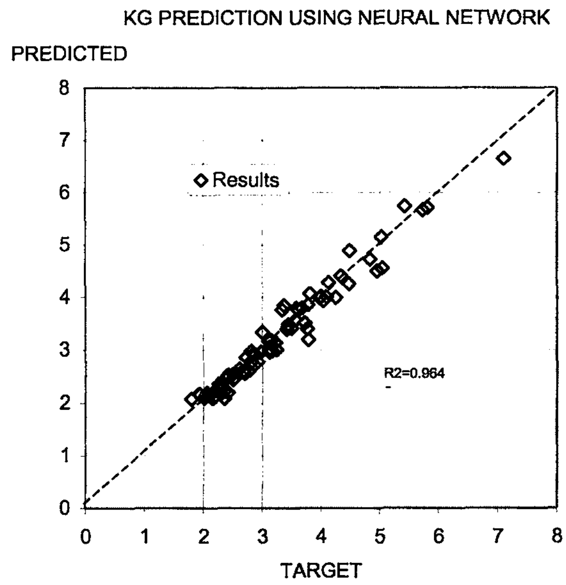


Figure 5.7 KG Analysis using an Artificial NN

For the KG model the database compromise 80 fishing vessels of which the KG is known. The characteristics for these vessels are given in Appendix B with the length, beam, draft, depth, block coefficient, displacement and finally KG. The values are used to train the NN, using 60 samples for training and 20 for testing the accuracy of the network, although all the results are shown in Figure 5.7. As can be seen, the trend in Figure 5.7 gives a correlation coefficient of 0.96

A database comprising a series of fishing boats was compiled from Yilmaz and Kükner (1999). They used the Doust Optimum Trawler series (Doust, 1962) and this database of 1080 vessels was used for the regression formulations. The optimum design range of these fishing vessels is as follows;

$$4.0 \leq L/B \leq 5.8$$
$$2.0 \leq B/T \leq 2.6$$
$$0.582 \leq C_p \leq 0.650$$
$$15 \leq L \leq 70 \text{ (m)}$$

Using this database, Yilmaz and Kukner (1999) were able to derive regression equations that give a correlation coefficient of 0.98. It therefore can be stated that the use of regression equations is of considerable use in the prediction of KG, as well as other characteristics derived by their equations.

A more accurate NN was derived than the simper one used in the previous example. Alkan and Gülez (2003) have conducted and analysis of fishing boat hulls using the same database and found the average error to be around two percent. Nevertheless issues regarding the training, modeling and application of the NN must be considered carefully when conducting this type of analysis. Although the full details are found in the reference, some observations can be made here.

In order to train the network, it was found that a single layer feed-forward network was not sufficient to maintain both generalization and accuracy. If the error between the target values and the calculated outputs squared is minimized by less than 0.0001, the generalization of the network becomes increasingly worse. Therefore following the example of Alkan and Gülez the two hidden layer model was used with better results.

Another issue with respect to the KG analysis by NN or by regression pertains to which regression formulation is utilized. The KG analysis by Grubisic gives a maximum and a minimum KG based on the inputs of maximum and minimum Beam. A comparison of the KG prediction by the NN model and each KG prediction shows the results in Figure 5.8. The NN model is closer to the minimum regression prediction but the minimum is consistently smaller. Using this minimum KG prediction would give more favourable results in the hull optimisation algorithm.

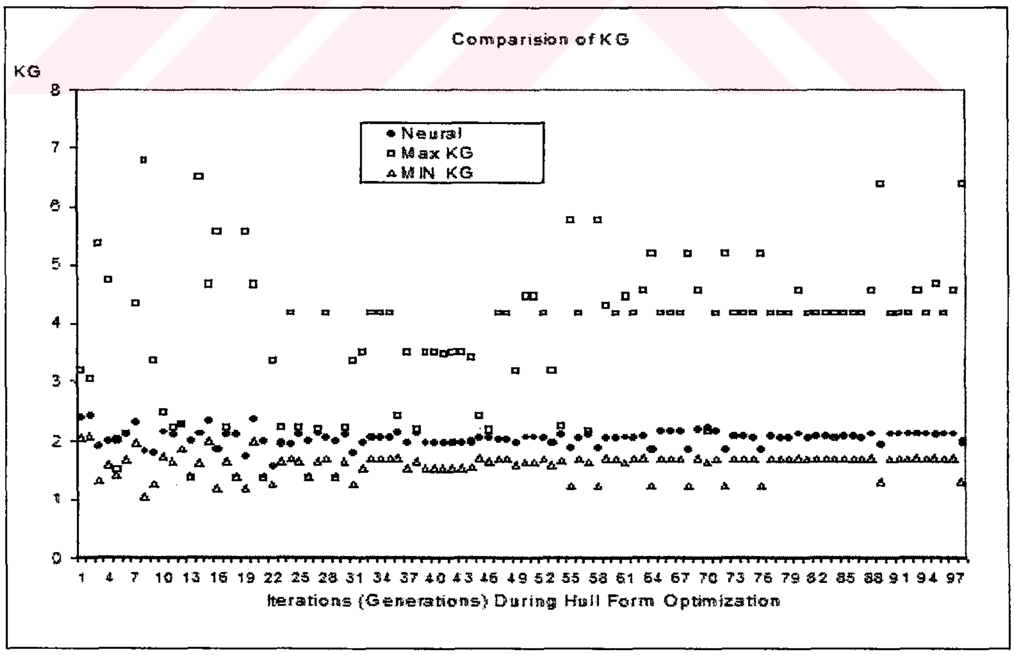


Figure 5.8 Comparison of KG from NN and Regression

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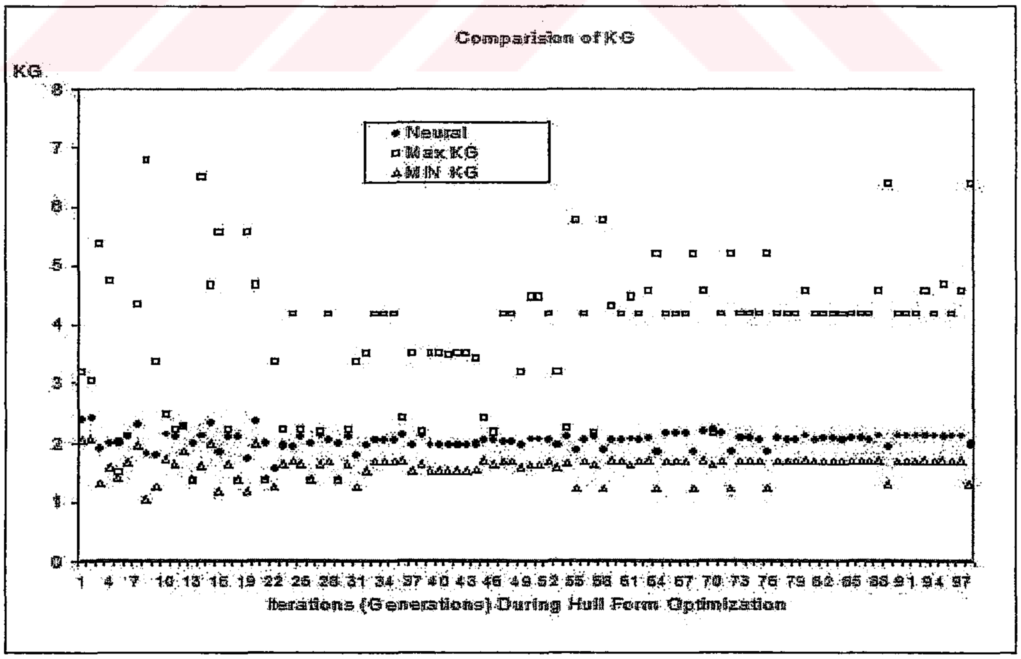

Figure 5.8 Comparison of KG from NN and Regression

5.6 Stability Summary

In trying to find a measure for stability, it is apparent that in order to minimize the number of objectives during the hull form optimization process, it was expedient to develop a measure of stability index. Stability indices are used in other hull design such as in yachts, but the need for a general index was required due to the variability in the problem that could be encountered.

As a result the use of both the GM as a constraint according to regulations and also a GZ curve is utilized. The positive area under the GZ curve up to the vanishing angle gives a good measure of the kinetic energy that can be absorbed by the hull while ϕ_{max} gives a good indication of the angle for which the hull will probably capsize.

Finally it became apparent that the use of the stability index undermines the fact that a single stability characteristic such as the area under the GZ curve or the vanishing angle can be erroneous as these single measurements may be the same for different hulls. As the objective is to compare different hulls then the measurement for stability must have the ability to differentiate between different hulls. Thus the combined stability index provides a fairer assessment for the purpose of evaluating which hulls should be considered as more optimal from a hull optimization perspective.

6. SHIP RESISTANCE EVALUATION

6.1 Ship Resistance For Hull Form Optimization

For the hull form optimisation, there are number of evaluation factors for the design which should be included. These are the hull hydrostatic stability performance, and hydrodynamic performance based on resistance and seakeeping. In this section the resistance evaluation is discussed. The resistance evaluation is used as an objective function in which the object is to minimize total resistance. In order to do so, a calculation of the resistance must be made that includes the hull form, as one of the purposes of optimizing the hull is to generate an optimal hull that combines best or near optimal characteristics including resistance.

The Coefficient of (Total) Resistance C_T or resistance component (Rawson and Tupper, 1984) is a non-dimensional form of the resistance that is assumed to be composed of the frictional resistance coefficient C_F and the wave making resistance coefficient C_W. The non-dimensional form is used so that the resistance from models used in the tow tank can be scaled up to full size. Further, non-dimensional numbers such as the Froude number and the Reynolds number are key elements from fluid dimensional analysis (Shames, 1982). The non-dimensional form of the total resistance R_T (N) is a function of the ship speed V (m/s) and wetted surface area S (m^2) of the ship,

$$C_T = \frac{R_T}{\frac{1}{2}\rho V^2 S} \tag{6.1}$$

where ρ = specific mass of water in kg/m^3

Ship resistance is made up of numerous other components including appendage resistance, air and wave breaking resistance. How these components are derived is based on some observations that, in general, resistance can be composed of both frictional resistance due to viscous forces tangential to the hull of the ship, and wave making forces in which energy is essentially taken from the ship to generate waves. Froude's hypothesis states that the resistance components are independent of each other.

However this is not strictly true. While wave resistance is more a function of the hull form this is not equal to the residuary resistance found by model testing. Wave resistance lends itself well to an analytical analysis of the hull shape based on potential flow theory, which will be discussed later. But viscous resistance is harder to quantify, as it is based on numerous factors including the shape, and speed of the flow over the hull surface which is a predominant factor in the type of flow, whether laminar or turbulent.

In practice, most ship's experience turbulent flow, but some analysis suggests that the turbulent flow is close to the ship hull, and increases in thickness with the length as in the observations made with the flow over a flat plate. Therefore the use of an equivalent skin friction formula is used to calculate the frictional resistance. The International Towing Tank Conference (ITTC) uses a frictional resistance formula based on the Reynolds number. The ITTC 1957 frictional line is quite simple to calculate as follows;

$$C_F = \frac{0.075}{(\log(\mathrm{Rn}) - 2)^2} \tag{6.2}$$

Taking the velocity V and the length of the ship L as the physical parameters for a ship give the Reynolds number R_n;

$$R_n = \frac{\rho VL}{\mu} = VL/\nu \tag{6.3}$$

where ρ = mass density
μ = viscosity
ν = kinematic viscosity

The viscous resistance is taken as (1+k) times the frictional resistance. The form factor k or k_1 (from Holtrop) is determined from the model test and is assumed independent of speed and scale. That is to say, the form factor can be obtained from observations in tow tanks test for a given, specific hull form. For example in the ITU fishing hull forms the tow tank test for the parent form of the ITU series, ITU 148/1-B, showed a form factor of 0.25 whose tests were done with 5 models with different scales (Kafali *et al*, 1979). This means the form is blunt enough as a fishing trawler form to add 25% to the frictional flat plate line as given by the Reynolds number.

The same form factor is then assumed for the full-scale ship. Larger ships with a higher L/B ratio may have a reduced form factor if the bluntness of the form is lower, of perhaps 10% or even less if the form is considered slim, such as may be the case of a long, slim catamaran hull. A blunt shaped tanker would have a higher form factor.

As can be seen, the analysis of total resistance begins to introduce factors that mean Froude's hypothesis cannot be strictly applied. In fact the separation of the resistance into components in reality is a little difficult. Interaction between the viscous and pressure components occurs, and transom stern resistance and bow wave breaking resistance are two obvious examples where the viscous and pressure components meet.

Holtrop and Mennen have numerous other regression-based formulas relating to overall resistance prediction. In their resistance equation the components are composed of the frictional resistance R_F including the form factor, and appendage resistance R_{APP}, the wave-making and wave breaking resistance R_W, the additional pressure resistance form the bulbous bow R_B, the additional pressure resistance of and immersed transom stern R_{TR}, and finally the model-ship correlation resistance R_A.

For the formulation here appendage resistance and the bulbous bow are not considered, expert in the form given previously. The use of various resistance estimators for the appendages such as bow thrusters and is not included in the formulation in this thesis as the hull is considered to be a bare hull.

The transom resistance is included in the formulation for the wave resistance. However the form factor must still be considered due to the significant influence on the friction correlation as previously described. Holtrop and Mennen give the following formulation for the form factor k_1;

$$1+k_1 = c_{13}\left\{0.93 + c_{12}\left(\frac{B}{L_R}\right)^{0.92497}(0.95-C_P)^{-0.521448}(1-C_P+0.0225\times LCB)^{0.6906}\right\} \qquad (6.4)$$

where C_P = prismatic coefficient
LCB = longitudinal centre of buoyancy

The length of the run L_R is a factor rather than a geometric parameter based on the following formulation;

$$L_R/L = 1 - C_P + \frac{0.06C_P LCB}{4C_P - 1} \qquad (6.5)$$

The factor c_{12} is related to the draft length ratio T/L and is given as

$$c_{12} = \left(\frac{T}{L}\right)^{0.2228446} \qquad \text{when } T/L > 0.05 \qquad (6.6a)$$

$$c_{12} = 48.20(T/L - 0.02)^{2.078} + 0.479948 \quad \text{when } 0.02 < T/L < 0.05 \tag{6.6b}$$

$$c_{12} = 0.479948 \quad \text{when } T/L < 0.02 \tag{6.6c}$$

The factor c_{13} relates to the specific shape of the afterbody and is given as a function of the stern coefficient C_{stern};

$$c_{13} = 1 + 0.003\, C_{stern} \tag{6.7}$$

The coefficient C_{stern} is given by some tentative guidelines, which are unfortunately not included fully in the text. However the number can be greater than +10 for a Hogner type stern with U shaped sections in the afterbody.

A possibly formulation that can be used if the previous afterbody coefficients are unknown is the Gross-Watanabe (1972) formulation for the form factor given by;

$$k = 23 \frac{C_B}{\left(\frac{L}{B}\right)^2 \sqrt{\frac{B}{T}}} \tag{6.8}$$

An assumed factor called the correlation allowance or roughness allowance helps to make the difference between calculated or measured wave making resistance and observed residuary resistance from the tow tank correspond better for scaling from model to ship. This correlation allowance is or roughness allowance accounts for the additional roughness of a real, ship, air resistance and other vagaries. It is added to the frictional and wave resistance components as follows;

$$C_T = C_F + C_W + c_a \tag{6.9}$$

The correlation allowance (c_a) is assumed to be approximately 0.0004. However this also cannot be guaranteed as it refers to ships of about 170 metres, whereas in this thesis we consider all hull forms, from fishing boats to kayaks. Nevertheless, without further data or analysis this amount can be used. An alternative is to use the Kuiper (1997) version of the formula given by Holtrop and Mennen (1982) as a fraction of the waterline length L_{WL} of the ship as follows;

$$c_a = 0.006(L_{WL} + 100)^{-0.16} - 0.00205 + C_{bulb} \tag{6.10}$$

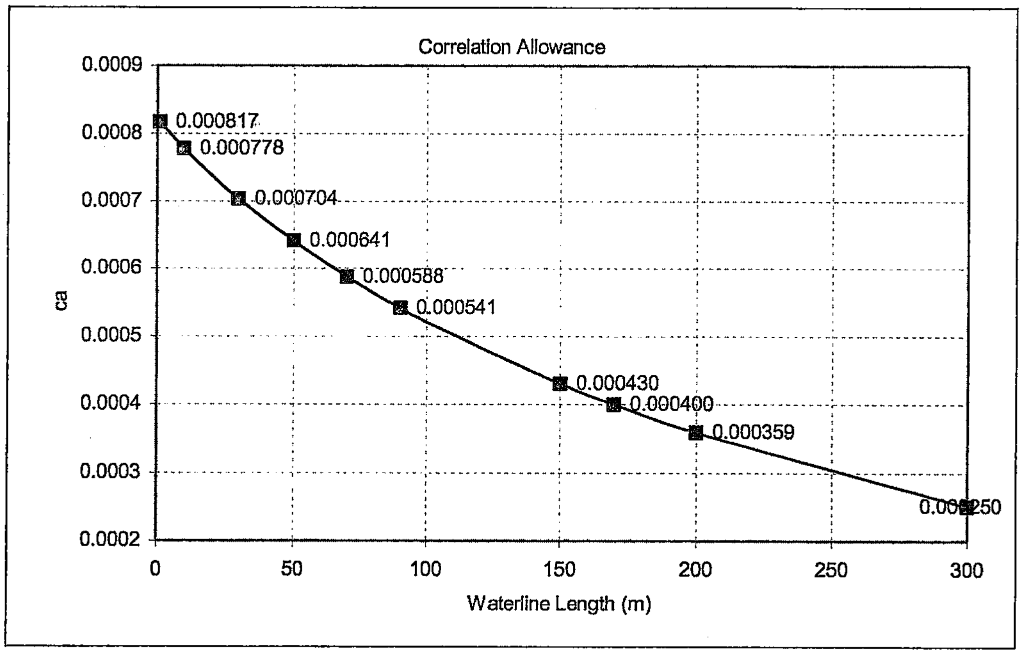

Figure 6.1 Correlation Allowance c_a as a function of Waterline Length with C_{bulb}=0.

Holtrop and Mennen have an additional factor defined here as C_{bulb} in (6.3) related to the moulded draught at the forward perpendicular T_F and the length. C_{bulb} is set to zero if T_F/L is greater than 0.04, but if this ratio is less than 0.04 then the additional term is;

$$C_{bulb} = 0.003\sqrt{L/7.5}C_b{}^4 c_2(0.04 - T_F / L) \tag{6.11}$$

where C_b = block coefficient, and

$$c_2 = \exp(-1.89\sqrt{c_3})$$

This latter factor relates to the influence of the bulbous bow on wave resistance. The coefficient C3 that determines this influence is defines as;

$$c_3 = \frac{0.56 A_{BT}{}^{1.5}}{BT(0.31\sqrt{A_{BT}} + T_F - h_B} \tag{6.12}$$

where A_{BT} = transverse bulb area
h_B = centre of bulb above keel line
B = moulded breadth
T = average moulded draught

A possibly simpler formula (Rawson and Tupper, 1983) for a roughness allowance is based on a factor for the actual roughness on the ship;

$$\Delta C_F = \left[105\left(\frac{k_s}{L}\right)^{1/3} - 0.64\right] \times 10^{-3} \tag{6.13}$$

where ΔC_F = roughness allowance
k_s = roughness of hull = 150×10^{-6}
L = Length of waterline

As can be seen from the previous formulations, the influence of various factors in the overall resistance prediction becomes a little difficult to quantify given different hull forms. Therefore the point in this study is to use more analytical methods rather than regression based formulas. However some regression based formulas such as the form factor and roughness allowance can still be used if no other information is available.

If information is available, then the use of regression-based formulas can perhaps be supplanted by the use of either regression formulas based on the available information, or alternatively the use of a NN to model the various coefficients. It is not expected that the roughness/correlation allowance will change, as the information is usually unavailable.

6.2 Formulation of a Resistance Index

While the resistance is now defined as a non-dimensional total resistance coefficient C_T, the resistance index must be formulated. The need for a resistance index stems from the observation by Day and Doctors (1997) that a small change in speed may demand and entirely different optimal hull form.

Day and Doctors made a number of simplifications in their study. First the form factor was set to unity. They state that little information would allow plausible prediction of the form factor for the wide range of ship hull being considered. They also included a correlation allowance of 0.0004 that was thought to be rather high for the high-speed aluminium ships being considered, as these are normally kept very clean. They maintain this factor as the frictional resistance is shown to be a large proportion of the overall resistance for these ships.

From a previous study using a single speed objective Day and Doctors (1997) showed unusual shapes resulted from using one speed. Therefore they used a minimum of the average value of three speeds, in which the lowest was 90 percent of the centrals speed, and the maximum was given as 110 percent of the central speed. For their study they varied the central speeds from 5 m/s to 25 m/s to examine different series.

In this thesis a resistance index is defined that covers any number of a range of speeds. While similar to using an average, in fact the area under the resistance curve is calculated and this is used as a resistance index. The resistance index is not actually a measure of work or energy but is useful as a performance measurement to compare and rank different resistance curves.

According to the number of Froude numbers tested, a resistance index (RCI) is then defined equal to C_T for a single Froude number or for a given number of speeds N using the trapezoidal rule;

$$RCI = \sum_{i=1}^{N-1} \frac{1}{2} * \left(C_T(i)) + C_T(i+1)\right) * \left(Fn(i+1) - Fn(i)\right) \tag{6.14}$$

where N = Number of Froude Numbers
$C_T(i)$ = Resistance coefficient at speed i
$Fn(i)$ = Froude number at speed i

If a resistance/speed curve were used for power, the integration represents the energy. Minimizing the RCI is in effect minimizing the energy requirements for the vessel as the objective. If a more detailed mission analysis is available the curve and RCI could be modified to reflect time spent at different speeds. The main element in the RCI is to measure the wave-making resistance as calculated from the hull form to the degree required for ranking different candidates. As different methods can be used to calculate the wave making resistance, the choice of which methodology to use for calculating the wave making resistance must be determined.

6.3 Choosing the Methodology for Resistance Evaluation

The focus in this thesis is the optimization of the hull form during the concept or initial design stages. Normally the method used for the resistance evaluation at this stage is regression-based equations derived from a database of previous designs. One of the thesis objectives is to introduce hydrodynamic analysis at this stage of the design rather than later in the design process. But the choice of what level of analysis to use must still be determined.

The methodology for conducting *local* optimization of a hull form is to minimize wave resistance and combined with frictional resistance, minimize the total resistance. Extensive use of Michell 'Thin Ship' Theory for calculating wave resistance based on potential flow theory has been used for conducting hull form optimization by Hsiung (1981), and using the same technique, by Goren and Calisal (1997). Despite the limitations of thin ship theory and the development of 3-D potential theories, the studies were effective for conducting hull form optimization. The study conducted on the optimization of fishing boat hull used thin ship theory to reconfigure the bow half of a fishing vessel. The hull forms known as the UBC series had previously known resistance characteristics that were then modified and showed improved resistance.

However the use of a 3-D potential flow theory for conducting local optimization of the hull form is the preferred area of research. Danışman, et al (2001) have conducted a study in the area of optimization of ship hull forms using Dawson panel method. If we define local and global optimization of the hull form, these studies would be considered as local optimization of the hull forms for which the offsets are modified to some degree but the principal parameters of the hull have already been determined.

Hydrodynamic analysis is not usually conducted for *global* optimization of the hull form. This form of optimization searches for the principal dimensions of the vessel, and the choice of a particular hull form, typically from a series of different candidates, is made at the concept stage that is used for subsequent development. Once the hull form has been determined, subsequent analysis is normally conducted as advanced engineering analysis to determine the best hull shape for local optimization, by determination of small changes in the hull offsets, bow form, bow bulbs, and stern shape.

An excellent treatise on the solution of the nonlinear ship wave resistance problem examining 3-D panel resistance methods was conducted by Raven (1990). The recent studies for local optimization of hull forms using 3-D panel methods by Dejhalla et al. (2001 and 2003) as well as Yasukawa (2000) have been conducted using GA optimization techniques to minimize the wave resistance. For these studies, GA in conjunction with 3-D methods was successfully utilized to modify the hull forms. The range that the offsets are modified from the original using the Series 60 or container ship hulls are between 90 and 110 percent of the original. These studies have demonstrated the significant merit of using GA techniques to minimize the wave resistance for hulls in which the principal characteristics are known.

However these analyses are also shown to be computationally intensive and therefore less feasible for concept ship design where the principal parameters are still being determined. The required population using GA is in the same order as the size of the binary string for the chromosome, which could be anywhere, from 10 to 100. A typical GA may run for 1000 generations. In the 3-D panel method computation, only 100 generations are use, with a limited population. The local optimization of the hull form as analyzed by Yasukawa was reported to take 48 hours on a Dec alpha workstation in order to compute an optimal hull form based on resistance. A typical ship problem will take 48 hours according to Yasukawa on a DEC Alpha workstation.

In the concept ship design problem, the problem becomes more difficult as the issue is not just the optimization of resistance but other attributes as well. In this research, analysis is conducted of the resistance, stability and seakeeping. In order to include the analysis of these attributes as well, thin ship theory is used for the resistance evaluation as it is comparatively quick to calculate and therefore more suitable to repeated iterations as used in the GA methodology. Future research may use 3-D methods.

6.4 Ship Resistance Evaluation using Potential Flow Theory

In the optimisation methodology the evaluation of hull resistance is calculated using a thin ship program first introduced by Gammon (1990) to accommodate a transom. Crouser et al (1998) used this methodology after it was promulgated at a towing tank conference. Gammon and Alkan (2001) applied this transom methodology to a series of fishing boats. Fishing boats often have a significant transom that combined with a low L/B ratio means that the potential calculated with thin ship theory alone is no longer valid. The potential using Michel thin-ship theory is determined using the longitudinal slope of the hull, which is valid over most of the hull but is inappropriate at the stern, since the slope becomes infinite. For this the use of a fundamental theorem of potential flow theory was utilized and a potential was derived for the transom.

At the time that the idea was first tested by Gammon in 1990, some improvement in analytical results by the transom model was observed for ship hull forms, but the difference was not significant in all cases though the method introduced was analytically correct. However as observed by Gammon and Alkan, when the L/B is reduced from 7 to1 as in the transom stern ship ATHENA to fishing hull forms with an L/B of 3 to1, the effect becomes more significant. From this study, the results show the effect of not incorporating the transom, and with the transom compared to residuary test results. In this case the transom model is significantly closer to residuary test results.

For the current problem the evaluation of the wave resistance is conducted using thin ship theory. However in order to accommodate hull forms with transoms, the modification of the theory is necessary. Thin ship theory is based on the assumption that the hull is long with respect to the beam, hence a perturbation in the beam of the ship can result in a linear solution of the source sink strength, making use of Green's function as the integral. For the source strength, the hull boundary condition provides the necessary strength function as it is related to the slope of the hull in the longitudinal direction.

However, at the transom, the slope of the hull length-wise becomes infinity, and therefore cannot be utilized. Another method of assessment is required and much research has gone into modeling of the stern flow, mainly through either empirical techniques or through intensive computational fluid dynamic analysis with very well formed discretization schemes of both the hull and the free surface around the transom.

In our case, we use a necessary requirement from potential flow theory to account for the transom effect. This was originally tested on ships (Gammon, 1990) but the effect was found to be marginal though encouraging. However, a recent application of Michell theory to low L/B ratio vessels in the form of fishing boats, and fishing boats having transoms, has seen a more pronounced effect, given that the transom is now a more significant part of the hull.

With this modification for the transom, thin ship theory can be applied to all manner of ship hull form types in the assessment of wave resistance. This still does not preclude the use of more advanced resistance calculations in the form of 3-D potential flow models especially for local optimization, but provides a significant advantage in reducing the computational time during the optimization process for conducting global optimization. However, some alternate methodologies may be considered and is discussed in the topics for future work.

6.5 Thin Ship Wave Resistance Formulation

The determination of the resistance by calculation of the wave resistance component is described next. A fuller description of the model and the previous development can be found in Gammon (1990). The method was promulgated at the 1990 Towing Tank conference and then formalized further by Crouser et al (1998). The flow is assumed to be an inviscid, incompressible, unbounded fluid with a free surface. For an irrotational flow there exists a perturbation potential that satisfies Laplace's equation:

$$\nabla^2 \phi(x, y, z) = 0 \tag{6.15}$$

The body-fixed co-ordinate system for the problem is shown in Figure 6.2.

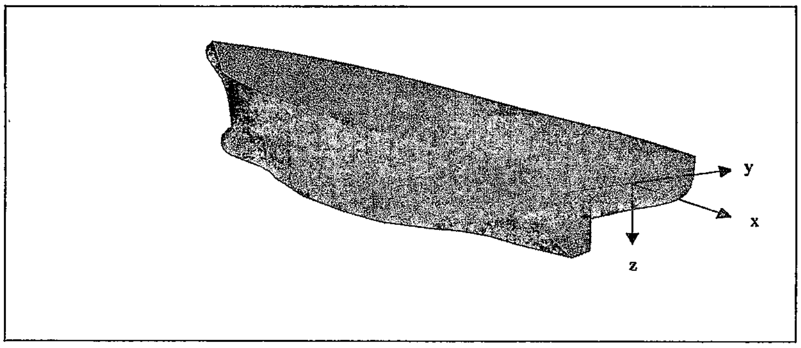

Figure 6.2 Co-ordinate System for Vessel Hull

The following parameters are used;

-c	=	Steady advancing velocity
B	=	Beam
L	=	Length of vessel
T	=	Draft
D_t	=	Average depth at the transom
B_t	=	Average breadth of the transom
S	=	Ship surface

The boundary conditions for the problem are described next.

Kinematic Boundary Condition on the Free Surface

The free surface S_f is described by $z = F(x,y)$. The normal velocity of the fluid at the free surface must equal the normal velocity of the surface itself $\phi_n = V \times n$, that is the substantial derivative of $z-F(x,y) = 0$ or vanishes on the free surface (Michell, 1898)

$$\phi_z + F_x(c - \phi_x) - \phi_y F_x = 0 \quad \text{on } z = F(x,y) \qquad (6.16)$$

Dynamic Boundary Condition on the Free Surface

From Bernoulli's Equation, assuming a pressure at the free surface equal to the ambient pressure, and a steady flow, one obtains:

$$F(x,y) - \frac{c\phi_x}{g} + \frac{1}{2g}(\phi_x^2 + \phi_y^2 + \phi_z^2) = 0 \text{ on } z = F(x,y) \qquad (6.17)$$

Kinematic Condition on the Ship Hull

Given the ship surface S described by $y = \pm f(x,z)$, the normal velocity of the fluid must equal the normal hull velocity hence;

$$\phi_y \pm f_x(c \mp \phi_x) - \phi_z f_z = 0 \text{ on } y = \mp f(x,z) \tag{6.18}$$

Radiation Condition

To ensure further that the waves propagate behind the ship we specify (Wehausen, J.V., 1973):

$$\phi(x,y,z) = O(\sqrt{x^2+y^2}) \quad \text{as } x^2+y^2 \to \infty \quad \text{for } x < 0$$

$$\phi(x,y,z) = O(1) \text{ as } x^2+y^2 \to \infty \quad \text{for } x < 0 \tag{6.19a}$$

or that there is no disturbance far ahead,

$$\lim_{x \to -\infty} (\phi_x^2 + \phi_y^2 + \phi_z^2)R = 0 \tag{6.19b}$$

where $R = \sqrt{x^2+y^2}$

In order to solve for (6.15) with the conditions given by (6.16-6.19), we first perturb the potential and therefore express it as the perturbation potential as follows;

$$\phi = \varepsilon\phi_1 + \varepsilon^2\phi_2 + \ldots \text{ where } \varepsilon = \frac{B}{L} \tag{6.20}$$

As a result, the Laplace Equation and the free surface boundary condition combined from the dynamic and Kinematic boundary conditions become linear. The Havelock moving source or the Green function G for the first order boundary value problem is used to obtain the potential;

$$\phi = \iint_{So} \sigma \; G \, ds \tag{6.21}$$

where $\sigma = \dfrac{-c}{2\pi} f_x(x,z)$ is the source strength in which $f_x(x,z)$ is the slope over the hull.

The Michell integral can be derived whereby the resistance is modeled by a continuous distribution of sources and sinks moving in deep water (Lunde, J.K., 1952):

$$R_w = 16\pi \rho \; k_o^2 \int_0^{\pi/2} [P(\theta)^2 + Q(\theta)^2] \sec^3\theta \; d\theta \tag{6.22}$$

$$\text{where} \begin{Bmatrix} P(\theta) \\ Q(\theta) \end{Bmatrix} = \iint_S \sigma \exp(k_o z \sec^2\theta) \begin{Bmatrix} \sin \\ \cos \end{Bmatrix} (k_o x \sec\theta + k_o y \tan\theta \sec\theta) dS \tag{6.23}$$

and $k_o = \dfrac{g}{c^2}$

The immersed body must be a closed form to satisfy the potential flow. This leads to a problem when a transom is encountered. The slope of the hull at the transom becomes infinite, and therefore the form of the source strength across the transom is unknown.

A method of dealing with the latter problem was proposed by Gammon (1990). First, the integration from equation (6.23) is separated into two parts; integrating over the hull using the centre-plane S_c and integrating over the transom S_t;

$$\begin{Bmatrix} P(\theta) \\ Q(\theta) \end{Bmatrix} = \iint_{Sc} \sigma_c \exp(k_o z \sec^2\theta) \begin{Bmatrix} \sin \\ \cos \end{Bmatrix} (k_o x \sec\theta + k_o y \tan\theta \sec\theta) dS_c + \iint_{St} \sigma_t \exp(k_o z \sec^2\theta) \begin{Bmatrix} \sin \\ \cos \end{Bmatrix} (k_o x \sec\theta + k_o y \tan\theta \sec\theta) dS_t = \begin{Bmatrix} P_c(\theta) + P_t(\theta) \\ Q_c(\theta) + Q_t(\theta) \end{Bmatrix} \tag{6.24}$$

Now that the integral is separate, the x term can be evaluated separately. If the original coordinate system is used the Q_t term disappears and the P_t term is reduced to unity.

The next problem is to determine what the source strength should be over the transom. For this purpose it was proposed that the fundamental condition for potential flow of a closed body be utilized. In order for a body to be closed, a necessary condition is that integration of the source strengths over the body surface must be zero, which can be interpreted as the condition where there is no flow in or out of the body. Otherwise we can presume the body is open, and there is flow through the vessel. This is expressed as;

$$\iint_S \sigma(x, y, z) dS = 0 \tag{6.25}$$

Using the source strength over the centreplane of the body the result is that the integration of the transom source strength plus the integration of the source strengths over centreplane must add up to zero. Hence the integration of the transom source strength makes up the remainder after integrating over the centreplane;

$$\iint_{St} \sigma_t(x_o, y, z) dS_t = \frac{c}{2\pi} \iint_{Sc} f_x(x, z) dS_c \qquad (6.26)$$

Since an infinite number of transom plane distributions exist, some assumption regarding the source strength distribution to be integrated must be made. The source strength is assumed to have an average density over the breadth of the transom at each depth. In this manner the integration at each respective waterlines corresponds to the source strength integration at each depth of the transom.

6.6 Istanbul Technical University (ITU) Fishing Vessel Wave Resistance

The results that follow are comparisons made with some of the ITU series of fishing vessels from the Istanbul Technical University tow tank by Kafali et al (1979). These residuary resistances from different fishing boats are compared to calculations made with the preceding theory, both with and without the transom formulation. The hydrostatic characteristics of the various hulls are given in Table 6.1 and the body plan of the parent vessel is shown in Figure 6.3 that will be referred to as ITU-148/1-B.

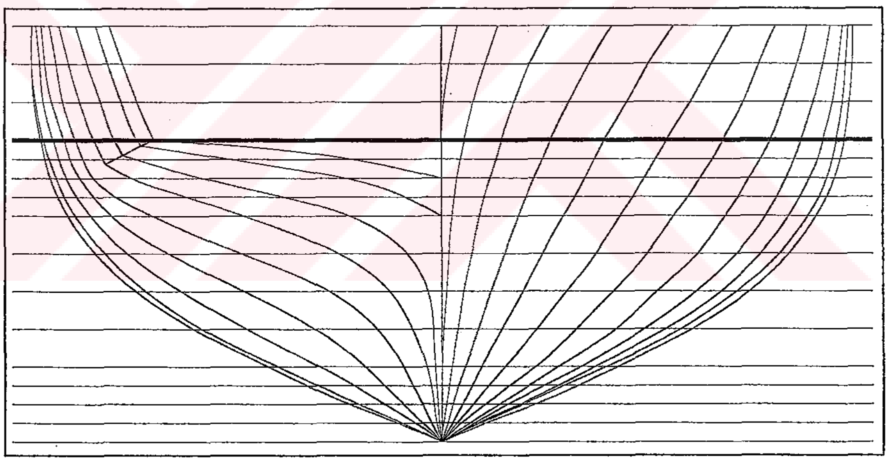

Figure 6.3 Parent Vessel Body Plan for ITU Fishing Vessel Family, 148/1-B.

Table 6.1 ITU Series Hydrostatic Characteristics

Vessel and Loading Condition	*LWL* (m)	*B* (m)	*T* (m)	*D* (m)	*CB*	*CP*	*CWP*	*V* (m^3)	*Δ* (kN)	*xCB* (m)	*B/T*	*L/B*	*L/Δ1/3*
1	18.50	5.24	1.714	3.22	0.342	0.562	0.651	56.83	572	0.43	3.05	3.53	4.81
148/1-B 2	20.00	5.71	2.286	3.22	0.378	0.572	0.73	98.68	995	0.83	2.50	3.50	4.32
3	20.34	5.84	2.858	3.22	0.441	0.619	0.753	149.71	1506	1.18	2.04	3.48	3.38
1	18.50	5.71	1.714	3.22	0.510	0.595	0.693	92.34	930	-0.32	3.33	3.28	4.09
148/2-B 2	20.00	5.71	2.286	3.22	0.535	0.599	0.789	139.67	1406	0.01	2.50	3.50	3.85
3	20.34	5.71	2.858	3.22	0.581	0.635	0.836	192.85	1937	0.25	2.00	3.55	3.52
1	18.50	5.44	1.714	3.29	0.355	0.591	0.659	61.24	616	0.38	3.17	3.40	4.69
148/3-B 2	20.00	5.71	2.286	3.29	0.406	0.607	0.727	105.99	1068	0.8	2.50	3.50	4.22
3	20.34	5.84	2.858	3.29	0.457	0.627	0.747	155.15	1560	1.09	2.04	3.40	3.79
1	18.50	5.71	1.714	3.25	0.460	0.54	0.655	83.29	838	-0.34	3.33	3.23	4.24
148/4-B 2	20.00	5.71	2.286	3.25	0.497	0.559	0.789	129.75	1306	0.02	2.50	3.50	3.95
3	20.34	5.71	2.858	3.25	0.564	0.619	0.836	187.21	1885	0.28	2.00	3.55	3.55
1	18.50	5.52	1.714	3.34	0.411	0.625	0.688	71.94	723	0.37	3.22	3.35	4.48
148/5-B 2	20.00	5.71	2.286	3.34	0.444	0.616	0.745	115.91	1166	0.63	2.50	3.50	4.10
3	20.34	5.84	2.858	3.34	0.494	0.688	0.753	167.71	1686	0.91	2.04	3.48	3.69
1	21.28	5.44	1.714	3.29	0.352	0.586	0.655	69.84	703	0.43	3.17	3.91	5.16
148/6-B 2	22.86	5.71	2.286	3.29	0.400	0.598	0.727	119.36	1202	0.91	2.50	4.00	4.64
3	23.19	5.84	2.858	3.29	0.455	0.625	0.749	176.11	1772	1.25	2.04	3.97	4.14
1	21.28	5.71	1.714	3.25	0.454	0.533	0.651	94.55	951	-0.39	3.33	3.72	4.67
148/7-B 2	22.86	5.71	2.286	3.25	0.491	0.553	0.789	146.51	1474	0.02	2.50	4.00	4.34
3	23.19	5.71	2.858	3.25	0.549	0.602	0.838	207.76	2092	0.32	2.00	4.05	4.14
1	27.06	5.44	1.714	3.29	0.351	0.585	0.644	88.56	890	0.54	3.17	4.97	6.07
148/8-B 2	28.57	5.71	2.286	3.29	0.404	0.604	0.727	150.66	1517	1.14	2.50	5.00	5.37
3	28.89	5.84	2.858	3.29	0.458	0.629	0.751	220.85	2223	1.56	2.04	4.94	3.91
1	27.06	5.71	1.714	3.25	0.449	0.527	0.64	118.91	1197	-0.48	3.33	4.73	5.50
148/9-B 2	28.57	5.71	2.286	3.25	0.493	0.555	0.789	183.85	1851	0.03	2.50	5.00	5.02
3	28.89	5.71	2.858	3.25	0.559	0.613	0.84	263.55	2651	0.4	2.00	5.05	4.78
1	18.48	5.46	1.714	3.30	0.357	0.563	0.652	61.74	621	0.41	3.18	3.38	4.67
148/3-K 2	20.00	5.71	2.286	3.30	0.401	0.574	0.68	104.69	1031	0.66	2.49	3.50	4.27
3	20.61	5.82	2.858	3.30	0.436	0.583	0.709	149.47	1503	0.89	2.03	3.54	3.88
1	18.45	5.71	1.714	3.22	0.465	0.543	0.694	83.96	849	-0.18	3.33	3.23	4.21
148/4-K 2	20.00	5.71	2.286	3.22	0.498	0.557	0.748	130.01	1308	-0.02	2.50	3.50	3.95
3	20.58	5.71	2.858	3.22	0.540	0.59	0.803	181.36	1826	0.17	2.00	3.6	3.63

Figure 6.4 shows the results for the ITU 148/1-B fishing boat model. The light draft loading condition (LC1) is shown. The thin-ship curve corresponds to the use of thin-ship theory without the transom modification. The Transom curve includes the effect of the transom. The Experimental curve indicates the residuary resistance results. Of interest is the reduction in resistance predicted when using the transom modified thin-ship theory. The effect is considerably noticeable at higher Froude numbers.

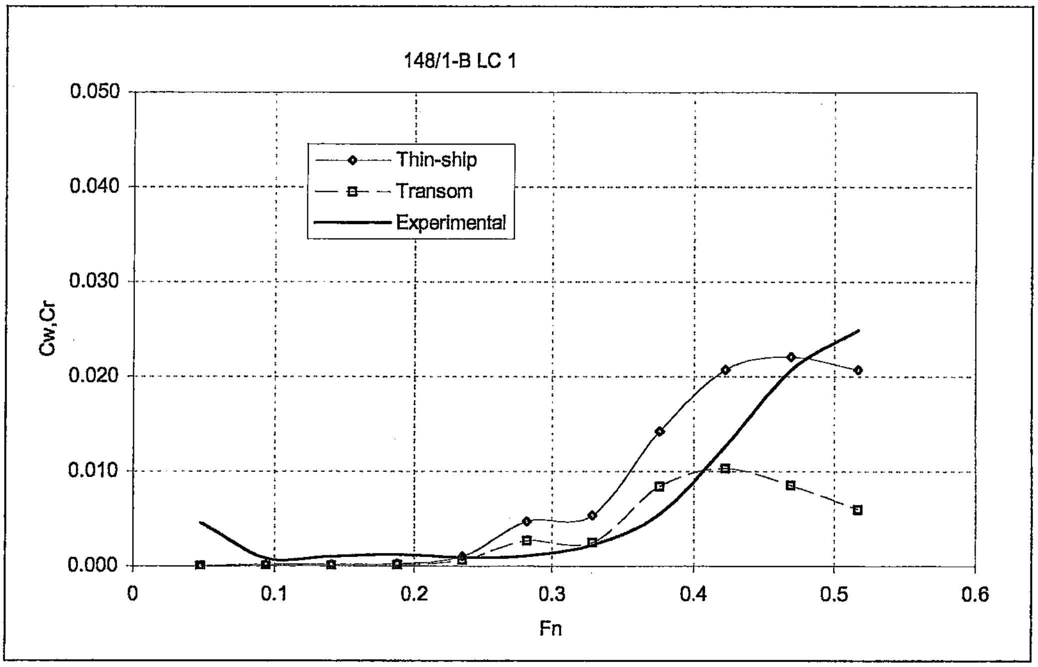

Figure 6.4 ITU 148/1-B Loadcase 1 Comparison of Wave and Residuary Resistance.

It would appear from Figure 6.4 that the effect of the transom effect is considerable for vessels with a low L/B ratio. At the higher Froude number of 0.5 the effect is over pronounced using the theory, but as the normal speed for the vessels of 10 knots would equal a Froude number of 0.38 for an 18-metre hull length, the prediction up to Fn of 0.4 is in good agreement.

Figure 6.5 shows the results for ITU 148/1-B using a deeper draught load case. In this case the Froude number range does not extend as high as the previous series, and a better agreement is obtained at the highest Froude number when using the transom modified Michell theory. The resistance prediction when compared to the previous result shows an increase in resistance with increasing draught as expected. For the purpose of comparing a model with different load conditions, either method may be utilized, but the transom-modified results are more comparable to the residuary results.

Figure 6.6 shows the results for ITU 148/2-B fishing hull form. In this case the results show a similar trend where the resistance coefficient increases above a Froude number of 0.35. This corresponds to the vessel speed above 9 knots. The transom-modified theory provides a better result at the higher Froude numbers.

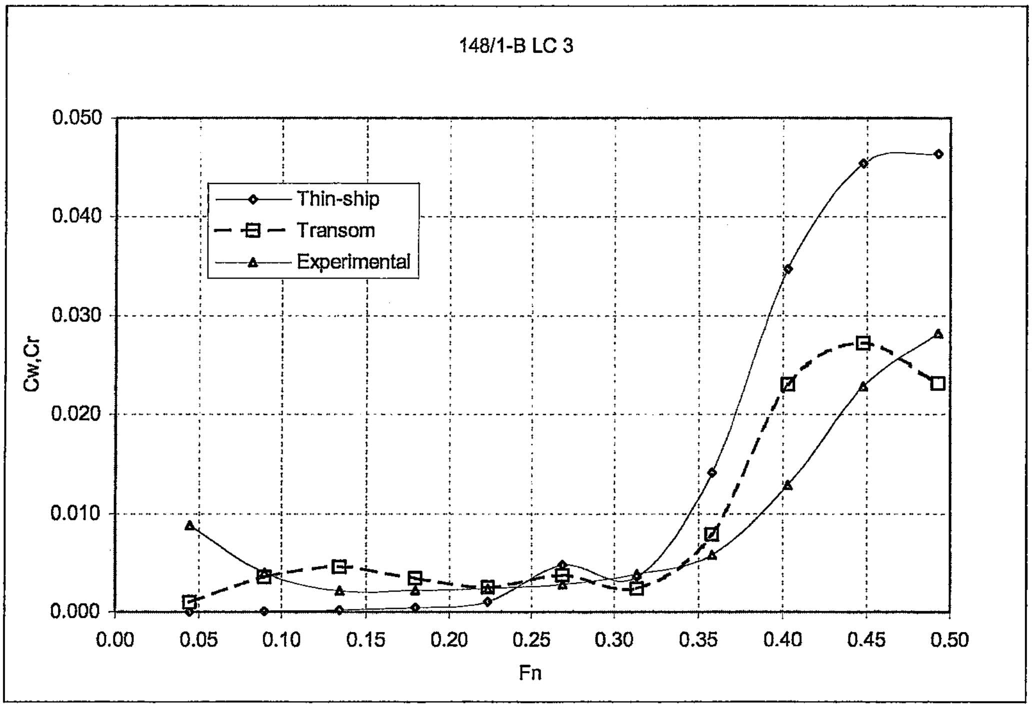

Figure 6.5 ITU 148/1-B Loadcase 3 Comparison of Wave and Residuary Resistance

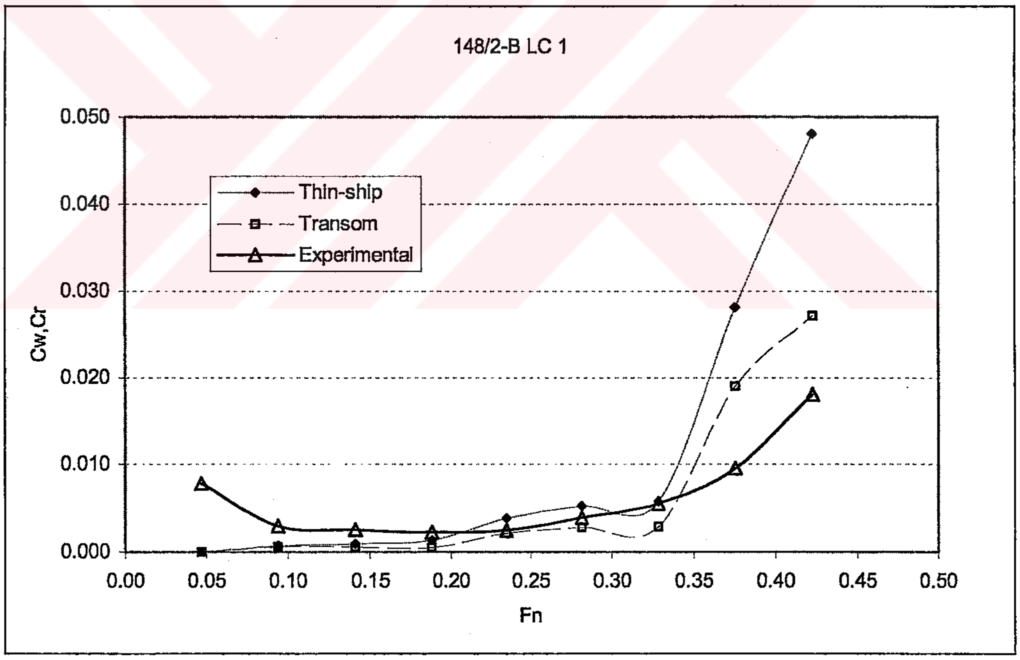

Figure 6.6 ITU 148/2-B Loadcase 1 Comparison of Wave and Residuary Resistance

As an example of when this may not always be the case, Figure 6.7 shows the results for ITU 148/4-B series in the light draft condition where good agreement is obtained at the higher Froude range above 0.40 using the normal Michell theory. One explanation could be that the light draft condition does not immerse the transom, and the modification of the theory uneccesarily reduces reistance coefficient.

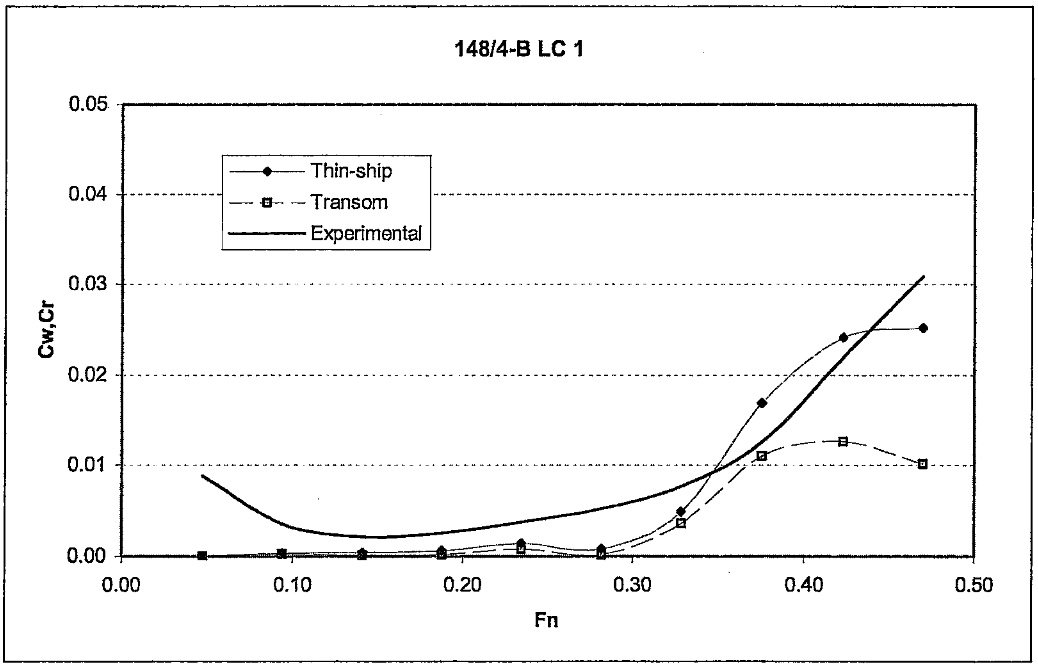

Figure 6.7 ITU 148/4-B Loadcase 1 Comparison of Wave and Residuary Resistance

The variation of hull form for the purpose of obtaining reistance results can be modified in length as well as by different loading conditions. For this purpose, the ITU series derived a number of other hull forms based on some of the initial experiments. An increase in hull length from 20 metres to 28.57 metres was made. The new model, shown in Table 6.1 as ITU 148/8-B was tested. Figure 6.8 shows the results for ITU 148/8-B for the light load case 1.

For this model, the increase in length while simultaneously maintaining beam has increased the L/B ratio. In this situation the Michell theory predicton is improved. However, the effect of the transom is still noted, and the transom modified theory is more compareable below a Froude number of 0.45, or a speed of 14 knots.

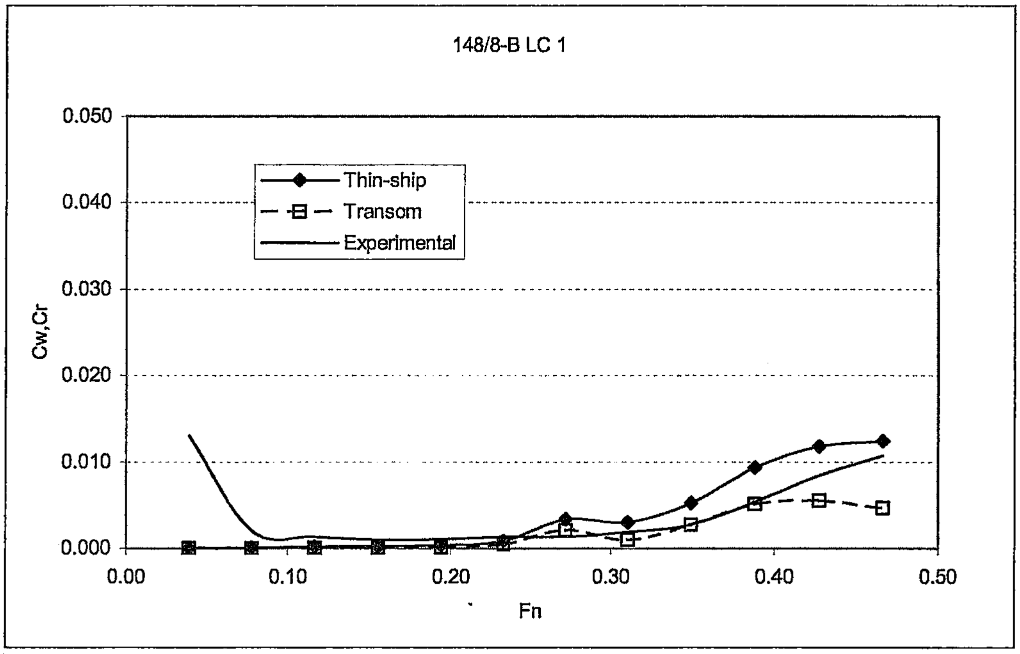

Figure 6.8 ITU 148/8-B Loadcase 1 Comparison of Wave and Residuary Resistance

6.7 A Note on 3-Dimensional (3-D) Resistance Evaluation Methods

One of the primary motives for obtaining a resistance calculation is for design optimization. While this study focused on the use of Michell theory, and moreover Michell theory in which the transom is included, other resistance calculation methods can be utilized. More promising is the use of panels in which source strengths are calculated on the boundary of the hull. However the accuracy of the panel method as described in various references does not always obtain a better result. Figure 6.9 shows the Wigley hull form using a panel method and Michell theory.

However, as noted elsewhere, the panel method may provide a better resistance calculation, particularly for vessels with a low L/B ratio, as in the case of fishing vessels. A study by Alkan and Gül (2001) showed how the offsets of a fishing boat were modified slightly to give better resistance, particulalry in the addition of a bow bulb.

The problems with using panel or nonlinear resistance methods concerns the computational time. A test of the necessary Greens function calculatons for obtaining the panel source strengths was conducted using the method presented by Şaylan (1979) and solved by Okan (2000). The calculation of 5 Froude numbers takes approximately 90 seconds on the fastest portable machine available, at 2.4Ghz Pentium 4 processor. The Michell calculation is in the order of 10 seconds, with the longest computational time given for the low Froude numbers. An ITU towing tank result is included for comparison (Binaroğlu, 1992).

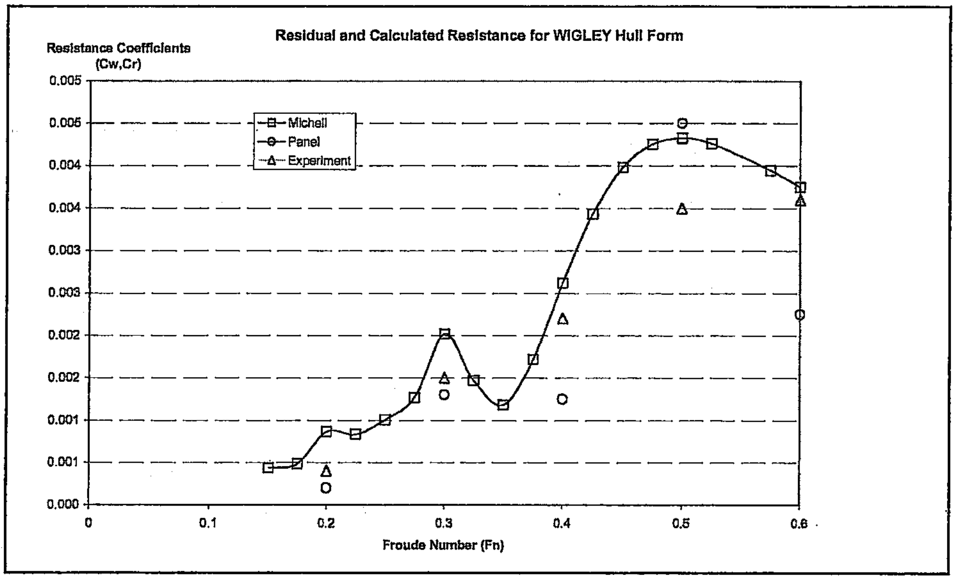

Figure 6.9 Comparison of Wave and Residuary Resistance for Wigley Hull using Panel Method and Michell Thin Ship Theory

This difference can be characterized for optimization purposes as follows. If a design population is tested for 256 ships in the first iteration, then followed by 128 in the second iteration, 64, 32, 16, 8, 4 and finally 2 ships in subsequent iterations, the total number of ship forms to be tested is 510. If we apply the rule of thumb above, the time to optimize using the Michell theory is approximately 1.5 hours. The use of panel method would take about 85 hours or about 3.5 days.

However, panel methods or more sophisticated nonlinear methods can be used to obtain more accurate results. Therefore, it is possible to envision a design sytem in which Michell theory is used as a rapid prototyping method, while final results, for example in the final four ship hulls in the optimisation scheme outlined above, could be utilised. This may be an area of further research.

6.8 Remarks on Resistance Evaluation

This main purpose of this research was to investigate whether thin-ship theory could be utilized for fishing boats, characterised by having a low L\B ratio. In fact, thin-ship theory can still be used for wave resistance prediction, as long as the limitations are recognized. Specifically, thin ship theory for low L\B ratio vessels may not provide an accurate powering estimate, as shown by the comparison to the residuary resistance curves for the ITU series of fishing vessels.

A better result can be obtained for those fishing vessels having a transom, since the transom effect van be incorporated into the Michell theory by making use of a necessary condition from potential flow theory. In this case the effect of including the transom stern is to moderate the prediction made by thin ship theory alone. This leads to a better result in most cases. A notable exception is that at the highest Froude numbers, the transom prediction deviates from the residuary resistance. An explanation may be that the closed hull form given by the closed body condition deviates substantially from the actual flow.

At a Froude number of 0.35, which translates into a speed of about 10 knots for a 20 metre vessel, the prediction is reasonably accurate by either method. For the purpose of comparing the resistance of different hull forms, we can form a table of results as shown in Table 6.2. In ranking, all methods favour 8B which is natural as it has a longer length for the beam. A toss-up is given between 1B and 2B, but while the thin-ship results would favour 2B, the transom-modified version gives a more equal result, whereas the residuary favours 1B.

Table 6.2 Comparison of Wave Resistance Coefficients at Design Speed (Fn=0.35)

Hull Form	Thin-ship		Transom		Experimental	
	C_w	Rank	C_w	Rank	C_r	Rank
ITU 1-B L.C. 1	0.0080	3	0.0040	2	0.0035	2
ITU 2-B L.C. 1	0.0060	2	0.0040	2	0.0050	3
ITU 8-B L.C. 1	0.0050	1	0.0027	1	0.0028	1

For the purpose of the resistance evaluation, the thin-ship theory modified with the transom is able to give the ranking of the different vessel hull forms. Therefore for the remainder of this thesis the transom modified thin-ship theory will be utilized. It should be noted that further resistance work could continue to be investigated, as the focus at this stage was only on ranking the candidates and for fishing hull forms in particular. However further work on different hull forms could be considered.

In particular, the use of a 3-D panel method may prove necessary to gain an accurate assessment of the resistance as some point in the design. For the purpose of preliminary design where many alternative hulls are being considered, thin-ship theory should prove to be accurate for determining the optimal hulls. Once the preliminary characteristics of the design are determined, further advanced hydrodynamic analysis would be prudent.

7. SEAKEEPING PERFORMANCE EVALUATION

7.1 Seakeeping for Design Evaluation

The need for a tool to evaluate seakeeping performance stems from the problems that occur when a vessel encounters wave and wind that degrades the calm-water performance. Rolling motion can become so severe as to effect stability. Pitching and heaving in heavy seas can cause water to be shipped over the bow. Slamming is both uncomfortable and requires the ship to reduce speed, as well as being detrimental to the ship structure. Adverse ship motion causes crew and passenger discomfort.

The techniques to evaluate ship motion have evolved from both tank testing and from theoretical predictions. The methods to model the seaway advanced with spectral analysis and continues to be investigated. Theoretical methods based on the flow around an oscillating cylinder in a free surface were also developed. Lloyd (1989) discusses the development of these methodologies leading particularly to the use of strip theory.

Strip theory is a methodology based on potential flow theory. It assumes that sections of a ship are part of an infinitely long cylinder and that interactions between the sections are independent. The problem of ship motion is characterized by the calculation of the added mass and damping coefficients that can be determined through this methodology. While there are limitations in the application, it has shown considerable success for numerous cases where ship speed is not excessive and ship motion is not unduly large. Further, despite the requirement of a slender ship, the theory has been successfully applied to vessels with a low L/B ratio, such as fishing vessels with an L/B ratio of 3 or less.

For concept design, strip theory provides an adequate means of measuring the performance of the prospective hull, and additionally has reduced computational time over more advanced methodologies. As in the previous case of a resistance evaluation, more advanced seakeeping programs based on a 3-D potential flow have been developed. However, these are more computational intensive and as the same limitation exists for optimization, this is an additional incentive for the use of strip theory for ship motion.

In a recent study by Grigoropoulos et al (2003) on a seakeeping assessment of high speed monohull, it was found that strip theory actually outperformed panel methods for lower ship speeds with a Froude number of up to 0.30 for a RoPax Ferry of 194 metres overall. This corresponds to a speed of 13 m/s or 26 knots. The comparison was done in head seas and looked at two different strip theory codes, SEAWAY developed by Journée of Delft University, while the other is an in-house code at the National Technical University of Athens.

7.2 Seakeeping Analysis Using Strip Theory

For the purpose of evaluating the candidate hulls, the ship or vessel is assumed to operate in a regular seaway, and for the simplest case, in a head sea. In order to model the seaway some characteristics are required. The first describes the encounter frequency of the wave and the ship.

Sinusoidal waves have a number of well-known characteristics, including the wavelength, amplitude, speed, wave number, and period. Each of these can be derived from the other (Bhattacharyya, 1978). In deep water, the wavelength L_W, wave speed V_W and wave period T_W are given by the relations,

$$L_W = V_W T_W \tag{7.1}$$

$$V_W = \sqrt{\frac{gL_W}{2\pi}} \tag{7.2}$$

$$T_W = \sqrt{\frac{2\pi L_W}{g}} \tag{7.3}$$

The period of these waves is an absolute period. When a ship is heading into waves the period will appear shorter as successive waves are met more quickly. The period of the waves encountered by the ship is the encountering period T_e. The simple relation gives the encounter frequency

$$\omega_e = \frac{2\pi}{T_e} \tag{7.4}$$

The encounter frequency is used rather than the wave frequency, as this is the frequency to which the ship reacts. The encounter frequency is a function of the ship speed, wave speed and angle of encounter or encountering angle μ between the ship and waves that is dependent of the ship heading. The relation between encounter frequency and wave frequency is given by;

$$\omega_e = \omega_w\left(1 - \frac{\omega_w V}{g}\cos\mu\right) \tag{7.5}$$

When, as in the case of head seas, the encountering angle is 180 degrees, the encounter frequency increases. A ship in a beam sea (u=90 degrees) has the same frequency of encounter as the wave frequency. In the evaluation encounter frequencies between 0.0 and 6.5 are used. The wave frequency is also specified between 0.5 and 2.5. Given the ship speed between 0.0 and 15 knots, the only variable left to evaluate would be the heading between the waves and ship.

For our case the head sea (u=180 degrees) is used. Therefore one of the other parameters would be dependent on the input. The motion at different ship speeds and the use of the wave frequency means that the encounter frequency is already determined.

The wave frequency and the ship motion is actually a probabilistic motion, defined from the Response Amplitude Operator (RAO) for the vessel and the sea spectrum. Various types of definitions for sea spectrums exist. Most use a significant wave height and wave period. For the ship motions used in the strip theory program the simpler Bretschneider spectrum is used. A typical input would use a significant wave height of 3.5 metres, corresponding to a normal Sea state 3. The wave period can vary, but 6.0 would be typical

The motions considered for the seakeeping index as described next are the heave and pitch. Coupled heave and pitch for head seas has been investigated analytically using strip theory and experiments have proved their validity (Bhattacharyya, 1978). The heave equation describing heave motion is given according to Newton's second law, where all the forces acting on the body at any instant is equal to the product of the body mass and its acceleration;

$$m\ddot{z} = \sum F \qquad (7.6)$$

where m = body mass
$\ddot{z}$ = acceleration
$\sum F$ = sum of vertical hydrodynamic and wave excitation forces

For pitching the equation is given by;

$$I\ddot{\theta} = \sum M \qquad (7.7)$$

where ΣM = sum of the corresponding moments acting on the vessel.

Since we are considering coupled motion between heave and pitch, the equations of motions are as follows (Rawson and Tupper, 1986);

$$(m+a)\ddot{z}+b\dot{z}+cz+d\ddot{\theta}+e\ddot{\theta}+g\theta=F_o\cos(\omega_e t+\alpha) \quad (7.8)$$

and

$$(Iyy+A)\ddot{\theta}+B\dot{\theta}+C\theta+D\ddot{z}+E\dot{z}+Gz=M_o\cos(\omega_e t+\beta) \quad (7.9)$$

It can be seen in (7.8) that the coefficients have some additional hydrodynamic coefficients represented by the added mass a, caused by the effective entrapment of water to the hull of the vessel. Determination of the coefficients is accomplished using strip theory.

Strip theory makes a number of assumptions as mentioned but the basic ones are as follows;

- Ship responses vary linearly with wave height
- Ship's length is much greater than it's beam and draft
- Viscous effects are negligible apart from roll damping
- Hull does not develop any planing lift.

As mentioned, the ship is assumed to be composed of thin sections that are known as strips. This is not too far from the truth as shown in Figure 7.1, but the strips are assumed to be part of an infinitely long cylinder, in order to treat each section independently as a two-dimensional flow. Obviously in the mid-section this may not be a bad assumption, however at the ends of the ship a 3-D flow must prevail and therefore 3-D methods are considered to be more accurate despite the recent comparison by Grigoropoulos et al.

The vertical force δF developed on a strip n with length δx is given by;

$$\frac{\delta F}{\delta x}=-m_n(\ddot{z}-x\ddot{\theta})-a_n\ddot{z}-(b_n+\frac{da_n}{dt})\dot{z}_r-c_n z_r \quad (7.10)$$

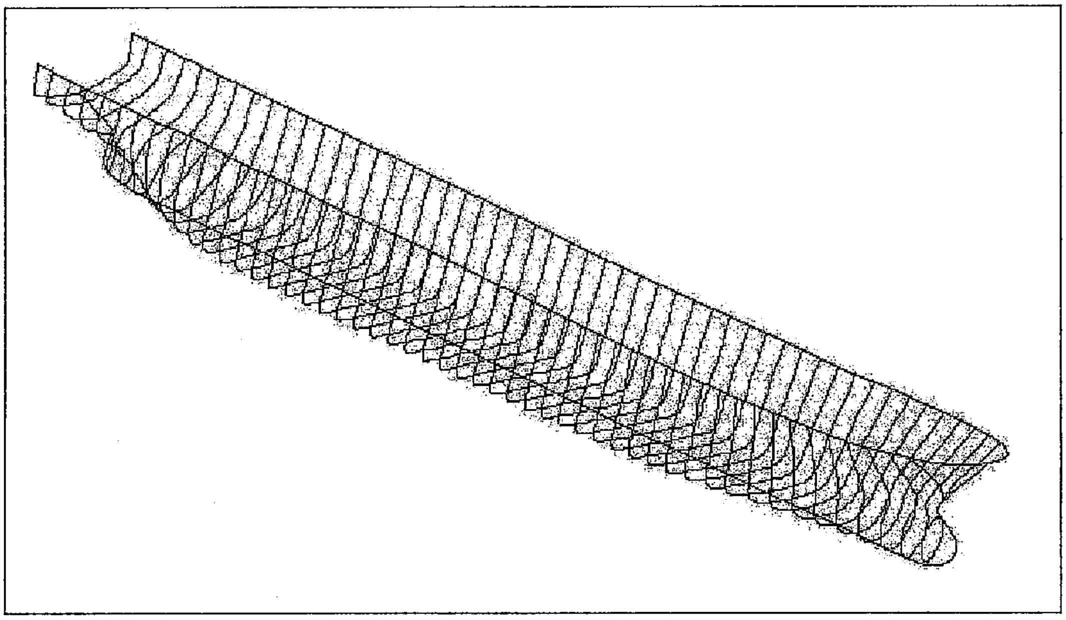

Figure 7.1 Tanker Sections Representing Strips

The added mass a_n varies somewhat with time and the encounter frequency will affect the actual coefficient. Each of the coefficients can be calculated, but the added mass and damping coefficient b_n in particular are determined using strip theory. It should be noted also that z_r represents the relative vertical change in the ship and wave used in the last two terms.

7.3 Development of a Seakeeping Index

The analysis of this performance attribute represents the third and final analysis of the hull optimization performance evaluations conducted using hydrodynamic analysis tools. The necessary calculations for any type of proposed candidate hull form needed resolution into a single seakeeping performance index similar to the resistance coefficient index in order to minimize the number of objectives.

The type of optimisation program drives the motivation for the resolution of the ship motion into one index. Since there are a number of objectives, and these represent aspects of the particular performance attribute of the hull form, it is prudent to reduce the number of objectives within a performance attribute if these can be resolved adequately. In ship motion, numerous seakeeping factors are relevant including the acceleration at various points on the vessels, slamming effects, crew response and the motion sickness index.

However, in the hull form optimisation the hypothesis is that the best hull form is the one that maximizes or minimizes all of the motions. While clearly there is a conflicting influence in the motions between heave and pitch and rolling, rolling is characterized by beam that may be regarded as part of the stability criteria. Therefore the focus can be centred on heave and pitch.

Naturally, this is only an assumption and bears further investigation. Nevertheless, using the same principle as in the resistance index, the vertical heave motion was combined into one vertical seakeeping motion index by integrating the values obtained at each heading (which in this case is further reduced to just head seas) and over each ship speed.

To make it simpler to understand seakeeping the output from a single output for the seakeeping motion response of a typical candidate can be systematically analyzed. The results for the University of British Columbian (UBC) hull series are given as follows as output from the seakeeping strip-motion program given in Table 7.1. As can be seen, for each heading and wave input, there are 8 resulting motions or accelerations that are of interest. These are surge, sway, heave, heave acceleration, roll, pitch, yaw, and pitching acceleration (not shown).

Table 7.1 Seakeeping Motion for UBC Hull Form

Heading (deg.)	Surge (m)	Sway Accel. (g)	Heave (m)	Heave Accel. (g)	Roll (deg)	Pitch (deg)	Yaw (deg)
170	2.024	0.007	1.551	0.056	10.108	3.564	0.629
150	1.993	0.022	1.559	0.058	28.052	3.253	1.753
130	1.942	0.035	1.573	0.064	41.403	2.598	2.395
120	1.916	0.041	1.581	0.068	46.114	2.11	2.485
90	1.876	0.05	1.596	0.078	52.169	0.243	2.221
70	1.895	0.045	1.589	0.072	49.492	1.438	2.144
40	1.968	0.028	1.567	0.061	35.386	2.738	1.834
20	2.012	0.014	1.557	0.057	19.594	3.186	1.112
10	2.024	0.007	1.554	0.057	10.117	3.297	0.594
0	2.028	0	1.553	0.056	0	3.334	0

*RMS MOTIONS IN SHORT-CRESTED SEAS - SPREADING ANGLE = 90.00 DEG
Sea State = 7 Significant Wave Height= 6.2484 M Wave Period = 15.0105 SEC

For the purpose of comparing candidates our problem can be simplified by considering only the vertical motion, which is derived from the pitch and heave. In this case referring to Figure 7.2 it can be seen that the total vertical motion at a point at the bow can combine the heave and pitch motion, however this should be multiplied by the heave acceleration to give an equivalent momentum of Meters*Metres/sec^2 and this in turn is averaged over each ship speed to determine and equivalent energy density. The mass of the vessel is deliberately left out as the combined pitch and heave are figurative and the maximum values of each motion do not actually in all probability occur simultaneously.

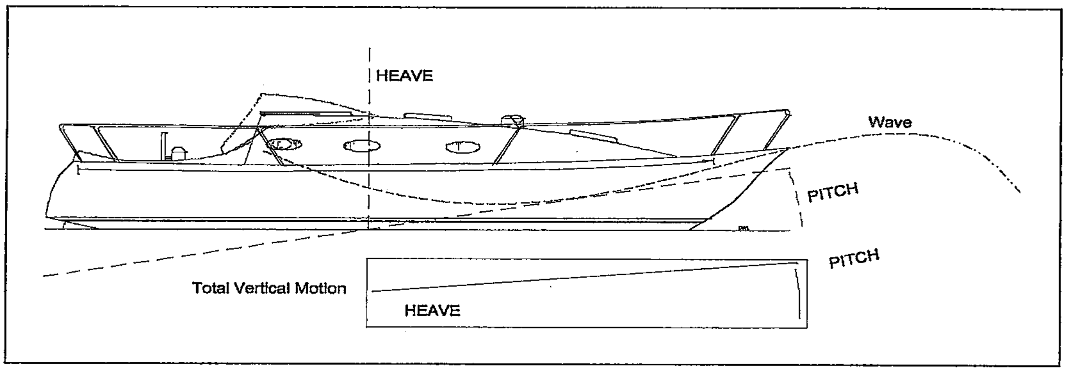

Figure 7.2 Vertical Motion from Heave and Pitch Multiplied by Heave acceleration

The equation for the seakeeping index is given by (7.11) where *Vert* represents the vertical calculation at each ship speed *V* using the heave (H_{rms}), pitch (ϕ_{rms}) and heave acceleration.

$$SKI = \frac{1}{2}\sum_{i=1}^{N-1}\left(Vert(i) + Vert(i+1)\right) \times \left(V(i+1) - V(i)\right) \tag{7.11}$$

and

$$Vert = H_{rms}\left(\frac{L}{2}\sin(\phi_{rms})\right) \times \ddot{H}_{rms} \tag{7.12}$$

The results can be seen as in Table 7.2. In practice the heading is simplified to either 180 degrees or 0 degrees for pitch and heave motion only (no roll). In this case there is only one heading but numerous ship speeds should be considered. As can be seen the vertical seakeeping index now gives a single value of 8.19 for the UBC hull. This can be compared to the results using a Wigley hull form in Table 7.3 where the Vertical seakeeping index is now 5.66. In this case we estimate that the Wigley hull produces less motion and therefore a lower seakeeping index which results in less energy, and a "quieter" ride.

The seakeeping index as plotted with length for ITU 148/1-B shown in Figure 7.3 indicates that increasing length will have a positive effect on the overall seakeeping ability while the sea state and wave height and other environmental parameters are kept constant. Therefore we can assume that in this case the seakeeping is not an adverse objective with respect to resistance minimization as both improve with increasing length. The lack of subjectivity can be utilized by simply determining the minimum capable vertical seakeeping index (SKI) for a hull form optimization run and setting the constraint for seakeeping below this value. The optimization will then treat this as an active constraint.

On the other hand as will be considered in Chapter 8, the form of the optimization is formulated as a multi-objective problem and seakeeping is then considered as an objective. If the vertical seakeeping index is insufficient to compare hull forms then further elements of seakeeping such as roll and acceleration at different points in the vessel can be utilized in a more elaborate index or the problem can be resolved by treating the problem as a more advanced multi-objective problem.

Table 7.2 Seakeeping Index Calculations for UBC Hull Form

UBC								
Speed Knots	Heading Deg	Surge m	Sway Acc. G	Heave m	Heave Acc. G	Roll Deg	Pitch Deg	Yaw Deg
0	180	2.586	0	1.894	0.062	0	4.556	0
5	180	2.018	0	1.881	0.101	0	5.307	0
10	180	1.616	0	1.802	0.159	0	7.783	
15	180	1.295	0	1.927	0.359	0	10.563	0
Seakeeping Index (Vertical)								
Speed Interval	Avg. Heave between Intervals		Sin	L/2	Total Vertical Motion	Total Vertical Multiply by Heave Acc.	Multiply Speed Interval	
5	1.8875	0.0815	24.2	4.9315	0.086	0.0859647	12.1	2.93
5	1.8415	0.13		6.5450	0.114	0.1139835	12.1	3.22
5	1.8645	0.259		9.1730	0.16	0.159416	12.1	3.79
Alternate* using averages								
15	1.876	0.17025	24.2	7.05225	0.123	0.1227744	12.1	3.36
						0.238605		1.193027
						0.418691		2.093455
						0.982499		4.912496
							Total Index	8.198978
						0.572307		8.584611

One reason not to add to many objectives comes from a built-in limitation in our thinking. For two-dimensional objects it is relatively easy to compare the different objectives and candidate as in the Pareto frontier. Three objectives are three-dimensional, in which surfaces rather than curves become a Pareto "Front" or Frontier. More than three objective means there is no longer a surface but now a multi-dimensional hyperspace that is difficult to visualize.

Table 7.3 Seakeeping Motion and Index for WIGLEY Hull Form

WIGLEY; L=20m								
Speed Knots	Heading Deg	Surge m	Sway Acc. G	Heave M	Heave Acc. G	Roll Deg	Pitch Deg	Yaw Deg
0	180	2.326	0	1.765	0.064	0	3.64	0
5	180	1.773	0	1.772	0.099	0	3.42	0
10	180	1.188	0	1.78	0.155	0	3.55	0
15	180	0.579	0	1.79	0.36	0	4.31	0
Seakeeping Index (Vertical)								
Speed Interval	Avg. Heave	Avg. Pitch (rad.)	Sin	Multiply L/2	Total Vertical Motion	Avg. Heave Acc.	Heave Acc. times Vertical Motion	Multiply Speed
5	1.769	0.0616	1.075e-3	0.01075	1.77975	0.0815	0.1405	0.7252
5	1.776	0.0608	1.061e-3	0.01061	1.78661	0.127	0.2269	1.1345
5	1.785	0.0686	1.197e-3	0.0197	1.8047	0.3925	0.7083	3.5415
							Total Index	5.40

Nevertheless, if required, the techniques can be used to model more than three objectives. In the next section multi-objective optimization techniques demonstrate how three objectives can be handled. As computation increases with each objective, it is prudent to design the problem accordingly.

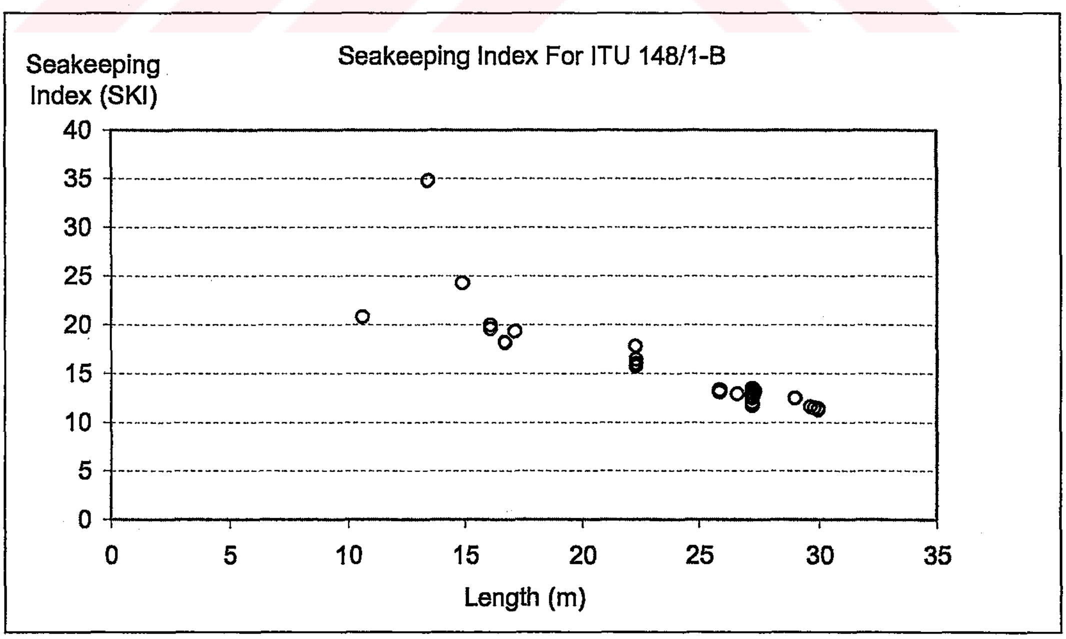

Figure 7.3 Vertical Seakeeping Index Variations with Length

8. Multi-Objective Evolutionary Algorithms

8.1 Multi-Objective Design Optimization with Aggregate Functions

The following aspects of multi-objective optimization are considered. The necessity for a multi-objective optimization or multi-criteria problems results from the consideration of different objectives that are dependent on the same or overlapping set of input variables. Multi-objective problems are also known as vector or multi-criteria optimization problems as can be seen in Figure 8.1. Pareto optimization is the most popular example of how multi-objective problems can be examined and V. Pareto first proposed the paradigms in the first part of the century as a methodology pertaining to economic models.

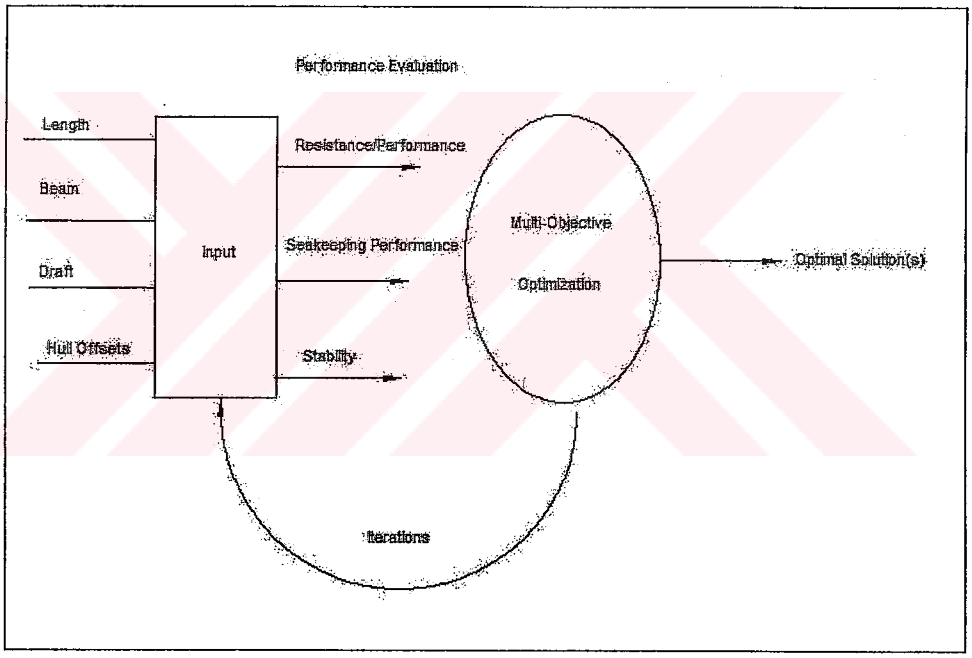

Figure 8.1 Multi-Objective Problems

Pareto put forward a definition which states that a solution to a multiple criteria problem is Pareto Optimum if no other feasible solution is at least as good as A with respect to every objective and is strictly better than A with respect to at least one objective. A solution is said to dominate another feasible solution if the solution is as least as good and is strictly better than the dominated solution with respect to at least one objective.

Once all the un-dominated solutions are found these represent a trade-off curve as a front for a set of Pareto optimum points. In the case where two objectives are minimized the curve tends towards zero, whereas if they are maximized the curve tends to grow. Other cases are shown in Figure 8.2 where one objective is maximized and another is minimized.

It should be noted that despite the extra information obtained form the construction of the Pareto optimal front, the designer or analyst must still decide which point on the curve is optimum for use in the design. In other words the introduction of a multi-objective problem automatically introduces subjectivity in the problem statement.

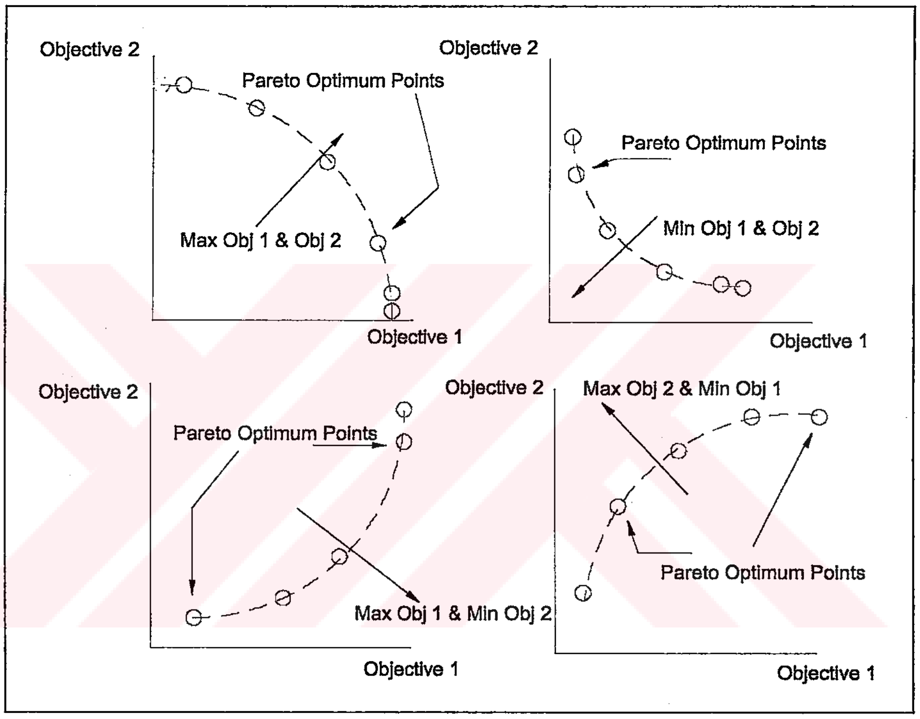

Figure 8.2 Pareto Optimal Curve for a Two Objective Multi-Criteria Optimization

The methods for treating multi-objective problems begin by extrapolating classical optimization by taking the Pareto-optimal points and forming a weighted average. Given the preference of the designer, the relative weight between each objective is used to compute a single aggregate function with which to determine a single optimum point. This effectively reduces multiple objective problems back into a single objective problem that can be solved by classical optimization methods. For a two objective problem;

$$G(w,F) = w_1 * F_1(x,z) + w_2 * F_2(x,y) \quad (8.1)$$

where G = Aggregated Objective Value
F_n = Objective Value of Function *n*
w_n = weighting factor for each objective

The weighting factors are normally equated to one, ie,

$$\sum w_n = 1.0 \quad (8.2)$$

As is often the case when the designer or problem does not have definite weights between the objectives then letting the weights be equal reduces the problem. The function values are also usually normalized.

The normalization of the function values needs to be considered because as values occur in each generation the minimum and maximum values for the normalization change. Gen and Cheng (2000) used for example the following method for normalization of the functions;

$$g(v_k) = \frac{f_{max} - f(v_k) + \gamma}{f_{max} - f_{min} + \gamma} \quad (8.3)$$

where f_{ma} = maximum function evaluation in current generation
f_{min} = minimum function evaluation in current generation
v_k = kth chromosome in the current generation
$f(v_k)$ = original objective function
γ = positive real augmentation factor restricted in open interval (0,1)

The purpose of adding the augmentation factor is to avoid any division by zero as well as to change the selection behaviour form fitness proportional to random selection. In our case the minimum value is set at zero, which ensures that the actual value will lie somewhere in the interval. The maximum value is also changed to be the maximum value evaluated as the optimization proceeds in order to generate increasingly standard scale for the function evaluations.

Using a weighting factor of 0.5 for each objective and comparing just the seakeeping index (SKI) with the resistance index (RCI), the different objectives were tested for a sample of 10 candidates for 100 generations. As shown in Figure 8.3 the design space between seakeeping and resistance has the overall objective of minimizing seakeeping and minimizing resistance. This tends to group the samples during the optimization towards the zero axis point.

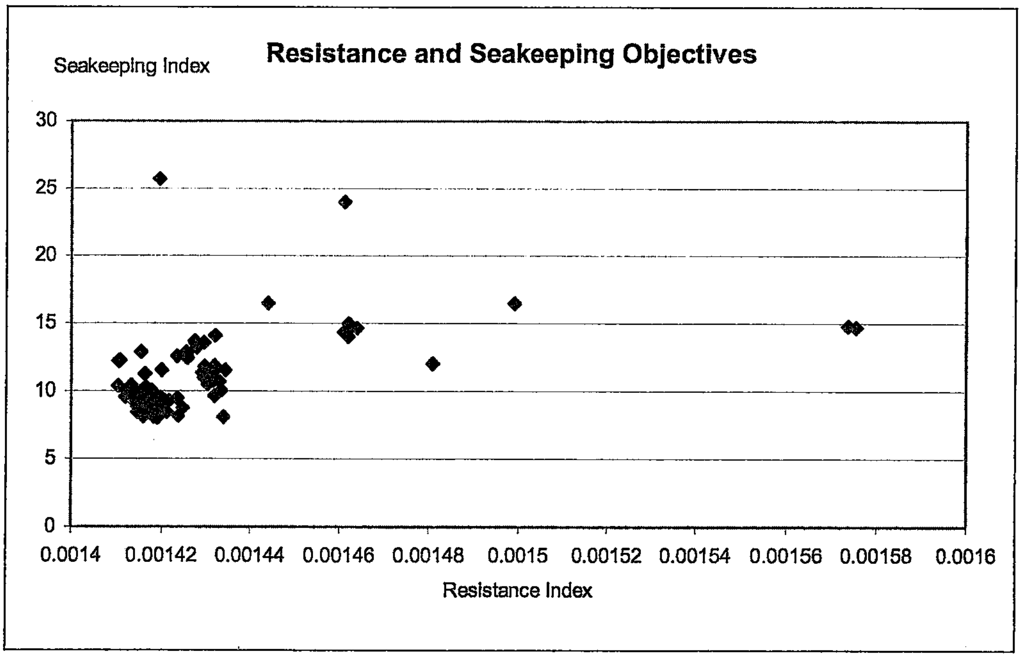

Figure 8.3 Multi-Objective Design Space with Resistance and Seakeeping Index

Figure 8.4 shows the evolution of the aggregate function. The function combining both objectives does show an increase (as fitness is calculated by the minimum) and therefore the overall objectives tend toward their respective minimums. However, in neither case is a result that is exceptionally large in one objective and very small in another equally better or worse than an aggregate solution in which the objectives are equally balanced. Also, the weights applied to the different objectives are necessarily subjective in nature and therefore subject to question in practice.

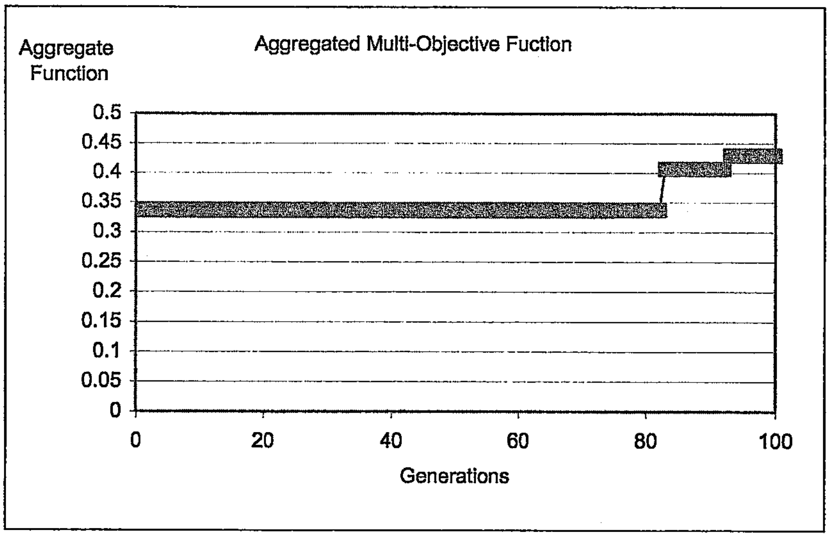

Figure 8.4 Evolution of the Aggregate Function

8.2 Multi-Objective Evolutionary Optimization using Pareto Ranking

The previous method is one approach to that can be used to measure the fitness function of the problem by measuring each objective and applying weighting factors to obtain a single objective. By constructing a Pareto optimal front, each objective is separately evaluated and examine with regard to whether it is dominated by another solution. The optimality is obtained by ranking each of a set of population and using those Pareto optimal candidates as better (but equivalent) parents with which to construct the new population. For example if there are four candidates with individual values in each of objective one and objective two as shown in Table 8.1 and plotted in Figure 8.5, and the objective is to minimize each objective then the ranks of each candidate can be given.

Table 8.1 Example Multi-objective Pareto Ranking Problem

Candidate	Objective 1 Fitness	Objective 2 Fitness	Pareto Rank	Equal Weights
A	2.7	2.5	1	2.6
B	3.65	1.0	2	2.325
C	1.5	2.0	2	1.75
D	1.0	3.0	2	2.0

As can be seen in Figure 8.5, the ranks of B, C, and D are equal as none dominate each other. However, all dominate the interior point A. If a weighting factor was applied to each objective of for example, equally important or preferred, then the multi-objective values are an average of each objective, and Point C becomes the minimum value.

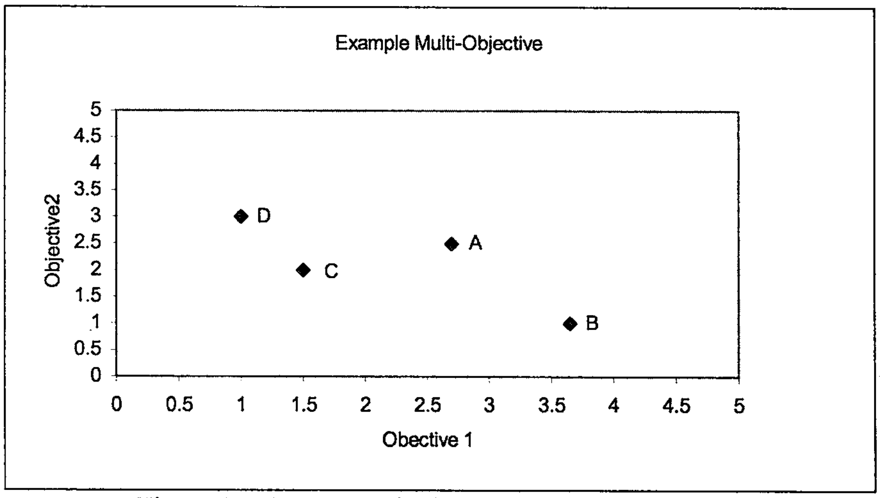

Figure 8.5 Pareto Ranked Multi-Objective Problem

The evolutionary optimization would utilize the Pareto ranking to determine the members of a Pareto optimal front. Alternatively if the preference matrix is known then the multiobjective problem again becomes a single objective problem by using the weighted average values. In this case the fitness function can either the Pareto ranked value to determine the best members or the single weighted average value to determine the single optimal value. The optimization can then proceed to select the candidates accordingly for use with the genetic operators.

A problem arises with using weights occurs when the preference matrix or weighting between the objectives is actually unknown. Then the designer is left with the choice of selecting among the candidates on the Pareto optimal front one that appears suitable according to experience. If the number of objectives is increased, the hyperspace becomes larger and the number of possibilities increases such that the designer may have difficulty in examining the trade-off between different objectives.

For example in the hull form optimization problem there can be two equally important objectives. The first is to minimize resistance, and the second is to minimize the ship motion. If the designer assigns an equal weight to the problem and Objective 1 and Objective 2 represent these as in the previous example then Candidate C may seem the optimal design. But in fact the motion values may not be very large for any of the candidates such that the minimum objective 1 may still be the best candidate. By asking the designer to arbitrarily select the weighting factor the optimal solution may not be the best solution according to the actual values. In other words some tradeoffs and compromise may create a more suitable design. Figure 8.6 shows a realistic example between seakeeping and resistance using a Pareto method, which is outlined next.

Carlos Artemio Coello Coello (1996) conducted a thorough review of the various methods available for mathematical programming multi-objective techniques. He also reviews multi-objective optimization using Genetic algorithms. The three methods forming the basis for multi-objective optimization are using aggregating functions, non-Pareto approaches based on ranking, and Pareto based approaches.

Using aggregating functions (as shown in the previous example) by assigning weights is known as the weighted sum approach. He points out that the problem with this method is how to determine the weights when there is insufficient information about the problem. Another method reduces the problem to a single objective problem by all objectives being kept constant except for one, and varying the constant constrained objectives while running the GA numerous times. However this method may be time-consuming or difficult to employ. By varying goals the relative vector of weights relating the under and over-attainment of goals can be used to compute solutions and the weights can be varied. Finally, penalty functions can be used.

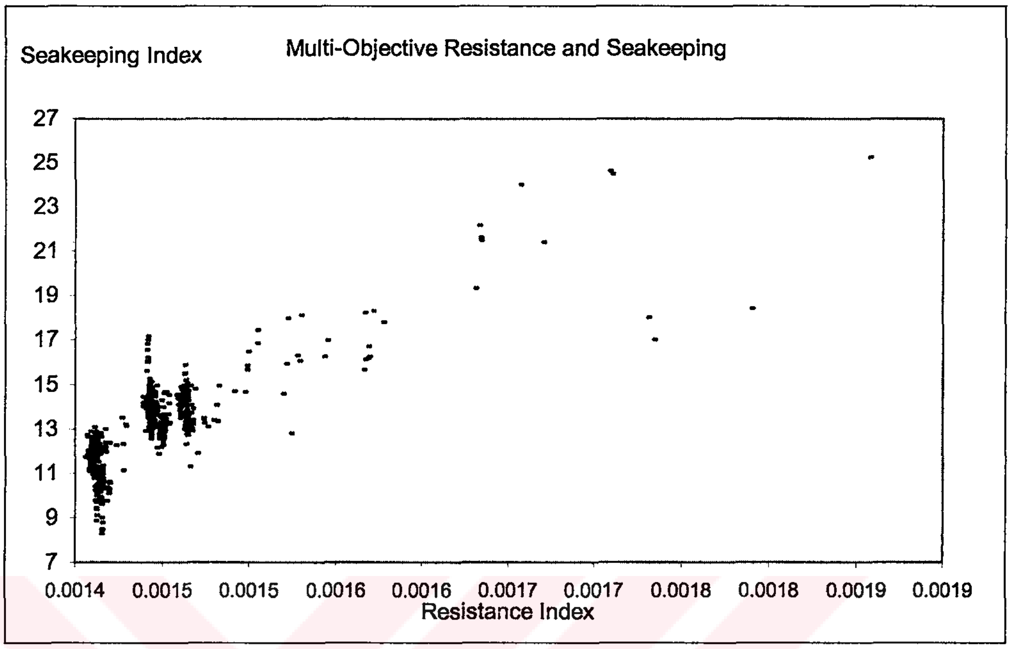

Figure 8.6 Comparison of Seakeeping and Resistance using Multi-Objective Non-Dominated Sorting algorithms (NSGA)

For the non-Pareto methods, Schaffer reported with some success on the use of a Vector Evaluated Genetic Algorithm (VEGA) that differs from the simple genetic algorithm in the manner in which selection is carried out. For each objective a subgroup of candidates are selected from the population using each performance evaluation. Subsequently the selected parents are shuffled and the genetic operators are applied to the entire group. Problems with this approach include an averaging of performance among the objectives. Schaffer in the review by Todd (1997) reports that VEGA tends to find only extreme regions of the Pareto front as it chooses specialists in each objective ignoring solutions that perform acceptably in some of the objectives.

Another technique known as lexicographic ordering determines the rank of each objective in order of importance. It then selects the parents based on the minimization or maximization of the first objective. When there are ties in the ranking of the candidates the next objective is used to break the tie. Some advantages are gained by ranking as opposed to measuring the difference in objectives, though averaging can still be a problem. Averaging is avoided by randomly selecting the objectives to be used for comparison.

In another method an evolutionary strategy is proposed for a multi-objective problem where the selection is based on the number of objectives. Each objective is selected randomly and according to a probability vector, the performance in the objective is used to delete the population. After selection, survivors are used as parents for the next generation. In a weighted sum approach, the weights are included in the chromosome and these are used in a single run of the GA.

A Pareto approach by Goldberg looks at the problems with Schaffer's VEGA approach. Basically the population is maintained by ranking the population to find members that are non-dominated. They are then assigned the highest rank and eliminated from the population. The next rank is assigned to remaining members of the population and so on until all members are ranked. Pareto optimality ranking was found to outperform the VEGA method.

Another method ranks the individuals by the number of dominating members in the population. Interpolating the rank, then averaging the fitness of individuals with the same rank gives the final fitness values. However problems occur that only a certain region of the trade-off surface can be developed.

A non-dominated sorting genetic algorithm (NSGA) as used in Figure 8.6 is based on layers of classifications. The population is ranked on the basis of non-domination, and classified into one category. Dummy fitness values are assigned to the category. Those members who have a higher fitness based on the domination then have a higher probability of being selected as parents. This method is the most popular and quite useful method for implementing a Pareto methodology. An alternative method is the Niched Pareto GA is based on multiattribute utility theory. It uses member who perform in each niche where good performance in one or more attribute represents a niche to investigate those regions. This method is useful for exploring the regions that show high performance in different areas, but may not be as useful for examination of the entire search hyperspace.

An alternate approach that does not use the weighting methodologies, but also does not compare non-domination or Pareto values is described in the next section. The purpose was to develop a method that explores candidates that perform well in all objectives without averaging the population. Also the population should not become fixed in particular niches. This apparent conundrum or paradox is approached in a relatively unconventional manner.

8.3 Sequential Objective Evolutionary Algorithm (SOEA)

During the optimization process the fitness function is calculated from the evaluation of the hull form with respect to the principal parameters and the hull offsets. Resistance is evaluated along with seakeeping and stability. Instead of deriving the Pareto optimal front, or evaluating a single objective as a combination of the multiple objectives and a weight vector, an alternate methodology is proposed.

The derivation of the multi-objective methodology based on weighting factors is necessary if a classical optimization methodology is used. In classic methods, the function evaluation of a single objective is used to direct the next search point, as the method uses the function evaluation to determine the direction of the next point. This is shown in Figure 8.7 where the function uses the slope to determine the next point to investigate.

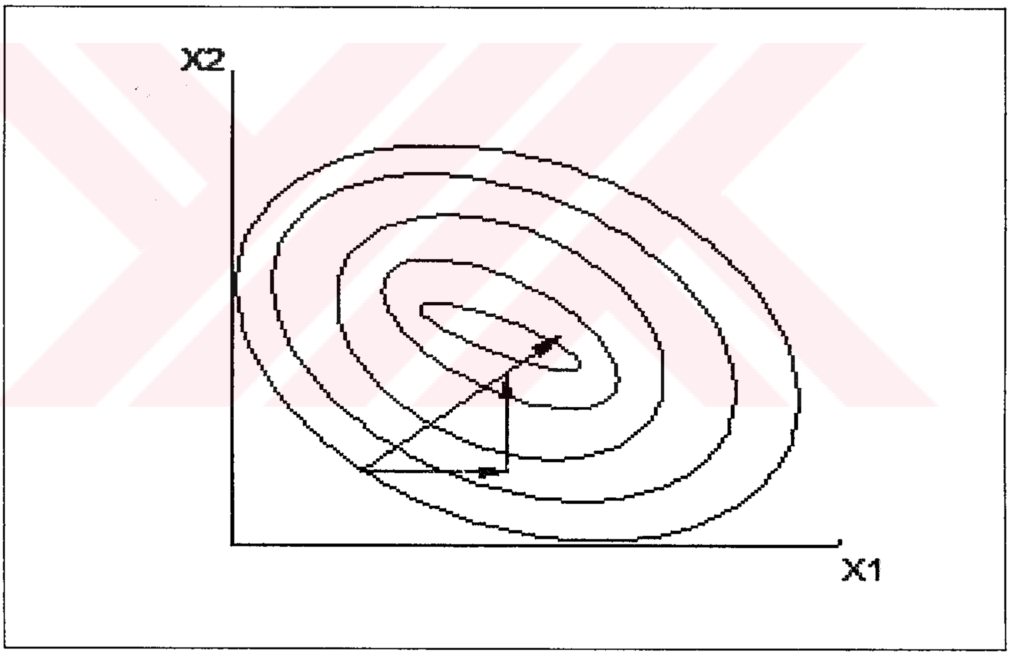

Figure 8.7 Function Directions by Gradient

In the classic methodology the single function evaluation is necessary in order to determine the next search point. Therefore the combined objective function is used for the search. While this methodology has been adapted for use with evolutionary algorithms the method is deterministic, while the evolutionary algorithm is stochastic.

Utilizing the population of solutions means that a single solution and therefore single function is not required. Rather than proceeding to the next solution from the single solution point, the next population can be derived form the previous population in stochastic manner. For the purpose of evaluating a single objective, the fitness of that objective is used to select the parents to generate the next population. From these the single objective optimization can proceed.

In the proposed methodology, each single objective is carried out in sequence. This method can be called the Sequential Objective Evolutionary Algorithm (SOEA). The population is evaluated with respect to a single objective and the parents selected. The next generation is generated using the genetic operators. This population is in turn evaluated with respect to the next objective. In turn the fitness is assigned, the parents selected and a new population generated. This continues in sequence with each objective.

In other words the population after iterating through each objective is more optimal with respect to each objective. Figure 8.8 shows a flow diagram of the algorithm as compared to the first general genetic algorithm.

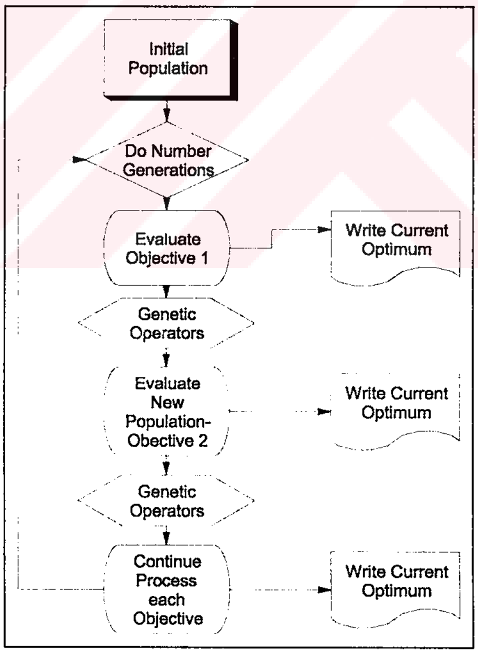

Figure 8.8 Sequential Objective Evolutionary Algorithm (SOEA) Structure

8.4 Test Function Comparison of Different Multi-Objective Methods

To compare the different methodologies three test problems are used. Valenzuelo-Rendon and Uresti-Charre (1997) used these problems to test their Non-generational Genetic algorithm for multiobjective optimization. The problems and their objectives are summarized as follows;

$$\text{Problem 1:}\quad \min f_1(x) = x^2; x \in [-6,6]$$
$$\min f_2(x) = (x-2)^2; x \in [-6,6]$$

$$\text{Problem 2:}\quad \min f_1(x) = \frac{1}{x^2+y^2+1}; x \in [-3,3]$$
$$\min f_2(x) = x^2 + 3y^2 + 1; y \in [-3,3]$$

$$\text{Problem 3:}\quad \min f_1(x) = x + y + 1; x \in [-3,3]$$
$$\min f_2(x) = x^2 + 2y - 1; y \in [-3,3]$$

Each problem is solved using the three types of multi-objective methods. In Figure 8.9 the solution to Problem 1 is shown using the aggregate function where the preference between the two objectives is set at 0.5 such that they are considered equal.

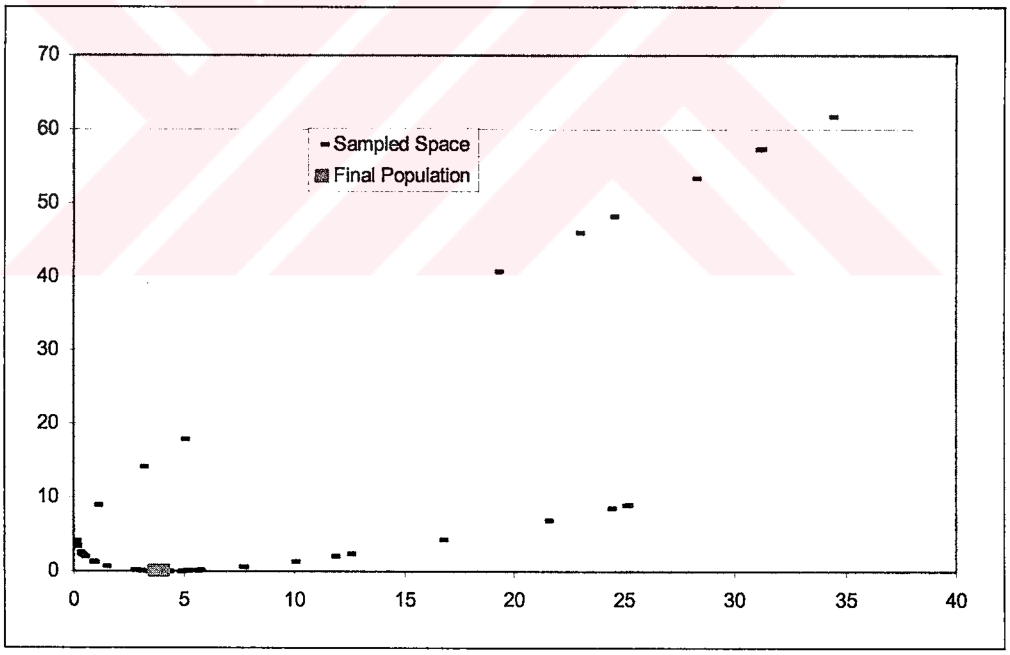

Figure 8.9 Problem 1 Solution using Aggregate Function with Equal Weightings

As can be seen the problem is a fairly simple one where the minimum values for each function would be between zero for the first function and 2 for the second function. The final sampled population is close to the apex of the curve where most of the samples are, signifying that the genetic algorithm is closing in on the optimal solution.

If instead of using an aggregate function, the use of NSGA that searches the Pareto front is utilized for the optimization, then the results are similar though more definite as shown in Figure 8.10. The curve is similar and the results are again heading in the direction of optimal points, where more points at the apex of the curve suggests this is where the algorithm is focusing. As this problem is not very complex, either methodology works well.

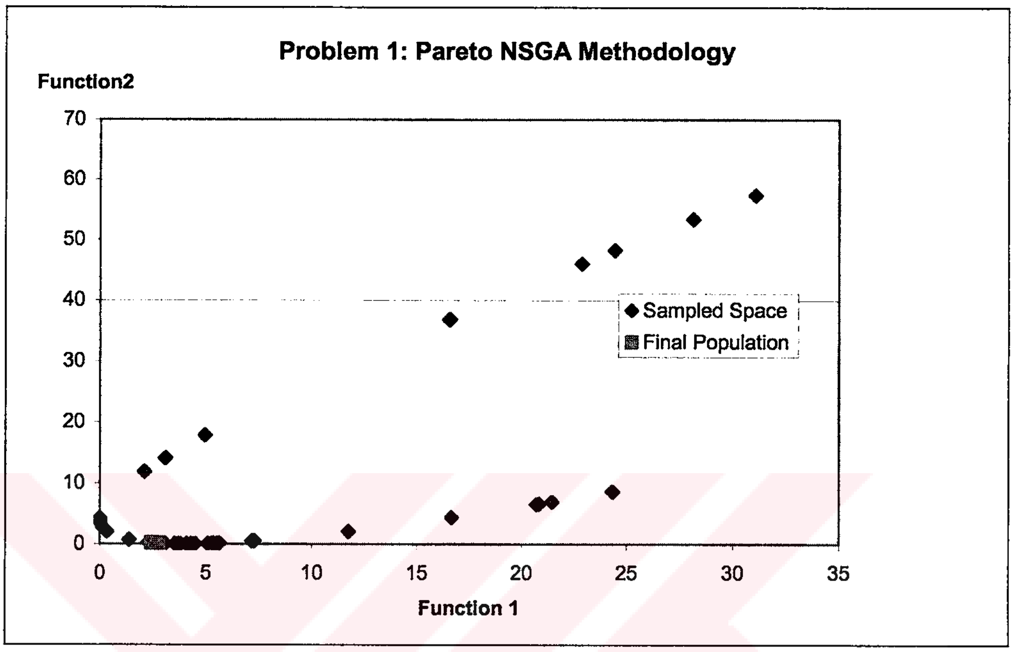

Figure 8.10 Non-Dominated Sorting Genetic Algorithm Solution to Test Problem 1

In Figure 8.11 the problem 1 solution is given using the SOEA method. The results are similar to the first two cases even though some small discrepancies occur. In this latest methodology, some members of the final population remain in the outer limits of the curve. However the optimal values are in fact closer than the previous two methods. The important point is that this method still determines the direction for optimal points as in the previous two methods. Therefore for simple problems the method can be quite applicable, though there may be reasons such s computational effort to use one of the other approaches.

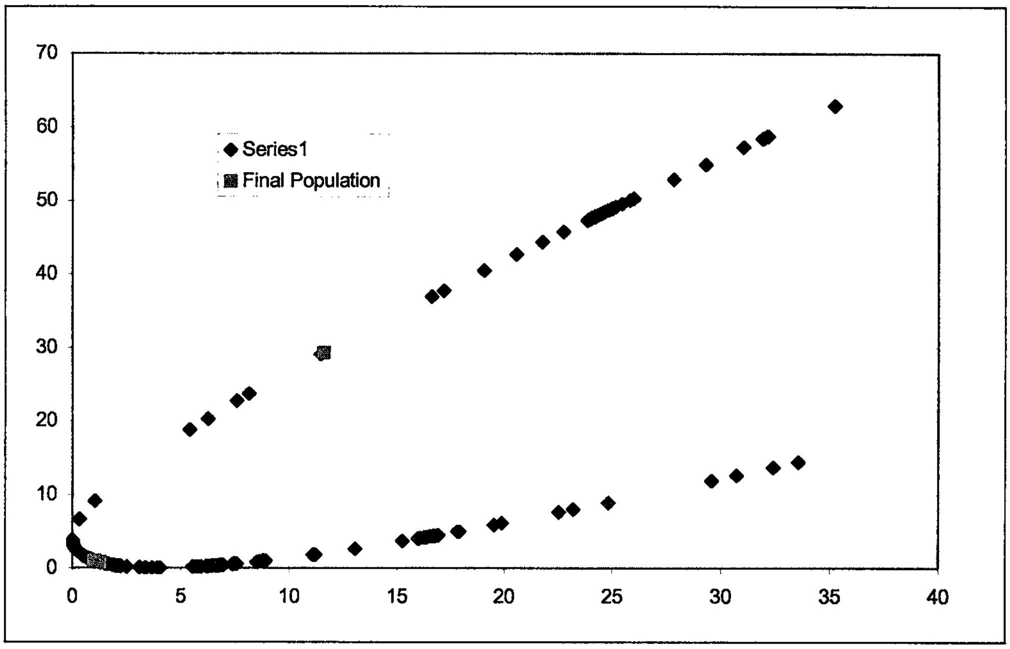

Figure 8.11 Problem 1 Solution using Sequential Objective Evolutionary Algorithm

The solution to problem 2 is shown next in Figure 8.12. Here the problem function is becoming more complex, but the aggregate method can still be used to drive the optimization. Figure 8.13 shows that the NSGA method is quite similar though perhaps less scattered and more definite in the outline for the Pareto front, with fewer members of the population in the interior or dominated positions.

The most striking example that can be seen in shown in Figure 8.14 using the SOEA methodology. In this case the front is largely abandoned and the algorithm focuses on the most optimal region, which is the minimum of both objectives. The Pareto front is now angular rather than curved, and the one or two members in the final population that still perform best in each objective are also maintained.

Looking at the values, the averaging method derives either (10,0.1) or (5,0.2) as possible optimal points in the final population. The NSGA method derives either (5,0.2) or (2.5,0.4) as the final points. The SOEA gives 3 points, most around (1.0,0.1), but also (12,0.08) and (1.0,0.3). These latter two are high individual performing members though not in both objectives, while the main group is better than the results from either of the previous two methods.

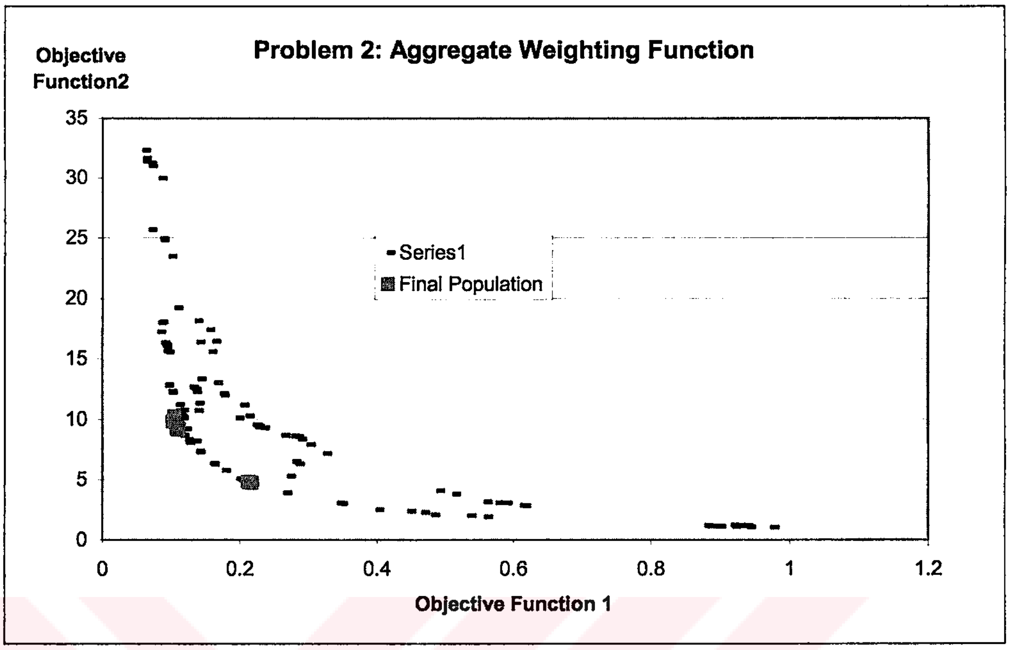

Figure 8.12 Aggregate Function Solution to Problem 2

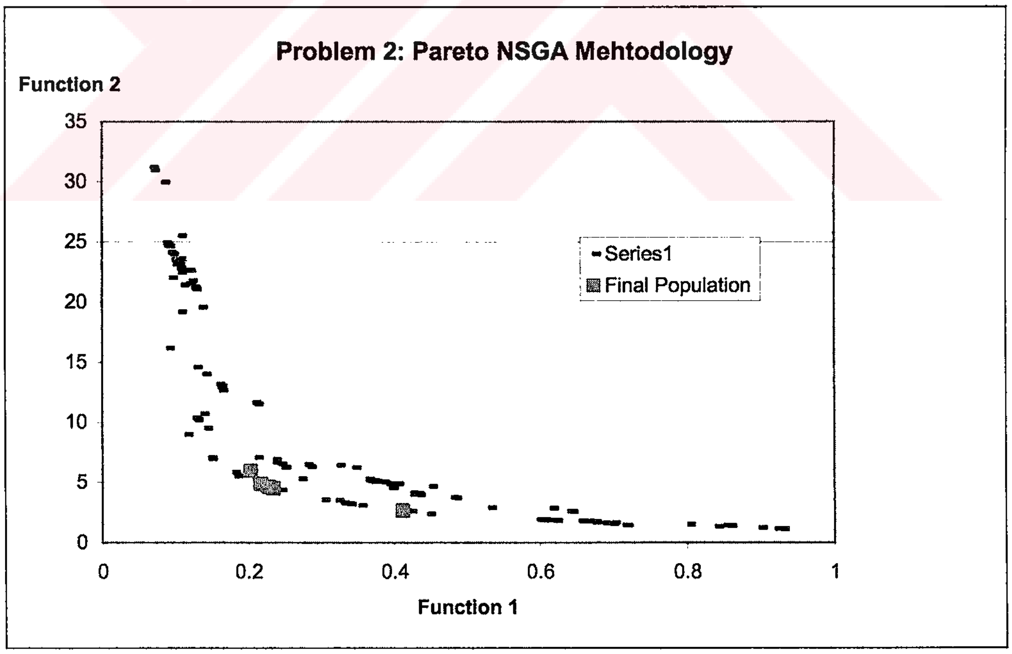

Figure 8.13 Solution to Problem 2 using NSGA Methodology

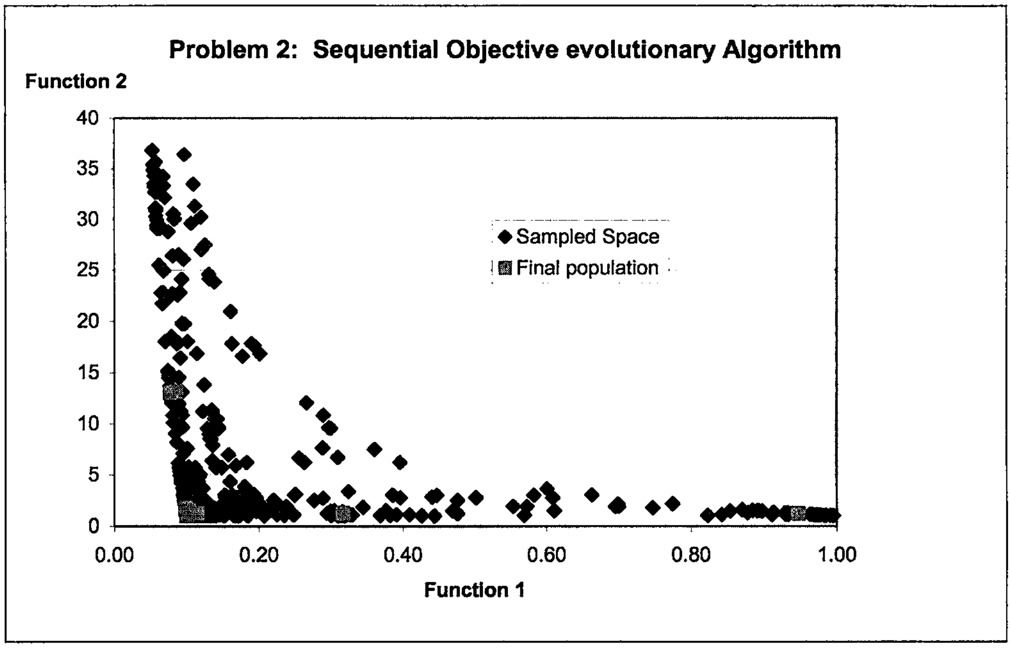

Figure 8.14 Solution to Problem 2 using the SOEA method

In Figure 815, the solution to problem 3 is shown using the aggregate function. Now the problem has a different region and a more complex function, and the aggregate function, while somewhat useful, is showing more scatter in the search.

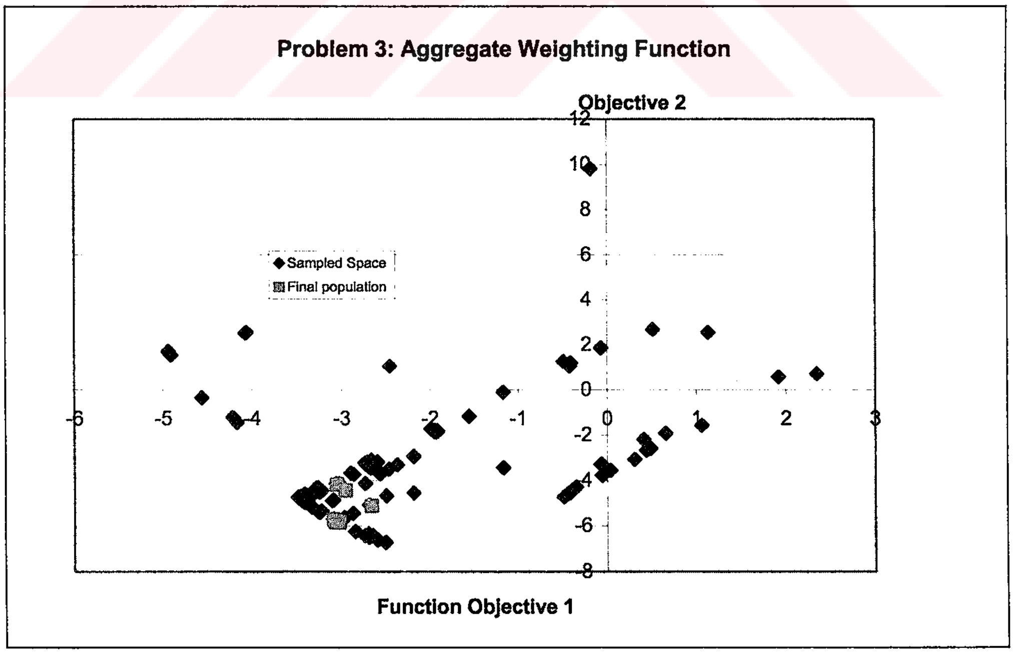

Figure 8.15 Problem 3 Solution using Aggregate Function Methodology

In Figure 8.16, the solution with the NSGA method is shown to be more definitive in searching the Pareto front, though difficulties are still encountered as shown by the different curves that are delineated during the search.

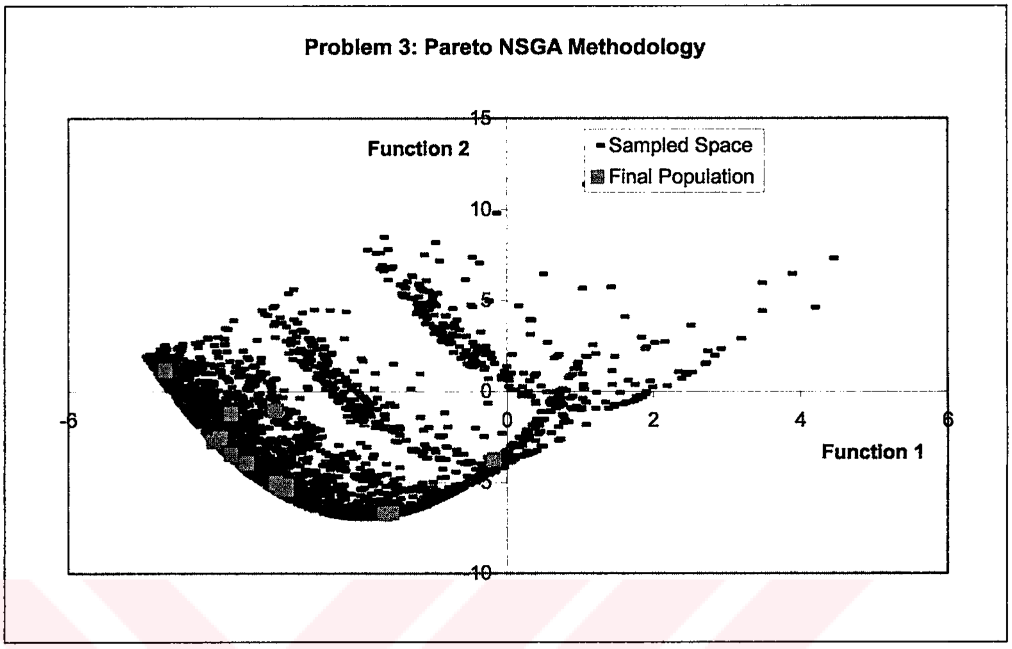

Figure 8.16 Problem 3 Solution using NSGA Methodology

Finally, problem 3 is solved using the SOEA methodology. While similar in shape to the previous method, the points are far less scattered and less delineation of the entire extensive Pareto fronts are shown. More of the population is grouped at the (-7, -3) region though a few outliers are maintained. In the previous method the Entire front from (-7,-2) to (-5,1) is maintained as none of these points are dominant. In the SOEA method, the group from (-7,-2) but also (-6, -3) are the focus while (-5,1) are also kept. Interestingly, a few points in the interior are also part of the final group.

While it is not clear that the SOEA method can be useful in all cases, it is certain that this method can be particularly useful when the weighting method cannot be used or may introduce vague assumptions with regard to the preference between objectives. Further, as the method is not concerned with domination, the idea of having to investigate the entire Pareto front is also abandoned in favour of the more pragmatic and idealistic approach of finding members that outperform in all objectives. This forms the basis of the multiobjective approach that is the new paradigm for this thesis.

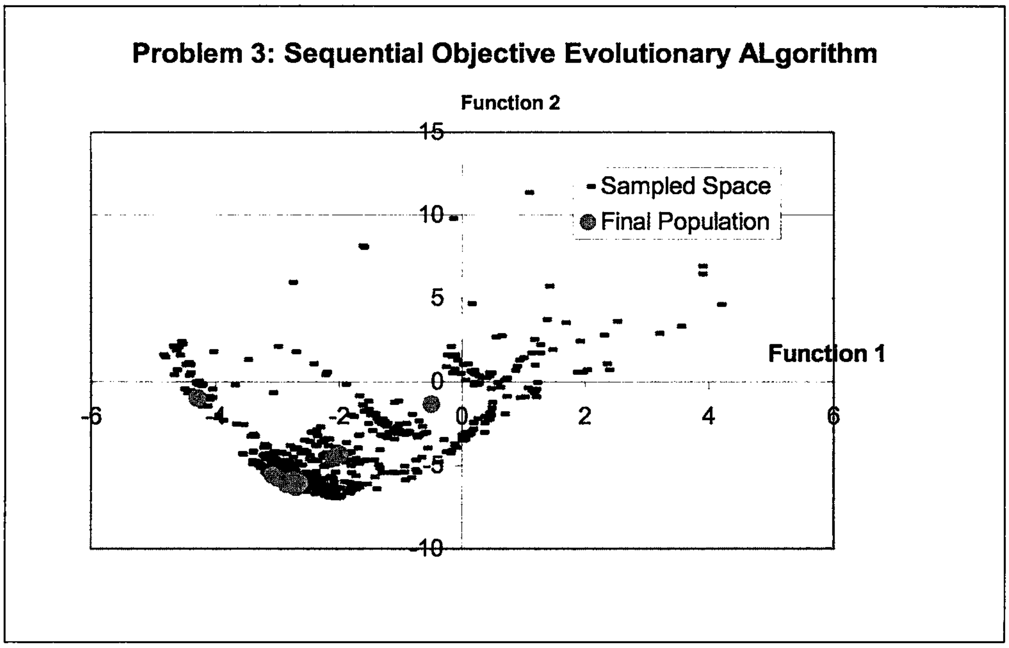

Figure 8.17 Problem 3 Solution using SOEA Methodology

There are some limitations to using this method. Compared to the previous two methods, this methodology takes more computational time, even though it may find the optimal region more rapidly. This is because each objective is now evaluated separately and the optimization is run sequentially. If some kind of parallelization of the process is feasible, then this would streamline the program, but in fact it may be better to run the program as a sequence in order to capitalize on the evolutionary nature of the algorithm.

Nevertheless, despite the increase in computational time from a single evaluation to a multiple evaluation based on the number of objectives, which for the hull form optimization problem is now three times the single objective problem, the methodology is successful in eliminating the challenges posed by the weighting preference matrix approach. Further instead of trying to investigate all members of the population that are non-dominated along the entire Pareto optimal front, it focuses on members that perform well in all objectives. For these reasons, the methodology is exclusively used in the application to hull form optimization.

9. MULTI-SPECIES EVOLUTIONARY OPTIMIZATION

9.1 Multiple Hull Form Requirements

The previous sections have been concerned with developing a methodology to conduct hull form optimization based on the methods of evolutionary algorithms using various tools to evaluate the hull performance. In developing the methodology a method to conduct multiple objective optimization is proposed in Chapter 8. The method does not require aggregating weights or the determination of which non-dominated solution is best from the Pareto front.

Another issue that is particular to hull form optimization that should be considered with respect to evolutionary optimization concerns the use of multiple hull forms. While the methodology is able to compare different vessels by running the program multiple times for different vessel hull forms and comparing the final results, there is the possibility of comparing different vessel hull forms while conducting the optimization process.

There are three ways in which the comparison of different hull forms can be conducted. These can be summarized as follows;

- Single Runs. Run the evolutionary optimization program for each hull form individually and compare the final results. This method may allow parallel computation on different machines and can provide more evaluations for a single hull form then a combined program. The drawback may be that forms which are not superior are required to be fully evaluated before being discarded.

- Parallel Optimization. This is actually a form of the previous method which maintains the same number of hull types form start to finish during the optimization so that each hull form is evaluated for as many generations as the program is run times as many members of the hull form is represented in the subpopulation for that hull form. The advantage is only that the program can input a number of different hull forms and can be left run as a batch run.

- Evolutionary Optimization. In this method the members of the population compete in the same manner as fitter members of a single hull type such that the fitter hull types will eventually take over the population. This utilizes the principal again of evolutionary optimization of survival of the fittest.

Thomas (1998) used the latter approach for different configurations of submersibles. In that application, each configuration had to be modeled using different chromosomes as different parameters are used as in Figure 9.1. For example the chromosomes on the left in the figure are from the same species and use the same chromosomes, where each of the variables or parameters have the same number of bits. In the chromosome on the right, the chromosomes have a different number of bits and represent different variable according to their coding of the problem solution. Even if the chromosomes have the same length or number of bits, the parameters may still represent different variables and should be used for crossing over.

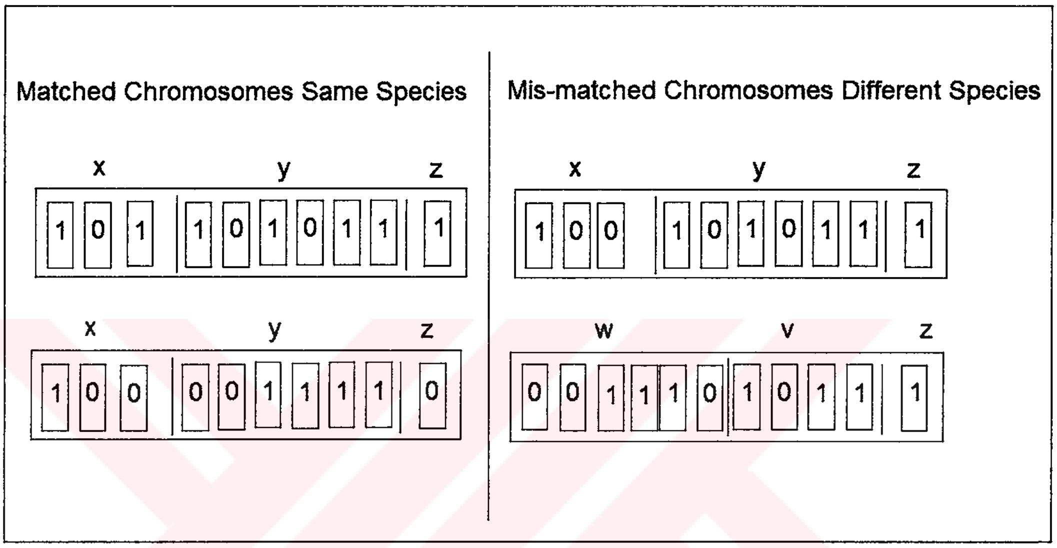

Figure 9.1 Matched and Mismatched Chromosomes from Different Species

In the multi-species methodology, the algorithm takes whichever configuration performs the best and uses this species in the selection for the new generation. As shown in Table 9.1, if Hull 1 performs the best by having lower resistance, then Hull 2 and so forth, then the species Hull1 has a higher probability of being selected for a parent. This necessitates having at least two variants of each hull form for the crossover.

Table 9.1 Examples of Species and Selection Probability

Species	Resistance Index	Fitness	Probability of Selection	
Hull 1	0.001	1	0.571429	57.1%
Hull 2	0.002	0.5	0.285714	28.6%
Hull 3	0.0025	0.25	0.142857	14.3%
Hull 4	0.003	0	0	0.0%
	Totals	1.75	1	

Several issues need to be resolved for this methodology to be implemented. While for the hull form optimization problem the chromosomes are the same, in fact a different set of offsets could be used with different waterlines and stations. Therefore it appears prudent that each hull form should be allowed to cross over with only members of its own hull form type. This separation of different types is referred to as different species. Each species is restricted to swapping chromosomes with its own member species.

However the possibility of crossover with different hull forms could be accommodated. Nevertheless, this apparent conflict would entail decidedly different hull forms being produced in a more random and almost haphazard fashion as shown by the tanker and sailboat hulls shown in Figure 9.2. Though this could be investigated separately, it seems prudent to limit the optimization to being able to compare different species.

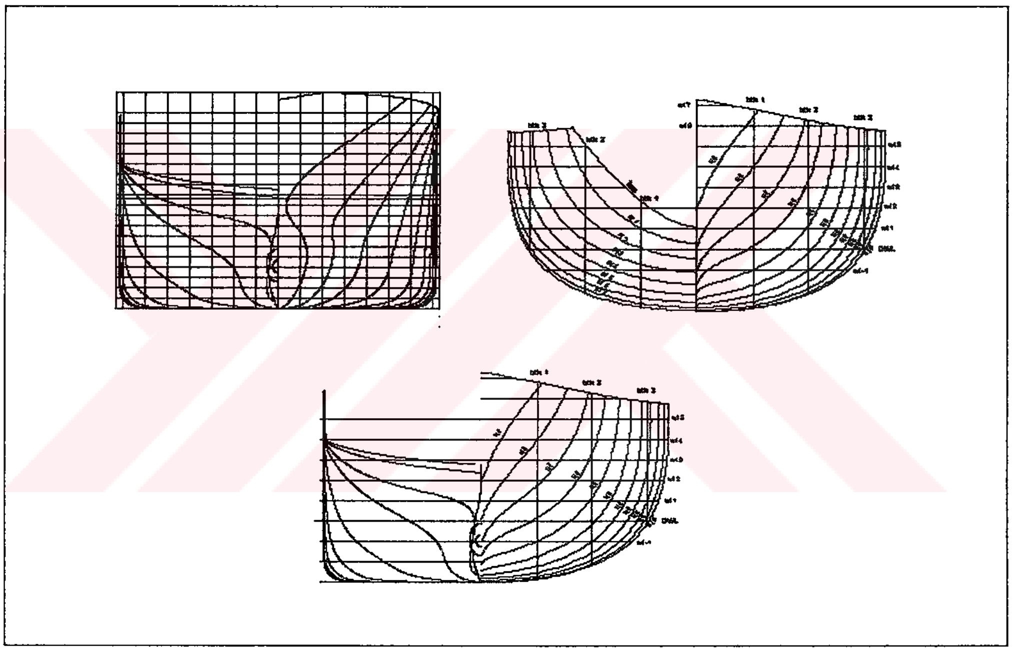

Figure 9.2 Mismatching Different Hull Forms

For that reason, a multi-species algorithm was produced. Though the example shown in Figure 9.2 was an extreme case, and the possibility does exist for combining hulls from a similar, if not the same species, the need for a multi-algorithm to compare different hull forms appears to be a typical question for a designer and therefore needed to be developed. Each members of the population now has an additional index to describe the species. According to the number of input files used for the hull forms there will be created a population with a number of variants in each hull form in the first population. These are then evaluated over the next generations.

Where the evolutionary optimization differs from merely parallel optimization is in the selection process. If a particular species is not performing well, then that competing during the selection process will eventually eliminate that species. This mean that eventually, only one species or hull form would be selected and this one would be the optimal hull form given the requirements.

9.2 Multi-Species Application

In Figure 9.3 an example population using 4 different hulls form the ITU series of fishing boats was evaluated using the multi-species algorithm, using only two objectives of seakeeping and resistance for clarity. In the figure, each point represents a sample with one of the hulls, and the final population after 51 generations is shown. For each of the four hulls, 20 random variants of each hull were created in the initial population for a total of 80 members. The final population consists of 79 members of only the second hull form along with a single member of the 4th hull type. Hull 1 and hull 3 were eliminated at the 14th and 24th generations respectively.

Figure 9.4 shows a comparison of the different hulls with individual hulls distinguished. Hull 2 can clearly be seen to be lower in resistance, while some members have a lower seakeeping index; Hull 2 is close to these other seakeeping values while having markedly lower resistance. The main issue of using a multi-species algorithm is to be able to compare these different hulls, and a designer could choose a hull having higher resistance but a lower seakeeping index if this was the main objective.

In Figure 9.5 only the optimal values for different hulls are shown which had both progressively lower seakeeping and resistance values. The final optimal Hull 2 shows the direction of progress. In fact Hull 4 does not have a global optimal value of both seakeeping and resistance but was maintained in the population up to the 51st generation. It is apparent that with one member of the population of 80 it has a small chance of winning over its dominant rival Hull 2. In developing the program a number of issues arise that are a common feature of evolutionary algorithms that deal with the diversity in the population. The performance criterion from the original fitness scaling formula causes quick elimination of the less fit hull types. In order to retain the hulls for more generations, the fitness function was changed to create smaller differences in the probabilities of between each hull form.

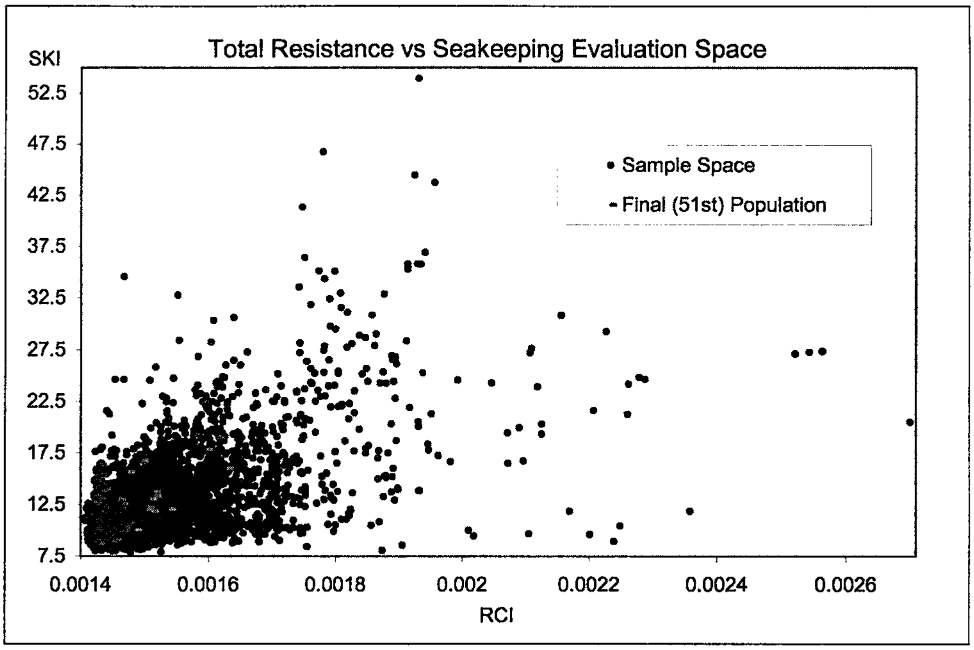

Figure 9.3 A Multi-species Evolution showing the Total and Final Population

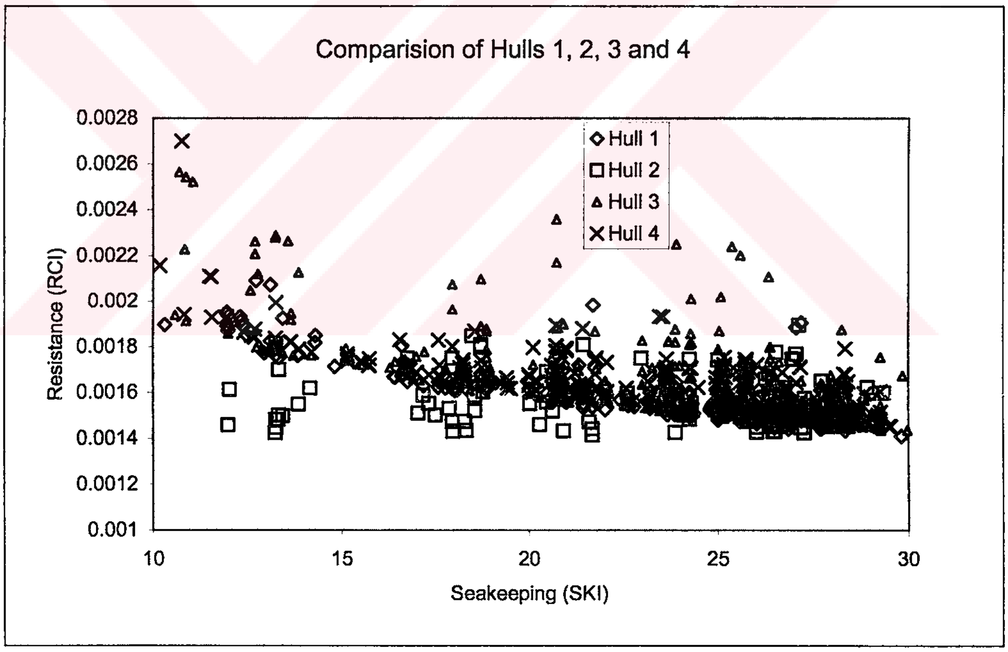

Figure 9.4 Comparisons of Four Different Hull Forms

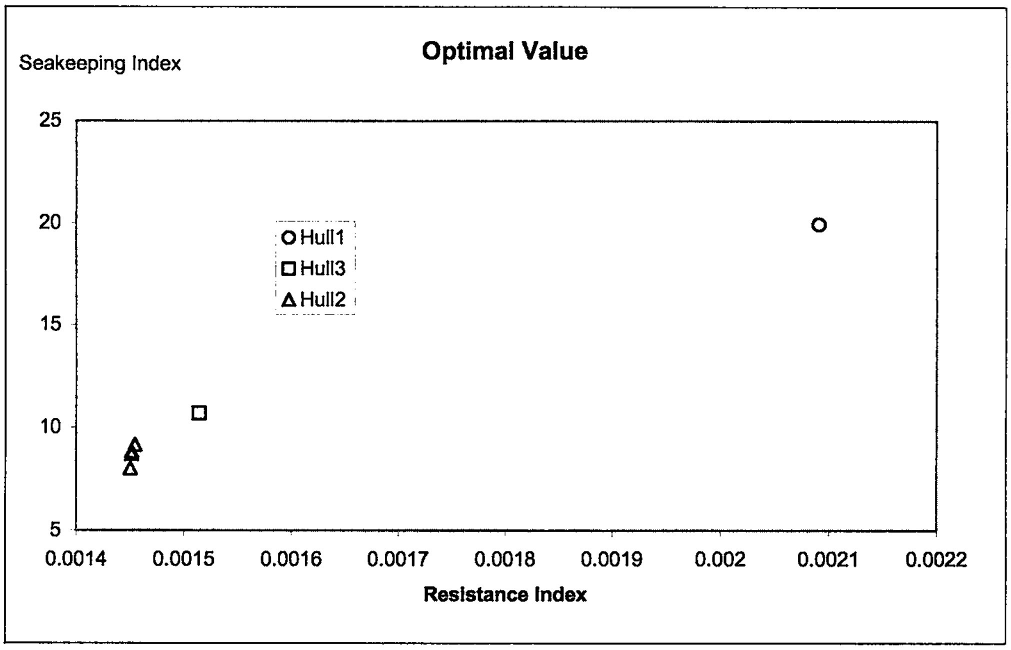

Figure 9.5 Comparison of Multi-Species Showing Optimal Results

The means by which this was accomplished was by expanding the range of the fitness function. This can be achieved by maintaining a global maximum or minimum and comparing each generation fitness to the global values rather than the local generation. While this helps to keep more variety in the population it only appears to extend each hull for an order of 10 generations from that shown in Figure 9.6 while a complete run may take 1000 generations. This aspect of maintaining the population may require further investigation.

One method that could be utilized is to deliberately keep different members of the population regardless of their performance. This could be achieved by marinating a few variants in each population that perhaps have the highest performance in their species during each generation, then filling the rest of the population with the species with the best performances. This aspect has not been investigated so far.

Another issue that arises in multiple species is how the initial population is developed. The population is based on the number of different hull forms multiplied by the number of variants of each hull form to create the total initial population. For example, if four hull forms are used and 10 variants for each hull is used then the initial population consists of 40 members.

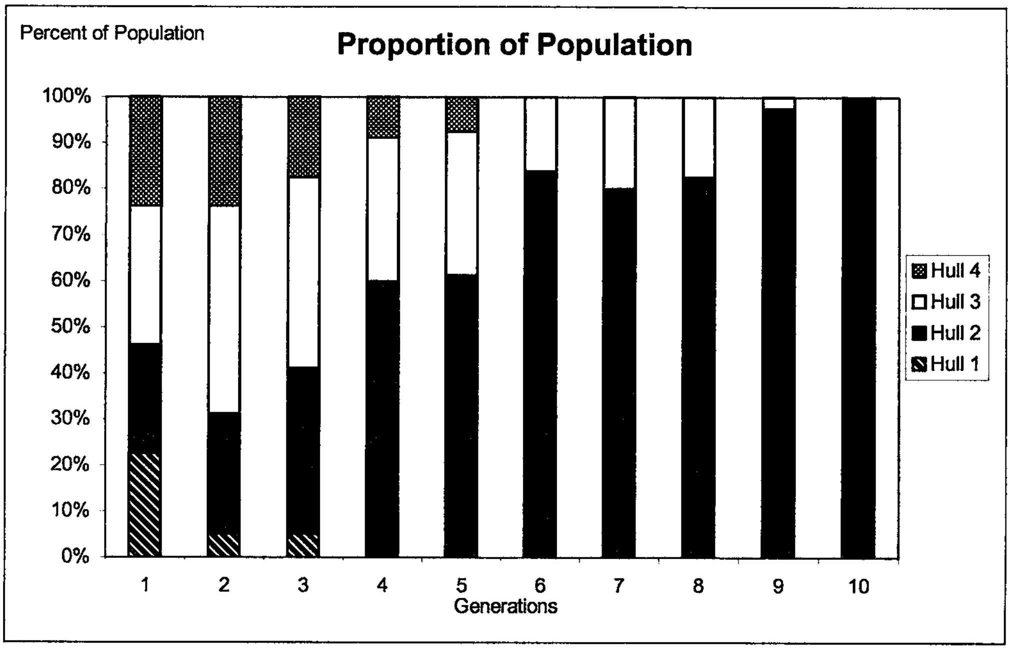

Figure 9.6 Proportion of Population for Each Hull Type

Given that the number of initial variants can be varied, it is possible that a different optimum hull can be found due to the fact that the initial variants of each hull form are randomly chosen. Therefore some promising candidates may not be created initially out of one hull form. So far the only method that can overcome this problem is to create sufficient number of initial variants such that the correct hull is determined as having the most benefit. However a large number of initial variants of each type may be required leading to the problem of having a large population.

10. RESULTS

10.1 ITU Fishing Boat Optimization Results

One of the main investigations in this thesis is based on developing a methodology that can be used for fishing boat hull optimization. The ITU fishing hull series have been used mainly to compare the optimal hulls derived with the well-known resistance characteristics of the original hull. As a series, the different hull forms are similar enough in application to test the methodology for the development an optimal fishing boat. Since none of the hulls are exactly alike, they represent a good series of offsets to use for the optimization.

While developing the program, some fishing boat hull characteristics as described in Chapter 4 on design requirements were utilized. These included a GM requirement that was set at 0.40 metres, and a fish hold volume requirement which using the example from Grubisic (1997) was set at 95.2 cubic metres. This is calculated using a correlation formula with respect to the length of the waterline. In addition the volumetric displacement was added for some cases.

When these requirements are made arbitrarily small then these restrictions, as penalties on the performance of the design, would no longer apply. Under Chapter 3 describing the hull model, the fishing boat example introduced some restrictions on the hull for the length, beam and draft. Grubisic used a length restriction between 10 and 30 metres. In all of the runs the length tends towards the largest length as being more optimal with regard to resistance. Unless the optimisation penalizes length possibly due to cost or another relation, if a smaller vessel is required then a limit must be imposed on the maximum allowable length. This maximum length restriction could be based on restrictions according to the type of fishing as imposed by quotas, or port restrictions, as well as by the cost of the vessel. Cost has not been included in the methodology.

The other principal parameters were chosen so as to be similar to other studies. In the example by Grubisic, the beam was restricted between 2.5-10 metres, but in the ITU series the beam is only as large as 5.714 metres. Therefore the upper limit for the beam was restricted. Initial runs were conducted with the limits on the beam imposed between 4-8 metres. Given that the minimum length is 10 metres, a beam of 8 metres would create a very boxy boat. Grubisic used additional constraints on L/B, B/T, B/D, C_b and the length to displacement ratios in his concept design methodology. These ensure that the hull form falls within the limits that are typical for these fishing boats for secondary hull form coefficients.

However in the current methodology imposing arbitrary limits on the hull form using known coefficients is replaced by the search of the design space driven by performance indices. However since these secondary coefficients are not used it is prudent to limit the main dimensions so as to not investigate designs that are too unreasonable, as discussed in Chapter 3. Therefore in addition to restricting the beam, the draft is further restricted on a case-by-case basis rather than using a broad range of parameters.

In order to provide a hull form satisfying the design requirements, a fish hold volume is included that is set at 95.2 square meters to compare with the example from Grubisic. The series of runs was conducted with the restrictions in place for the minimum fish hold requirement of as well as the GM requirement of 0.40 metres. This is to be able to compare with the Grubisic example concept (GEC) fishing boat. An additional design requirement was imposed for a waterplane coefficient of 0.80. Although this is represented by a secondary hull form coefficient, the requirement was not directed to modify the hull form but as a means of maintaining a workable deck area. Another and possibly better method for ensuring deck area would be to specify the deck area as a constraint for the size of vessel being considered. In some cases this waterplane coefficient restriction is not used.

10.2 ITU 1B with Fixed Dimensions

Two different members of the ITU series are optimized with the given constraints on the length, beam, and draft. However it is convenient for comparison to look at the resulting hull form if the principal parameters remain constant, and the displacement is set as a constraint. In this case the only change is the hull form and offsets and the fish hold constraint is removed. Two iterations of the B-spline surface are used to obtain a fair hull, and the maximum variation in the offsets is $\pm 90\%$ of each offset interval as described in Chapter 3. Figure 10.1 shows the change in the hull form in which the principal dimensions are fixed for ITU 148/1B using an initial population of 20 hull variants which are optimized over 100 generations. The last optimal hull as listed in Table 10.1 is used in Figure 10.1. The changes in the hull form are not very great as expected, though some difference in the sections can be seen. The extreme ends of the hull appear to have widened whereas the mid-ship, though nearly the same, has narrowed. The waterline except at the mid-section shows a tendency to narrow. This is probably in response to minimize the resistance, which is subsequently made up in the rest of the body by having fuller sections elsewhere. However, since the optimization is not solely a function of resistance, this observation cannot be made on the basis of one performance index.

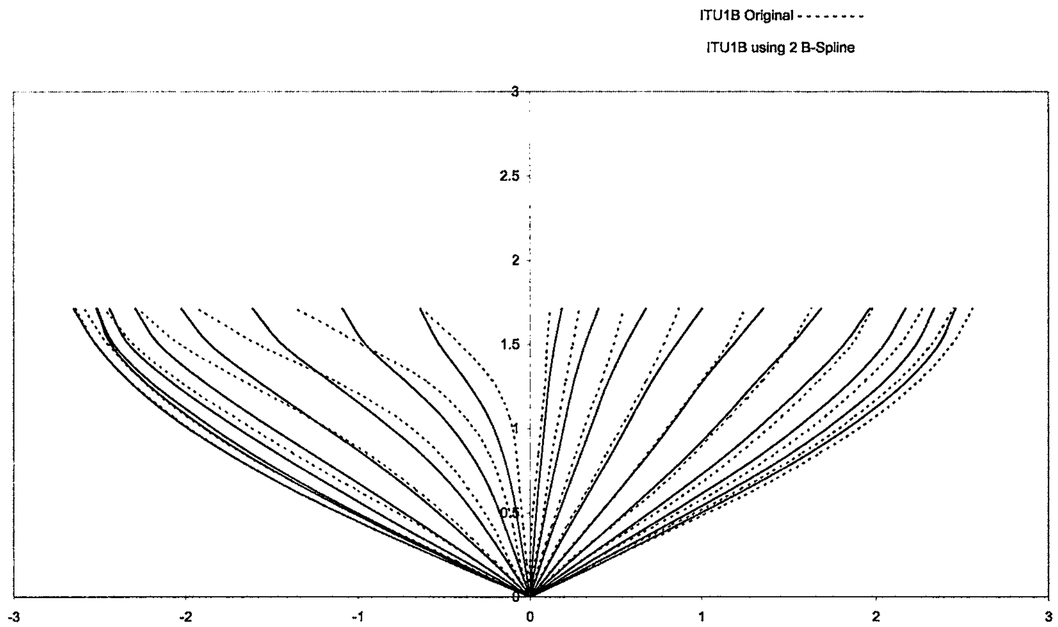

Figure 10.1 ITU 148/1-B Original and Modified Hull with Fixed Principal Parameters

Since there are improvements in the performance as shown in the table up to the 55th generation, an exhaustive search of the design space would use a greater number of generations. The results given by Dejhalla et al (2002) and Yasukawa (2000) after a few hundred generations are limited and further refinement might be obtained. To optimise an already fixed hull form as in this ITU1b example, using GA to change offsets gives better wave and total resistance. Using a 3-D resistance theory provides a more definitive resistance evaluation of candidates, but it is more difficult to conduct an exhaustive search due to the limited number of generations.

However as shown by the performance objectives in Figure 10.2, improvements in the hull form can still be made with a limited number of runs. The optimal results tend to plateau quite rapidly. Only 100 generations are used to demonstrate the methodology in most of the following examples. More runs could be conducted for an exhaustive study of a particular hull form.

Table 10.1 ITU 148/1-B Fishing Boat Hull with Fixed Dimensions

Generation	Population	Species	Length	Beam	Draft	Volume	GM	Fish Hold	RCI	SKI	STBX
1	2	1	18.5	5.24	1.71	50.91	0.97	52.06	0.007205	4.669693	0.050104
1	3	1	18.5	5.24	1.71	50.85	0.99	52.06	0.007017	4.494296	0.051683
1	4	1	18.5	5.24	1.71	50.75	1	52.06	0.007115	4.437648	0.051134
1	6	1	18.5	5.24	1.71	51	1	52.06	0.007114	4.479531	0.051749
1	12	1	18.5	5.24	1.71	50.99	1.02	52.06	0.007014	4.438541	0.052489
1	6	1	18.5	5.24	1.71	51.09	1	52.06	0.007105	4.479757	0.051963
9	1	1	18.5	5.24	1.71	51.13	1.01	52.06	0.00694	4.325109	0.052591
10	3	1	18.5	5.24	1.71	51.11	1	52.06	0.006944	4.284772	0.052369
10	18	1	18.5	5.24	1.71	51.12	1.01	52.06	0.006941	4.267691	0.052512
11	11	1	18.5	5.24	1.71	51.15	1.01	52.06	0.006938	4.250943	0.052617
11	6	1	18.5	5.24	1.71	51.15	1.01	52.06	0.006939	4.277811	0.052617
11	9	1	18.5	5.24	1.71	51.16	1.01	52.06	0.006937	4.277811	0.05268
11	11	1	18.5	5.24	1.71	51.15	1.01	52.06	0.006938	4.277811	0.052617
12	1	1	18.5	5.24	1.71	51.16	1.01	52.06	0.006937	4.244972	0.052663
12	10	1	18.5	5.24	1.71	51.16	1.01	52.06	0.006937	4.244276	0.052696
12	12	1	18.5	5.24	1.71	51.14	1.01	52.06	0.006937	4.247	0.052713
12	15	1	18.5	5.24	1.71	51.14	1.01	52.06	0.006937	4.247	0.052713
13	7	1	18.5	5.24	1.71	51.12	1.01	52.06	0.006937	4.242437	0.052822
13	18	1	18.5	5.24	1.71	51.14	1.01	52.06	0.006936	4.247386	0.052713
13	6	1	18.5	5.24	1.71	51.13	1.01	52.06	0.006932	4.23457	0.052726
13	15	1	18.5	5.24	1.71	51.12	1.01	52.06	0.006937	4.242437	0.052822
13	19	1	18.5	5.24	1.71	51.12	1.01	52.06	0.006936	4.242437	0.052789
14	9	1	18.5	5.24	1.71	51.12	1.01	52.06	0.006936	4.242437	0.052789
14	16	1	18.5	5.24	1.71	51.13	1.01	52.06	0.006935	4.241389	0.052856
14	3	1	18.5	5.24	1.71	51.13	1.01	52.06	0.006935	4.241389	0.052856
15	3	1	18.5	5.24	1.71	51.13	1.01	52.06	0.006934	4.240547	0.052856
21	10	1	18.5	5.24	1.71	51.18	1.01	52.06	0.006934	4.220845	0.052856
22	5	1	18.5	5.24	1.71	51.18	1.01	52.06	0.006934	4.22006	0.052856
23	13	1	18.5	5.24	1.71	51.19	1.01	52.06	0.006931	4.206808	0.053036
23	15	1	18.5	5.24	1.71	51.19	1.01	52.06	0.006932	4.206576	0.053036
24	20	1	18.5	5.24	1.71	51.2	1.01	52.06	0.006931	4.205126	0.052919
25	6	1	18.5	5.24	1.71	51.21	1.01	52.06	0.006931	4.203059	0.052919
25	7	1	18.5	5.24	1.71	51.2	1.01	52.06	0.006932	4.204811	0.052935
25	9	1	18.5	5.24	1.71	51.19	1.01	52.06	0.00693	4.205237	0.053053
26	3	1	18.5	5.24	1.71	51.21	1.01	52.06	0.006931	4.203484	0.052935
27	4	1	18.5	5.24	1.71	51.18	1.01	52.06	0.006931	4.206887	0.053036
27	14	1	18.5	5.24	1.71	51.18	1.01	52.06	0.00693	4.205089	0.053103
27	18	1	18.5	5.24	1.71	51.19	1.01	52.06	0.006931	4.205469	0.053036
28	11	1	18.5	5.24	1.71	51.18	1.01	52.06	0.00693	4.205436	0.053166
28	15	1	18.5	5.24	1.71	51.19	1.02	52.06	0.00693	4.20513	0.05312
28	15	1	18.5	5.24	1.71	51.19	1.02	52.06	0.00693	4.205283	0.05312
28	19	1	18.5	5.24	1.71	51.19	1.02	52.06	0.00693	4.20513	0.05312
29	12	1	18.5	5.24	1.71	51.19	1.02	52.06	0.006929	4.205631	0.05312
30	5	1	18.5	5.24	1.71	51.19	1.02	52.06	0.006929	4.204849	0.05312
30	10	1	18.5	5.24	1.71	51.19	1.02	52.06	0.006929	4.204849	0.05312
30	11	1	18.5	5.24	1.71	51.19	1.02	52.06	0.006929	4.205631	0.05312
30	17	1	18.5	5.24	1.71	51.2	1.02	52.06	0.006929	4.2054	0.05312
30	20	1	18.5	5.24	1.71	51.19	1.02	52.06	0.006929	4.205002	0.05312
30	10	1	18.5	5.24	1.71	51.2	1.02	52.06	0.006928	4.205002	0.05312
31	3	1	18.5	5.24	1.71	51.18	1.02	52.06	0.006928	4.205438	0.053196
31	16	1	18.5	5.24	1.71	51.2	1.02	52.06	0.006929	4.204564	0.05312
41	5	1	18.5	5.24	1.71	51.14	1.02	52.06	0.006927	4.207366	0.053166
41	13	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006928	4.19998	0.053183
41	8	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006928	4.199855	0.053183
42	4	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006927	4.200319	0.053233
42	9	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006926	4.200444	0.053216
47	11	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006927	4.203287	0.053229
49	18	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006927	4.200474	0.053246
49	2	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006927	4.200474	0.053246
49	7	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006926	4.199787	0.053246
50	18	1	18.5	5.24	1.71	51.14	1.02	52.06	0.006925	4.200195	0.053229
50	19	1	18.5	5.24	1.71	51.14	1.02	52.06	0.006925	4.199595	0.053246
52	1	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006926	4.199562	0.053246
53	1	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006926	4.199562	0.053246
53	10	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006925	4.199244	0.053229
53	11	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006925	4.195307	0.053229
53	11	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006925	4.192929	0.053229
54	3	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006924	4.192537	0.053229
54	20	1	18.5	5.24	1.71	51.15	1.02	52.06	0.006924	4.194913	0.053229
55	6	1	18.5	5.24	1.71	51.16	1.02	52.06	0.006924	4.199739	0.053229

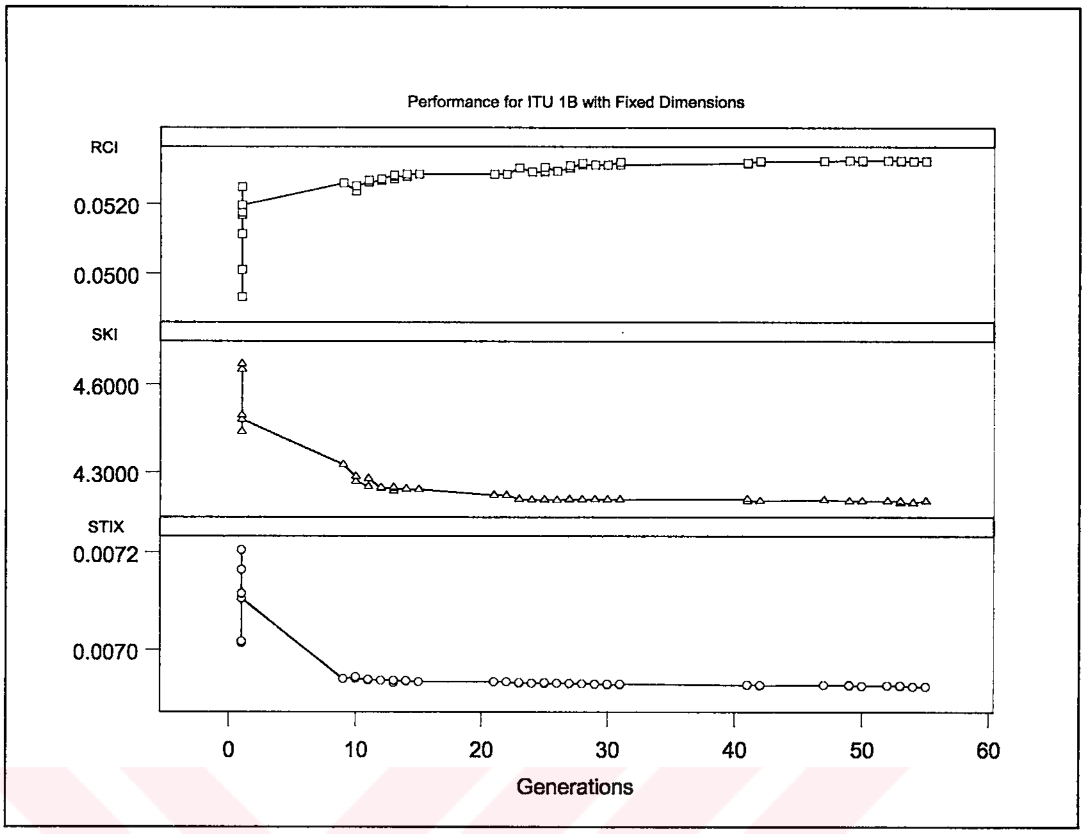

Figure 10.2 ITU 148/1-B Performance Objectives for Fixed Dimensions

The performance indices for resistance, seakeeping and stability are plotted in Figure 10.3 to show how the results are grouped. The corner of the x and y axis with most of the samples indicate that the minimum resistance and ship motion is in this area. The z-axis shows the stability index. While the resistance and ship motion index are being minimized, the stability, possibly due to the minimum change in the dimensions, changes very little. Nevertheless as shown previously in Figure 10.2, some improvement in the index during the optimization is possible.

Comparing the actual performance from the evolved hull with the original ITU 148/1-B hull, the pitch is somewhat larger at lower Froude numbers but is reduced at higher Froude numbers, as seen in Figure 10.4. The heave as shown in Figure 10.5 is lower at lower Froude numbers and coincides at larger Froude numbers. The overall result is to lower the seakeeping index.

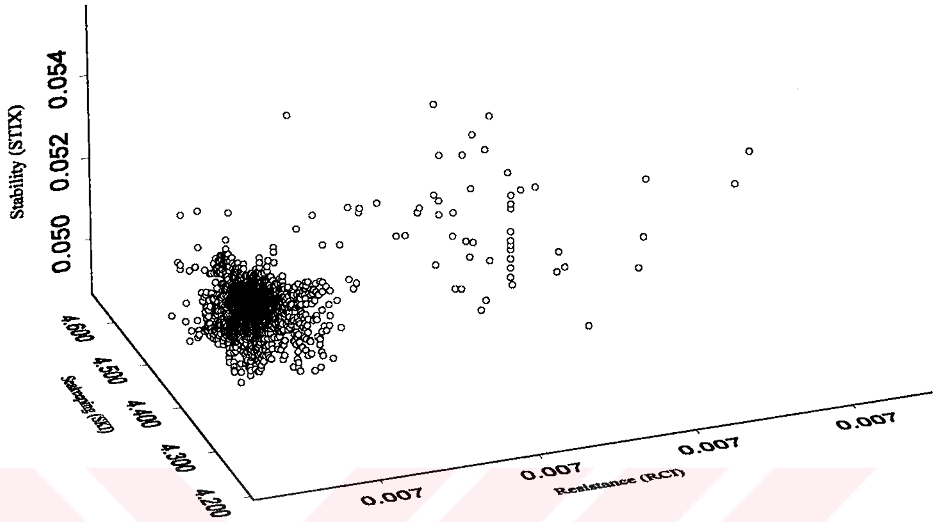

Figure 10.3 ITU 148/1-B Performance Objectives

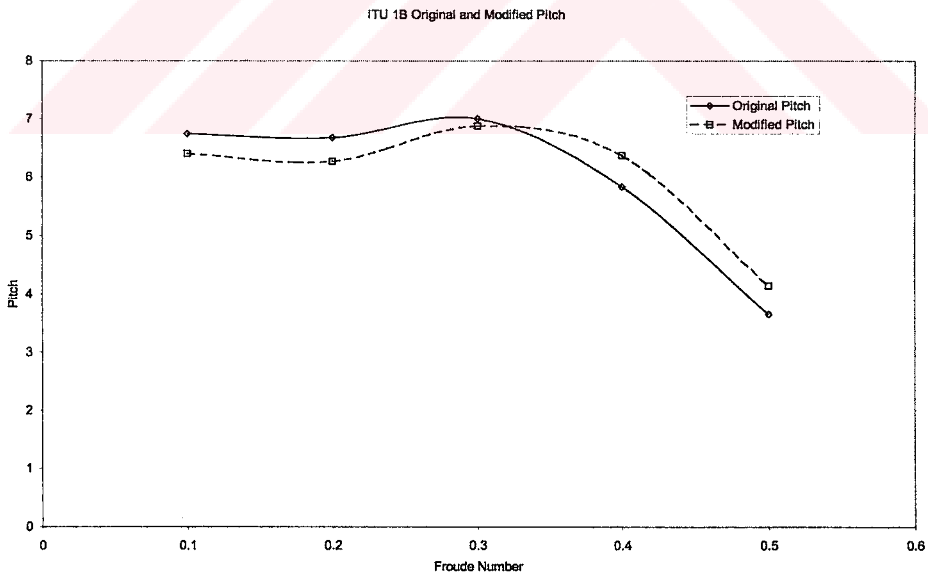

Figure 10.4 ITU 148/1-B Original and Modified Pitch Motion

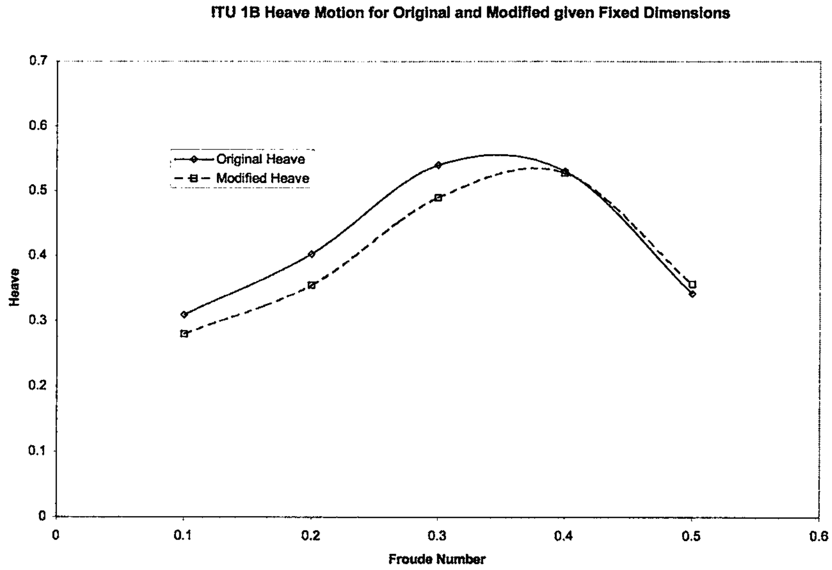

Figure 10.5 ITU 148/1-B Original and Modified Heave Motion

For resistance, the total and wave resistance coefficients are shown in Figure 10.6. The wave resistance at higher Froude numbers is considerably lower, from 3.85e-2 to 3.28e-2 at a Froude number of 0.5, which is a reduction of 14.8% of the wave resistance.

These improvements come with a cost in stability from the original hull form, as dynamic stability as given by the area under the GZ curve shown in Figure 10.7 is somewhat reduced. The stability however varies a great deal as shown by the samples in Figure 10.3, and a different optimal form having good resistance and seakeeping as well as stability characteristics can be chosen. For the ITU 1B example the GM is 1.057 metres for the modified hull and 1.111 metres for the original hull form. The KM, which is independent of KG, is 2.749 metres and 2.65 metres for the original and modified hulls respectively.

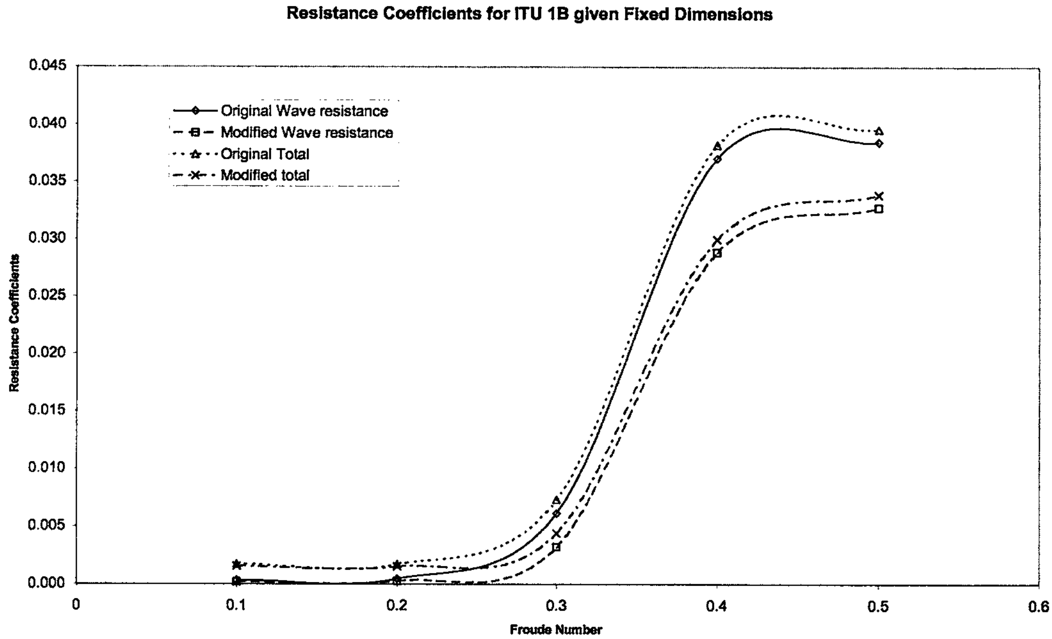

Figure 10.6 ITU 148/1-B Original and Modified Resistance for Fixed Dimensions

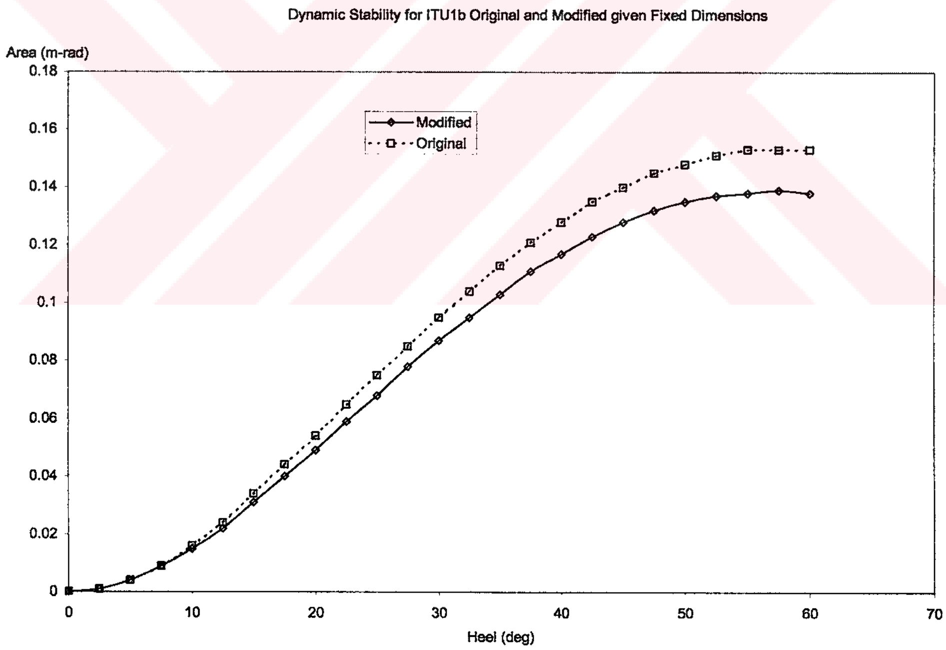

Figure 10.7 Original and Modified ITU 148/1-B Dynamic Stability for Fixed Dimensions

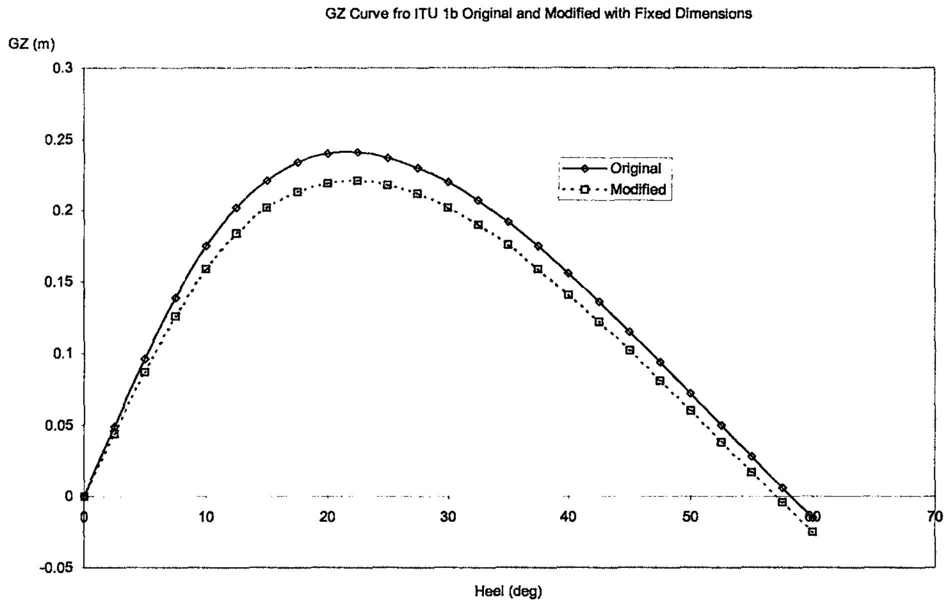

Figure 10.8 GZ Curve for Original and Modified ITU 148/1-B given Fixed Dimensions

10.3 Evolving ITU 1B by Changing Principal Parameters

If the principal parameters are allowed to vary according to the limits described previously, some quite different and unusual results occur. Using a fish hold volume requirement 95.2 cubic metres, as in the example by Grubisic, re-running ITU 148/1-B yields the optimal hull as shown in Figure 10.9. No constraint is set for the actual displaced volume in this particular run.

The beam in this case is quite wide and the draft quite shallow. The limits in the main dimensions explored a space with a minimum draft of 1.5 metres, a maximum beam of 8 metres and a maximum length of 30 meters. In trying to achieve minimum resistance the hull is evolving towards maximum length, while for stability the hull tends towards the maximum beam. The shallow draft is driven by the minimization of resistance given that there is no restriction on displacement. The displacement achieved was only 110 cubic metres. However much that this wide flat hull is notable in Turkish fishing fleets, the results may be impractical.

As in the previous case only 100 generations with a population of 20 variants was run without competition from other species. The favourable winners from these could be used in a multi-species competition to derive the optimal hull using the multi-species evolutionary optimization approach. Two iterations of the B-spline surface is used to obtain a smooth hull and $\pm 90\%$ variation in the offsets interval is allowed. The body plan shown in Figure 10.9 for the optimal hull shows a larger beam to achieve a larger vessel to match the requirement for the fish hold volume. This results in a vessel with more displacement but, interestingly, a shallower hull.

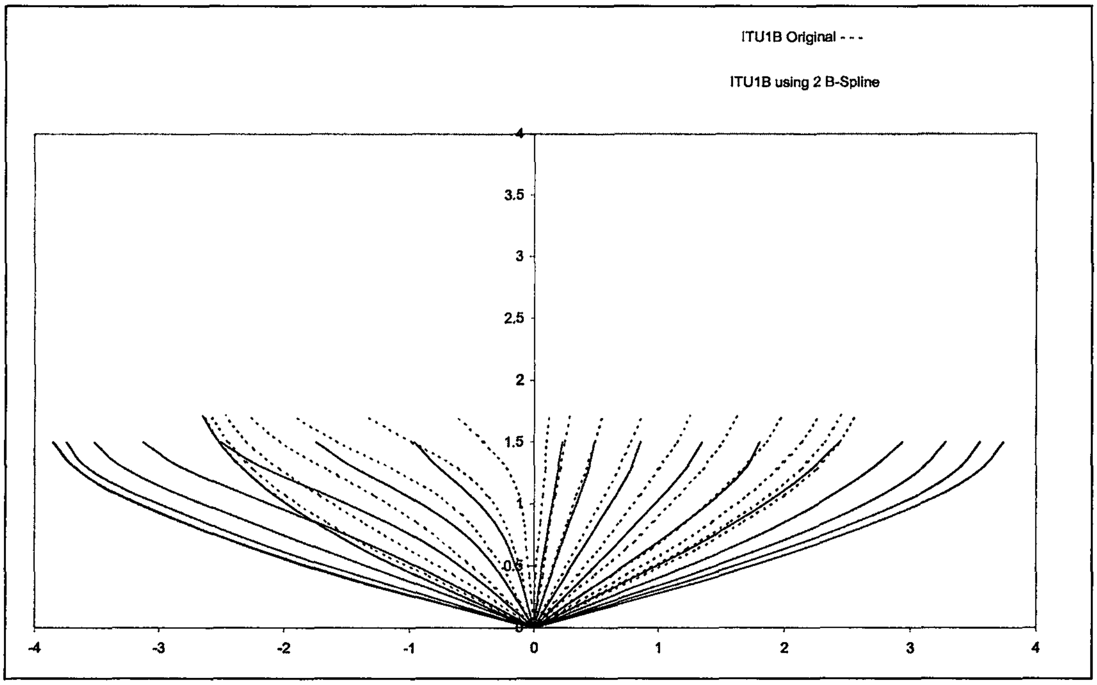

Figure 10.9 ITU 148/1-B Original and Evolved Hull Form

The performance characteristics are shown in Table 10.2. Improvements in all the performance characteristics are seen, however the fish hold volume is very large as it is calculated using a maximum depth formula from Grubisic. Figure 10.10 shows one view into the performance for resistance and seakeeping as they tend toward their respective minimums, with the 100^{th} generation or last population plotted to show how the optimization is working.

Though the performance of the vessel is optimal, comparison with the original hull form is hardly valid since the vessels have quite different displacements. Comparing with the example from Grubisic is also more difficult since there is no actual hull produced in the optimal solution by Grubisic. Table 10.3 summarizes the principal form parameters derived by Grubisic for a fishing boat hull with 95.2 cubic meters. As can be seen by the displacement, the weight of the fishing vessel to satisfy the design requirements for this size of fish hold volume is much more than the previous example. Therefore it may be required to be able to set a target volumetric displacement as well as fish hold volume in order to derive a hull with sufficient displacement for the expected weight. This does mean that a requited target displacement is available through other concept design methodologies.

Table 10.2 Performance Characteristics of ITU 148/1-B Hull Form for 100 Generations, 20 Variants

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	Fish Hold	RCI	SKI	STBX
1	2	1	16.89	7.7	2.71	61.09	2.74	63.82	0.005465	4.926985	0.492255
1	6	1	16.92	7.31	1.68	145.83	0.61	120.5	0.004392	2.533462	0.03613
1	10	1	23.72	6.96	2.99	42.15	0.81	21.09	0.011114	4.887931	0.039046
1	13	1	11.16	5.88	2.19	140.82	1.6	194.02	0.003252	2.462135	0.099192
1	19	1	29.29	7.22	2.16	44.95	1.81	47.35	0.004825	4.700465	0.160285
1	9	1	28	7.22	1.83	110.81	2.29	176.94	0.002903	3.613776	0.232249
1	14	1	28	7.31	1.68	101.02	2.74	179.5	0.002769	4.299418	0.49168
2	10	1	28.52	6.19	1.97	103.11	2.73	187.54	0.002693	2.924094	0.493401
2	20	1	28.61	7.31	1.68	101.01	2.74	179.5	0.002769	4.182054	0.491704
2	5	1	28.61	7.31	1.68	103.11	2.73	187.54	0.002693	2.896334	0.493475
2	11	1	28.61	7.31	1.68	103.09	2.73	187.56	0.002693	4.076886	0.493548
3	4	1	28.65	7.31	1.59	97.86	3.15	188.08	0.002622	3.970182	0.845163
3	16	1	28.65	7.31	1.68	103.5	2.78	188.08	0.002689	3.970182	0.501623
4	1	1	28.64	7.31	1.68	97.85	3.15	188.08	0.002622	3.757704	0.84521
4	15	1	28.72	7.31	1.59	98.12	3.15	189.14	0.002614	3.727604	0.84521
27	5	1	29.81	7.66	1.52	103.87	4.17	215.44	0.00259	1.756291	1.709745
27	2	1	29.81	7.66	1.52	103.91	4.17	215.44	0.00259	1.90745	1.70954
64	5	1	29.81	7.59	1.52	105.19	4.25	217.29	0.002585	1.708843	1.820032
64	12	1	29.81	7.72	1.52	105.48	4.3	217.29	0.002573	1.522815	1.822859
64	6	1	29.81	7.72	1.52	105.46	4.3	217.22	0.002574	1.732527	1.822859
65	14	1	29.81	7.72	1.52	105.42	4.29	217.22	0.002573	2.337786	1.823413
65	3	1	29.81	7.72	1.52	105.44	4.29	217.29	0.002573	1.474306	1.823413
65	16	1	29.81	7.72	1.52	105.46	4.31	217.22	0.002571	1.474306	1.824426
65	20	1	29.81	7.72	1.52	105.44	4.29	217.29	0.002573	1.474306	1.823413
66	18	1	29.81	7.72	1.52	105.3	4.28	217.29	0.002571	1.440974	1.827251
67	13	1	29.79	7.72	1.73	104.9	4.42	218.31	0.002567	1.525751	1.948366
68	18	1	29.81	7.7	1.51	104.05	4.28	216.65	0.002573	1.698565	1.869538

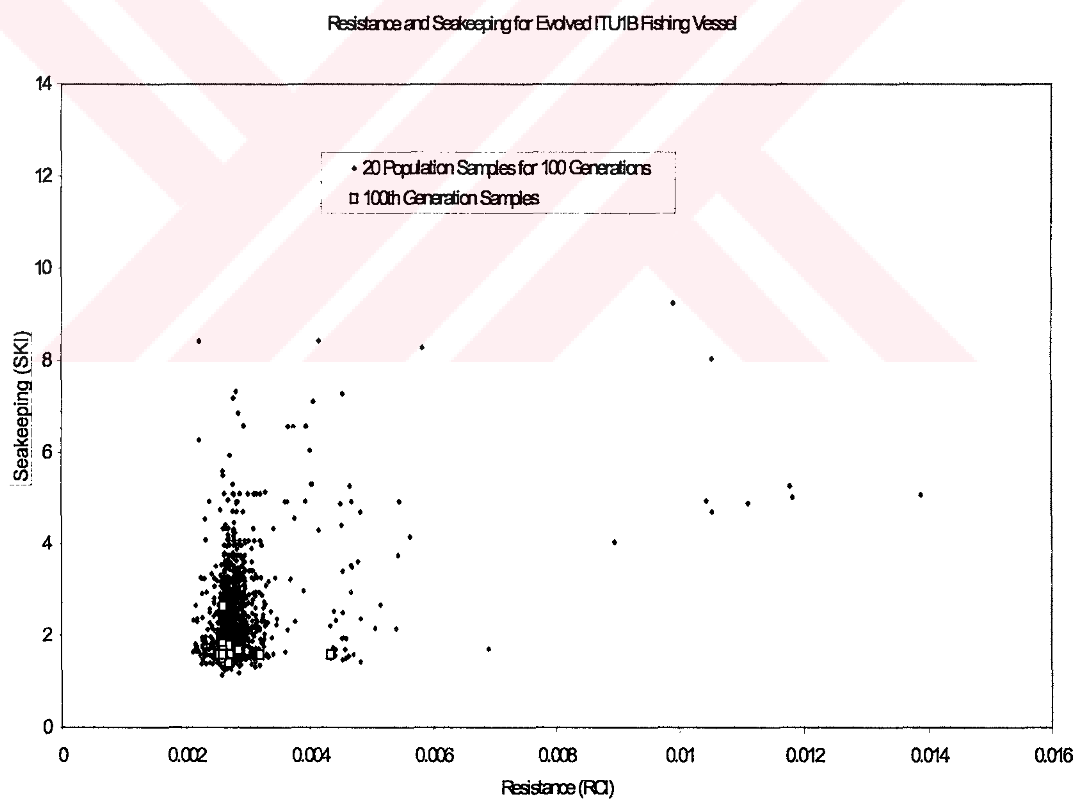

Figure 10.10 Seakeeping versus Resistance for ITU 148/1-B with Changing Dimensions

Table 10.3 Grubisic Example Concept (GEC) Fishing Boat Design Parameters

Characteristic	Optimal Result	Characteristic	Optimal Result
LOA	25.756 m	KG (arrival)	2.714 m
LPP	22.160 m	GM (arrival)	1.0 m
LWL	23.500 m	FHV	95.2 m^3
B	6.750 m	LCB/LWL	0.526
T	2.350 m	LCF	N/A
Volume	171.9 m^3	C_p	0.619
Displacement	178.1 t	C_b	0.461
V_{max}	10.68 kn	C_{wp}	0.797

Though it is impractical to compare the resistance, stability and seakeeping of the concept design through examination of a hull form with this example. Regression formulations such as Holtrop and Mennen can be used to give values of resistance, as shown in Figure 10.11.

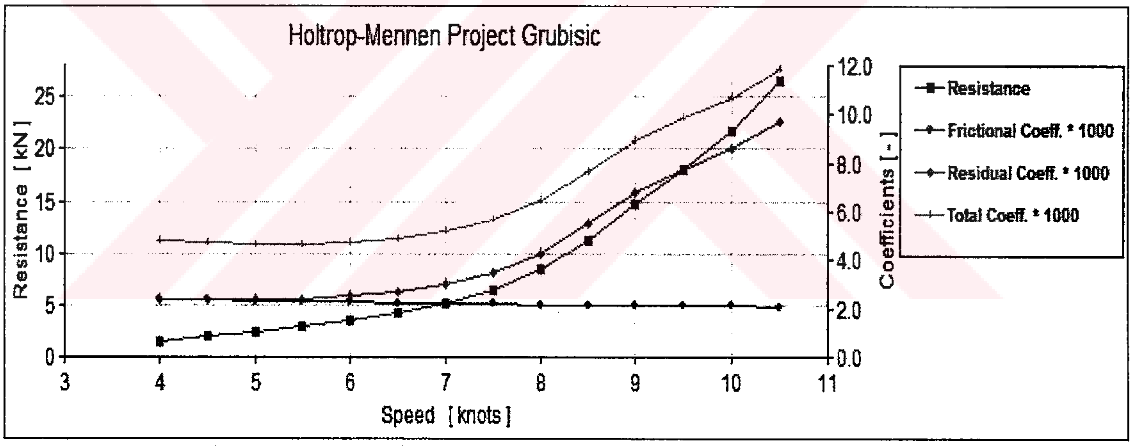

Figure 10.11 Resistance Predictions for Fishing Boat Example

In order to develop a hull that would additionally have the required displacement, the previous example could be increased in draft, or alternatively, an optimization run can be conducted with the volumetric displacement entered as a design requirement. Using the volume of 171.9 cubic meters from the Grubisic example, a run was conducted to derive the optimal hull based on ITU 148/1-B.

However due to the beam and draft restrictions allowing a wide shallow hull to be produced, the resulting hull forms could not achieve the target displacements, and remained similar in size to the previous example shown in Figure 10.9. As mentioned there are no secondary coefficients used to guide the design. For that purpose the parameters from the GEC fishing boat are explored to determine if ITU 1B can achieve a similar displacement but better performance. The beam is restricted from 6 to 8 meters, the length from 20-30 meters and the draft from 2-3 meters. The required volumetric displacement is set at 171.8 cubic meters and the fish hold volume of 95.2 meters is maintained.

As can be seen in Table 10.4, while in the initial population the displacements achieve the target along with satisfying the fish hold volume, there is excess in fish hold volume. This means that hulls with less displacement that still satisfy the fish hold requirement are maintained as the resistance is lower and the stability index is higher. This suggests that for the required displacement to be achieved, a deeper draft is required.

Table 10.4 ITU 148/1-B Hull Form Given Displacement and Fish Hold Volume

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	Fish Hold	RCI	SKI	STBX
1	2	1	27.03	6.28	2.13	172.5	1.01	132.76	0.003462	1.539907	0.0481
1	10	1	29.76	7.14	2.65	171.55	1.33	134.03	0.003215	1.799868	0.067106
1	16	1	27.03	6.28	2.13	111.03	1.02	80.84	0.003062	3.422175	0.048955
1	20	1	29.9	7.6	2.49	171.65	1.34	134.03	0.003215	1.824001	0.067229
1	1	1	29.9	7.6	2.49	171.92	1.34	134.03	0.003214	1.71013	0.067958
1	4	1	29.9	7.6	2.24	154.39	1.72	119.57	0.003083	1.71013	0.104316
3	16	1	29.28	7.1	2.24	141.19	1.37	108.13	0.003018	2.374882	0.072311
3	9	1	29.28	7.1	2.25	141.29	1.37	108.23	0.003005	2.365547	0.072735
4	12	1	29.28	7.1	2.25	141.54	1.37	108.25	0.003016	2.29882	0.073079
7	12	1	29.28	7.6	2.07	123.56	1.41	92.16	0.002775	2.086852	0.077385
7	9	1	29.28	6.6	2.08	124.14	1.43	92.16	0.002783	2.032069	0.078357
12	15	1	29.28	7.6	2.07	122.97	1.43	91.41	0.002756	1.920013	0.079846
21	2	1	29.9	7.04	2	130.45	1.91	97.35	0.00278	1.731499	0.129767
24	6	1	29.9	6.6	2.01	122.51	1.5	91.17	0.002679	1.809109	0.087633
28	13	1	29.9	6.82	2.07	130.59	1.6	97.41	0.002759	1.840400	0.094342
28	6	1	29.9	6.82	2.07	130.62	1.61	97.41	0.002756	1.820179	0.095005
37	4	1	29.9	6.72	2	124.71	1.63	92.63	0.002744	2.110093	0.097489
37	9	1	29.91	6.72	2	124.76	1.63	92.67	0.002741	2.796151	0.097608
74	11	1	29.73	6.72	2.01	124.77	1.65	92.44	0.002724	1.853646	0.100106

Table 10.5 shows the results when the draft is constrained 2.5-3.0 meters around the GEC value of 2.65 meters. In this case the displacement of 161.3 cubic meters is achieved, close to the target value of 171.8 cubic meters, but the fish hold volume exceeds the requirements at 121.9 cubic meters. The difference in displacement and cubic volume between the GEC value and this evolved hull form may be due to the simplified fish hold volume calculation used in the optimization, as well as the simpler design requirements.

Table 10.5 ITU 148/1-B Hull Form with Restricted Range of Draft

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	Fish Hold	RCI	SKI	STBX
1	2	1	27.03	6.28	2.63	154.7	0.61	121.25	0.003027	1.791197	0.039843
1	3	1	29.53	6.27	2.8	127.47	0.73	91.44	0.004258	3.288167	0.038484
1	4	1	22.87	6.68	2.72	184.31	1.17	141.61	0.003376	1.842463	0.057184
1	8	1	27.03	6.28	2.52	132.19	0.77	97.12	0.003089	2.497392	0.042249
1	12	1	27.03	6.28	2.52	132.21	0.77	97.12	0.003089	2.489153	0.042249
3	1	1	28.98	6.51	2.64	154.35	0.8	116.05	0.00295	1.821592	0.044912
19	15	1	29.28	6.49	2.53	148.95	0.89	111.71	0.002905	1.800255	0.047076
20	18	1	29.28	7.33	2.78	161.32	1.13	122.77	0.003078	1.587692	0.056752
29	20	1	29.24	6.96	2.53	159.83	1.14	120.3	0.003041	1.633744	0.05799
29	20	1	29.24	6.96	2.53	159.83	1.14	120.3	0.003041	1.633744	0.057973
79	16	1	29.24	7.35	2.51	161.31	1.22	121.94	0.003037	1.560304	0.062282

The resulting hull form for the evolved ITU 148/1-B vessel is shown in Figure 10.12. The draft is near the limit proposed, while the beam is wider and the length longer then the GEC boat. As it is possible that a cost relation would impose limits on length, the optimal form here should not be taken as the best concept design. The purpose here is to compare the hull forms developed with a known fishing boat concept design methodology.

Using the non-dimensional coefficient C_t for total resistance, and converting the speeds to Froude numbers, gives the results shown in Figure 10.13. The GEC vessel has a much higher coefficient of total resistance, but as mentioned, since an actual hull form is not used it is only a relative comparison.

Similarly a comparison of seakeeping could be conducted but the comparison may be rather arbitrary. However for the purpose of being able to conduct a comparison with known designs having only concept design parameters, the use of a regression equation for seakeeping could theoretically be used. For example, a ranking equation based on the seakeeping results for ITU fishing series can be used to compare the vertical motion of fishing boats. Unfortunately it requires knowledge of the centre of flotation and the vertical prismatic coefficient that is undetermined for the GEC fishing boat parameters.

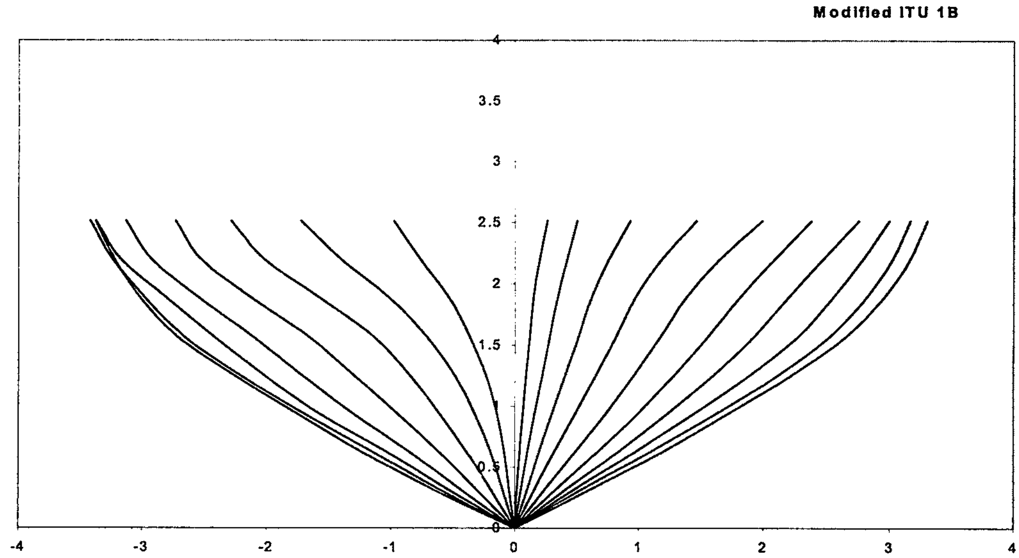

Figure 10.12 ITU 148/1-B Evolved Fishing Boat Given Target Displacement

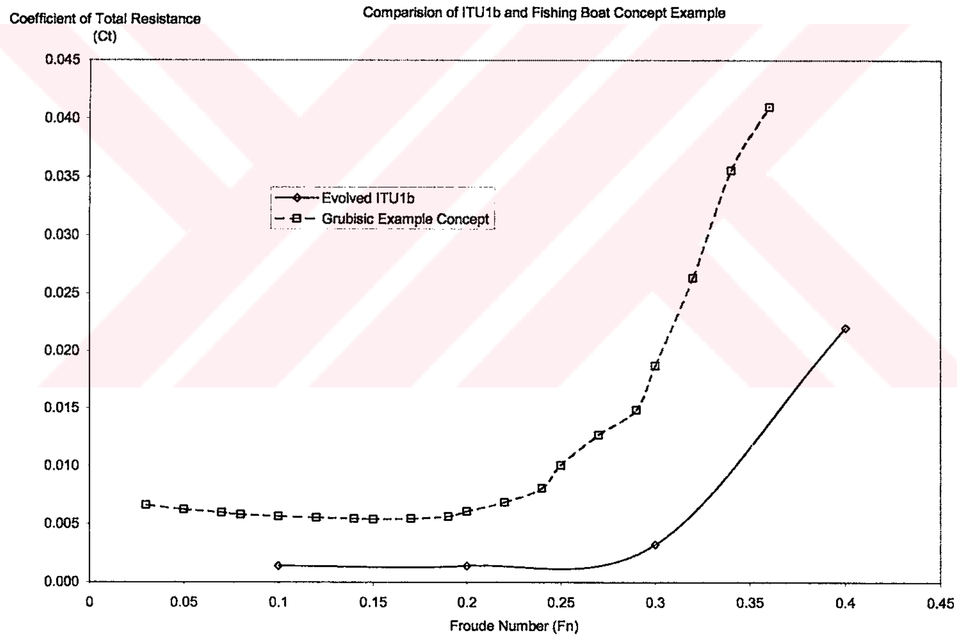

Figure 10.13 Comparison of Coefficient of Total Resistance between Grubisic Example Concept (GEC) and Evolved ITU 148/1-B Fishing Boat Hulls

10.4 ITU 148/4-B Fishing Boat Hull Form Optimization

The next fishing boat hull form is ITU 148/4-B, representing a considerably different and fuller hull than ITU 148/1-B. The same constraints and parameters as used in the last run for ITU 148/1-B is used to compare with the GEC parameters. Figure 10.14 shows the original and the last optimal hull after 100 generations. As in the previous case, a larger hull is required to meet the fish hold and displacement requirements. Table 10.6 shows the evolved performance characteristics. In this case the hull tends towards all the constraints of maximum length and minimum draft but the beam is somewhere between the limits and in fact closer to the GEC example.

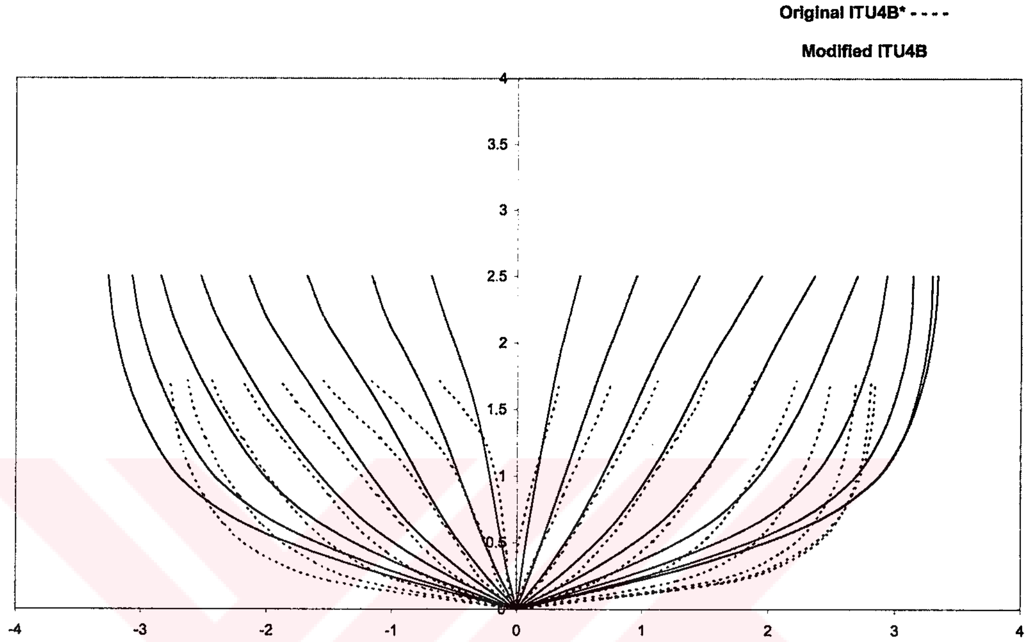

Figure 10.14 Modified and Original ITU 148/4-B Fishing Hull Forms

The volumetric displacement of 200.97 cubic meters exceeds the required displacement. The fish hold volume is also satisfied. The performance characteristics of the optimization shown in Table 10.6 show that improvements in all three objectives are seen, however the improvement in stability is only marginal. Since the final optimal hull variant was determined at the 61st generation, out of a run of 100 generations, as in the previous cases it is foreseeable that other more optimal variants exist. A complete run of 1000 generations would enable a more exhaustive search of the design space.

It is apparent that the fuller hull form of ITU 148/4-B has an easier task of achieving the required displacement than the ITU 148/1-B optimal model. When the performance characteristics of each are examined, the higher displacement of the ITU 148/4-B is also higher in resistance but not significantly. ITU 148/1-B has a better stability index but a somewhat lower seakeeping index. Both models tend toward the shallowest draft, and maximum length, with differences in beam accounting for the different displacements. ITU 148/1-B has a wider beam to provide more displacement that also gives it better stability, while the narrower but fuller ITU 148/4-B has better seakeeping.

Table 10.6 ITU 148/4-B Evolution of Performance Characteristics

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	Fish Hold	RCI	SKI	STBX
1	2	1	25	7.81	2.74	170.02	0.23	93.3	0.004875	2.119801	0.006452
1	4	1	22.01	6.72	2.88	221.08	0.67	129.15	0.0038	1.40294	0.02304
1	5	1	27.77	7.55	2.64	168.23	0.23	96.47	0.003143	2.084402	0.006481
1	8	1	27.7	6.06	2.52	198.16	0.41	115.2	0.003322	1.597329	0.012198
5	5	1	29	6.71	2.56	202.92	0.45	115.75	0.003294	1.479279	0.014172
17	6	1	23.96	6.95	2.51	201.99	0.53	117.75	0.00329	1.277399	0.017027
21	17	1	28.95	6.72	2.5	199.11	0.54	112.96	0.003258	1.136074	0.017947
61	13	1	29.04	6.76	2.51	200.97	0.53	114.3	0.003255	1.155905	0.018133

The non-domination in performance means that either vessel might satisfy a designer based on other criteria or personal intuition. This problem highlights the difficulties facing a designer and in multi-objective and multi-criteria optimization. However, in terms of the methodology, both hull forms assume the shape necessary to satisfy the requirements as well as provide the best performances for which they are capable. Nevertheless, given that resistance is normally critical, though less so in fishing boats which are typically overpowered, and given the better stability index of ITU 148/1-B over ITU 148/4-B, for which safety in fishing boats is the major concern, the slightly less favourable seakeeping performance might be acceptable and the better hull from a performance standpoint would be ITU 148/1-B. The desire for reserve buoyancy and a fuller hull may still be required for other practical reasons such as ease of construction, and these factors often influence designers and builders to produce non-optimal hulls for fishing.

10.5 WIGLEY Hull Form

The Wigley hull form is a mathematical hull that is used to calibrate programs with well-known resistance characteristics. For that purpose the optimization of the hull form keeping the principal dimensions fixed was conducted. The changes in the hull form are slight as shown in Figure 10.15. Table 10.7 shows the evolution of the performance indices. The resistance and seakeeping indices are somewhat improved but stability remains quite constant.

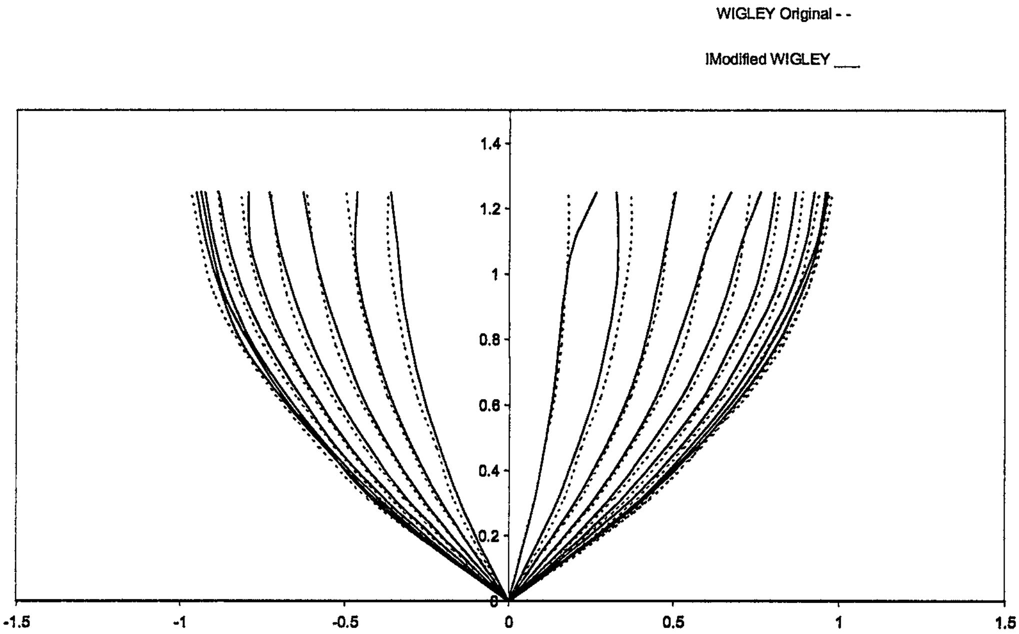

Figure 10.15 WIGLEY Modified and Original Hull Form

Table 10.7 WIGLEY Evolution of Performance Characteristics

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	Fish Hold	RCI	SKI	STBX
1	2	1	20	2	1.25	21.02	0.28	24.28	0.002701	4.302978	2.280992
1	4	1	20	2	1.25	21.02	0.28	24.28	0.002675	2.997802	2.2898
1	5	1	20	2	1.25	21.02	0.28	24.28	0.002664	4.146503	2.28548
1	14	1	20	2	1.25	21.04	0.28	24.28	0.002657	3.460831	2.28786
1	19	1	20	2	1.25	21.07	0.28	24.28	0.002655	3.024531	2.291562
18	2	1	20	2	1.25	21	0.28	24.28	0.00265	2.989881	2.288841
71	14	1	20	2	1.25	21	0.28	24.28	0.002645	2.944359	2.289313
77	12	1	20	2	1.25	20.98	0.28	24.28	0.002643	2.956697	2.290158

The comparison of the resistance coefficients between the original hull form and the evolved hull is shown in Figure 10.16. Some improvement in the wave resistance and thus the total resistance in obtained in the evolved Wigley hull. There was no significant change in the frictional resistance as each hull has a similar displacement and wetted surface.

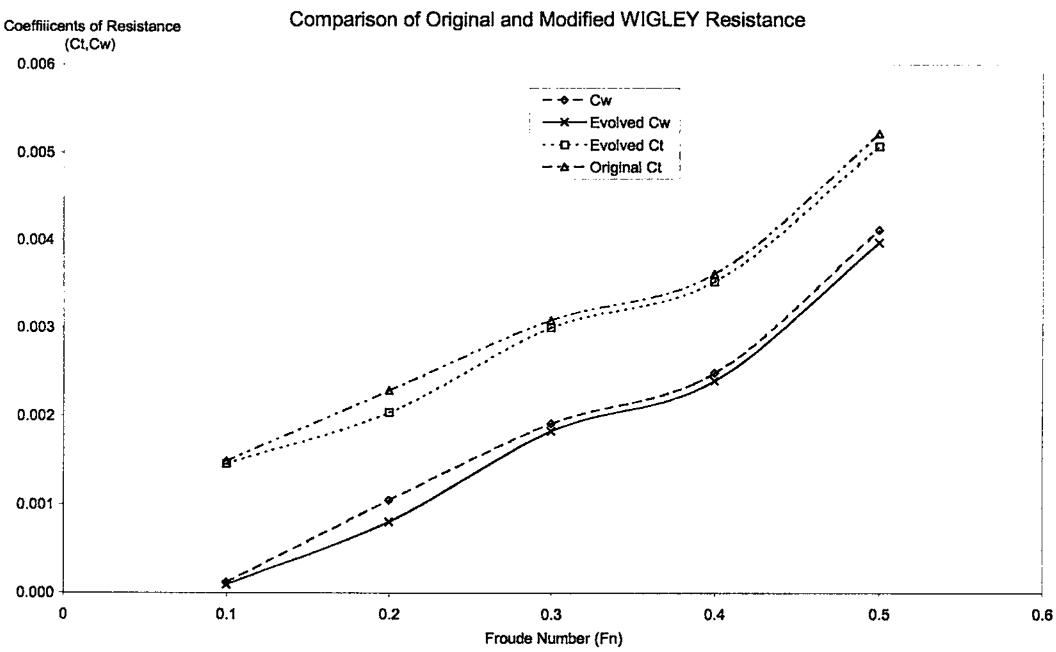

Figure 10.16 Comparison of Original and Modified WIGLEY Resistance Coefficients

Similarly a comparison of the motion for the original and evolved Wigley hull forms is shown for heave in Figure 10.17 and pitch in Figure 10.18. In both cases a reduction in the motion of these parameters can be observed. In the case of heave the motion is less at all Froude numbers but in the case of the pitch motion the motion is only marginally less at some Froude numbers but a Froude number of 0.5 it is marginally more.

It summary it can be seen that the Wigley hull form represents a narrow and therefore difficult hull for which to make any drastic improvements. However, the fact that some small improvements have been made using the methodology shows promise for other hull forms. It should also be noted that in this case the displacement and main dimensions are fixed which further limits the changes and therefore improvements that can be made.

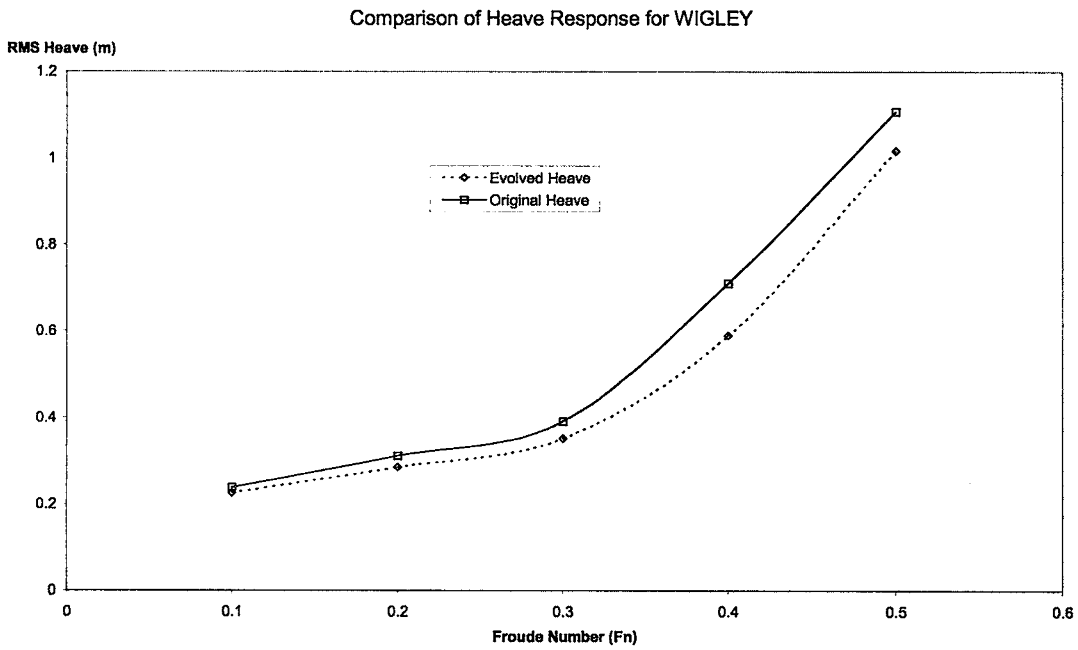

Figure 10.17. Heave Response for Original and Modified WIGLEY Hull Form

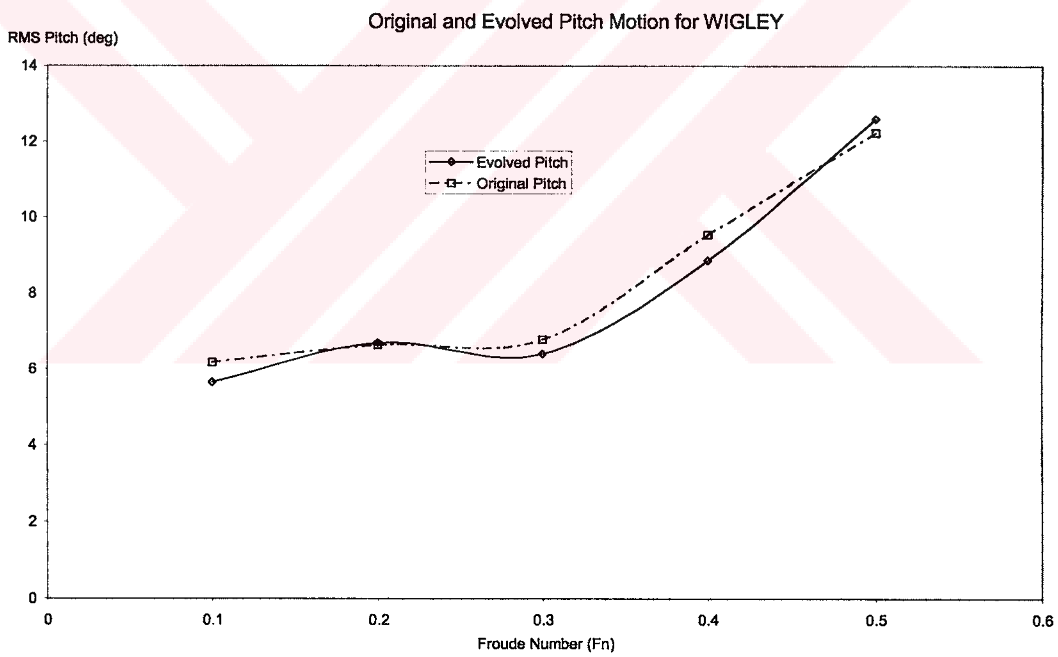

Figure 10.18 Pitch Motion Comparison of Original and Evolved WIGLEY Hull Form

10.6 ATHENA with a Transom for Fast Patrol Craft

The next hull form is a ship hull nearly 47 meters in length representing a patrol vessel. The ATHENA hull form is a transom stern ship for which resistance data is readily available. The hull form is shown in Figure 10.19 with the optimal hull form superimposed. The optimal hull was found by running 20 candidates for 100 generations, keeping the principal dimensions fixed.

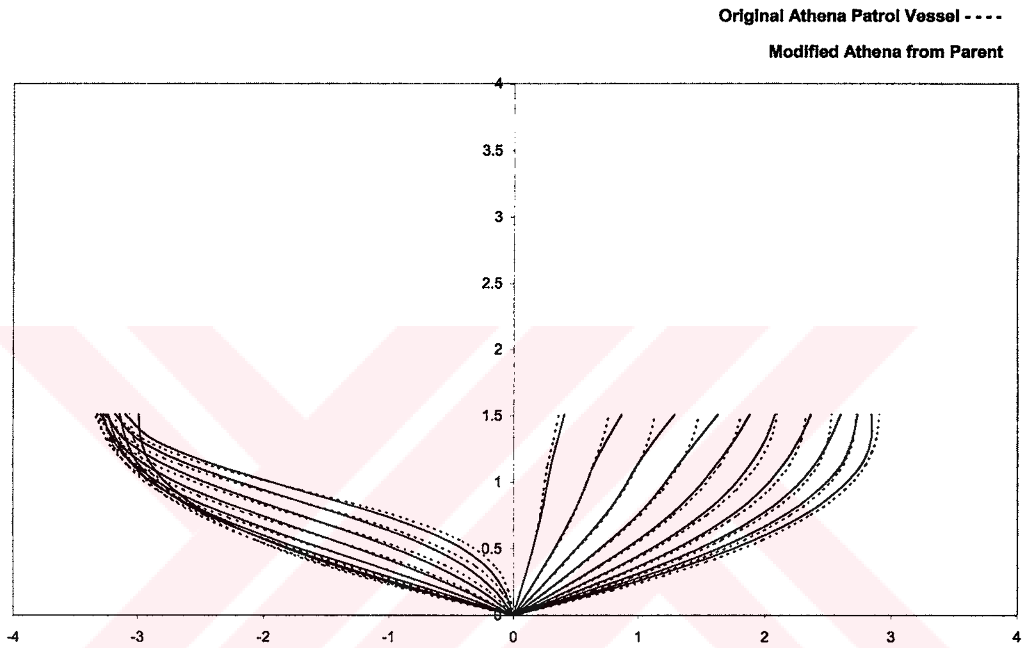

Figure 10.19 ATHENA Modified and Original Hull Form

The performance characteristics are shown in Table 10.8. As in the case of the Wigley hull form, improvements in all performance objectives are observed but are limited.

Table 10.8 ATHENA Evolution of Performance Characteristics

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	HV	RCI	SKI	STBX
1	2	1	46.94	6.9	1.51	200.68	4.03	123.67	0.010353	35.843925	2.32485
1	4	1	46.94	6.9	1.51	200.67	4.06	123.67	0.010348	35.281628	2.327545
1	5	1	46.94	6.9	1.51	200.96	4.08	123.67	0.010229	31.246418	2.330663
1	15	1	46.94	6.9	1.51	201.23	4.07	123.67	0.010256	33.38028	2.329525
1	19	1	46.94	6.9	1.51	200.54	4.09	123.67	0.010253	31.484085	2.332231
2	7	1	46.94	6.9	1.51	200.97	4.08	123.67	0.010229	31.230215	2.330708
2	20	1	46.94	6.9	1.51	200.97	4.08	123.67	0.010229	29.500683	2.331367
3	20	1	46.94	6.9	1.51	201	4.08	123.67	0.01022	30.112764	2.331572
6	9	1	46.94	6.9	1.51	200.93	4.08	123.67	0.010228	29.683184	2.331594
8	15	1	46.94	6.9	1.51	200.99	4.08	123.67	0.010214	29.52187	2.331845
12	7	1	46.94	6.9	1.51	201.08	4.09	123.67	0.010218	29.405655	2.332434
14	19	1	46.94	6.9	1.51	201.07	4.08	123.67	0.010211	28.909369	2.332343
41	2	1	46.94	6.9	1.51	201.19	4.08	123.67	0.010193	26.629152	2.332457
84	9	1	46.94	6.9	1.51	201.2	4.09	123.67	0.010173	28.789204	2.333275
85	11	1	46.94	6.9	1.51	201.21	4.09	123.67	0.010173	28.789059	2.332524
89	2	1	46.94	6.9	1.51	201.19	4.09	123.67	0.010175	28.509317	2.333182
89	10	1	46.94	6.9	1.51	201.17	4.09	123.67	0.010173	28.501286	2.333273

When the total resistance curve of the original hull is compared with the last optimal hull form, as in Figure 10.20, an improvement in the resistance is observed at all Froude numbers. It should be noted that for this hull, given the extreme breadth of the transom, the method for creating an artificial station as described in Chapter 3 was abandoned. Instead the last control points in the station past the transom are set equal to the previous control points.

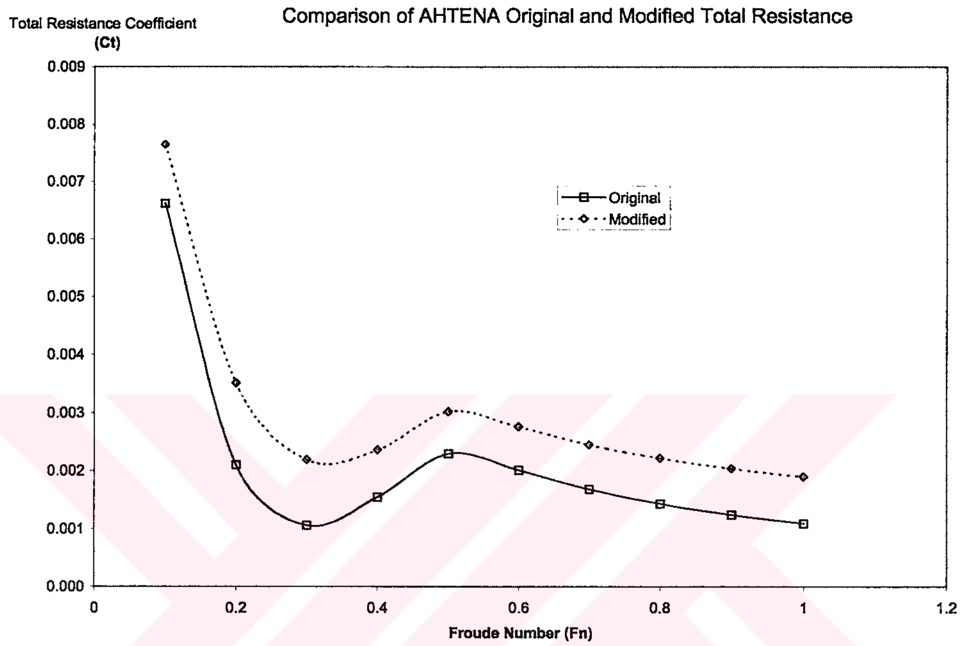

Figure 10.20 Comparison of Original and Modified ATHENA Hull Form

Examination of the pitch response as shown in Figure 10.21 and the heave response as shown in Figure 10.22 indicate that in both cases the motion response is reduced in the modified hull.

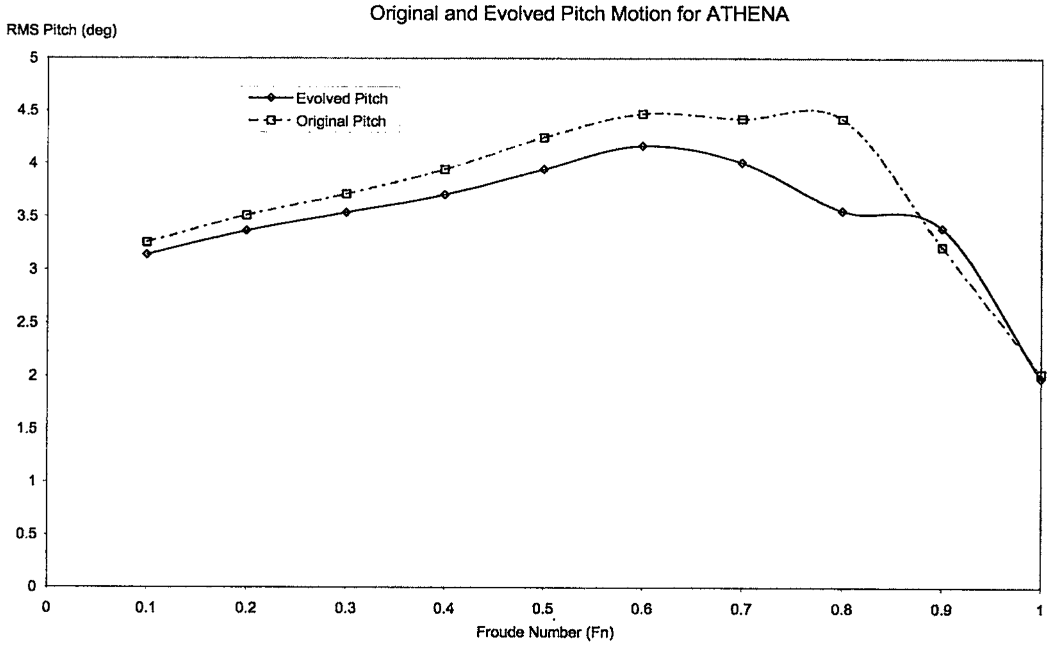

Figure 10.21 Modified and Original Pitch Motion for ATHENA

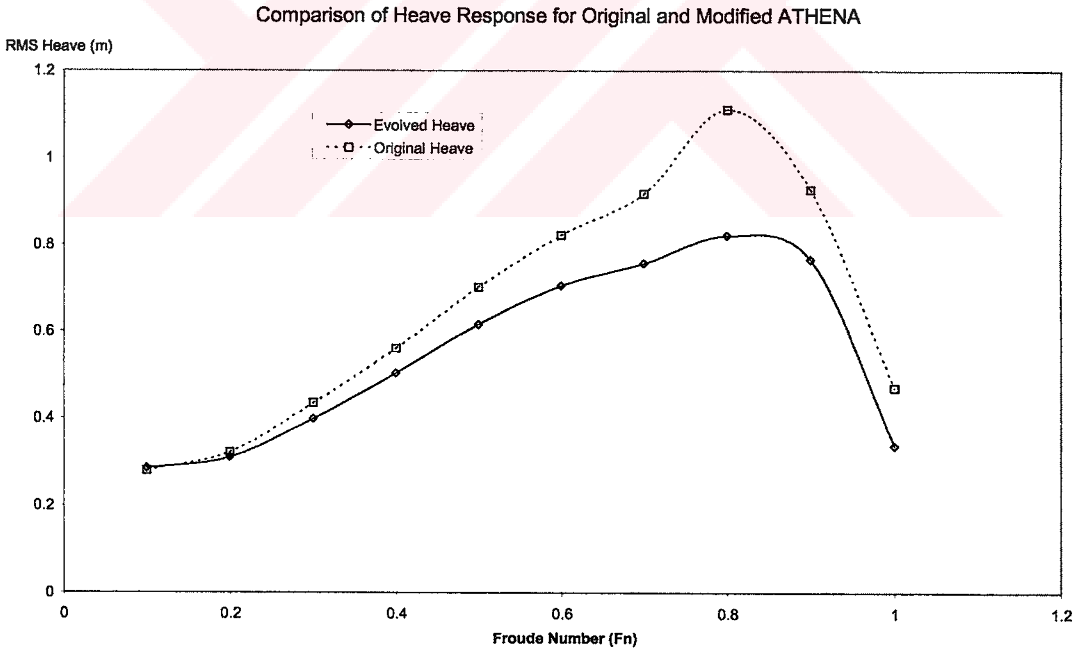

Figure 10.22 Heave Response for Original and Modified ATHENA Hull Form

10.7 Series 64 Hull with Transom Stern

The series 64 ship hull also has a transom that is tested for improved performance based on the hull form alone, keeping the principal parameters and volumetric displacement the same. Again using 20 variants for 100 generations, the original and modified hull forms are shown in Figure 10.23. The performance indices are shown in Table 10.9 showing improvements in the performance objectives.

A comparison of resistance between the original and modified hull in Figure 10.24 shows that while a reduction in resistance index is possible, the resistance is only reduced slightly at the higher Froude numbers.

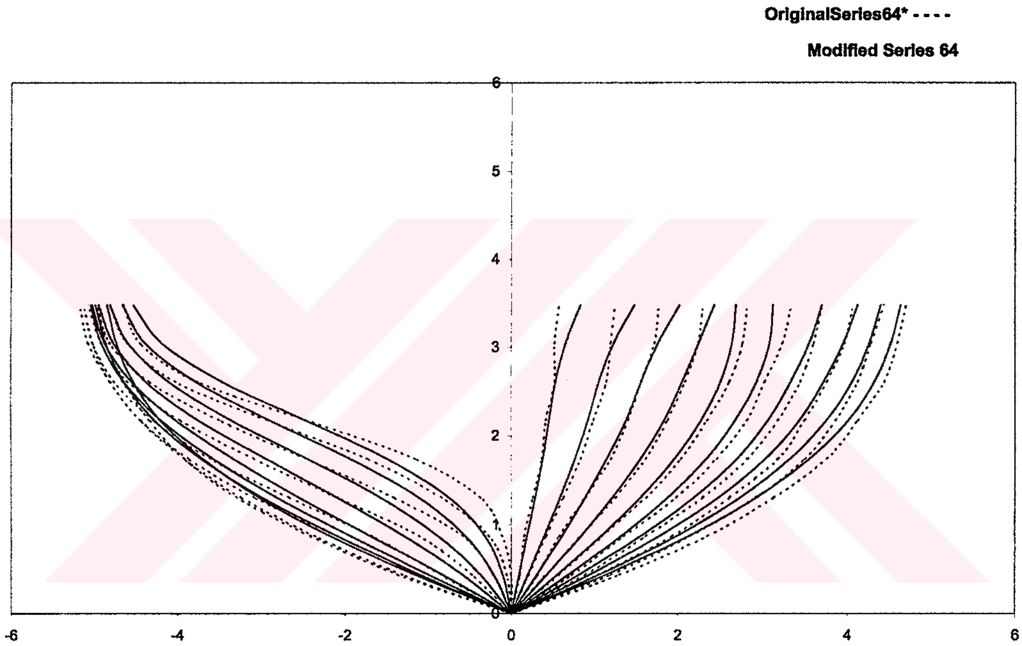

Figure 10.23 Series 64 Original and Evolved Hull Forms

Table 10.9 Series 64 Evolution of Performance Characteristics

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	HV	RCI	SKI	STBX
1	2	1	119.99	10.45	3.48	1810.62	5.43	1560.16	0.005814	1.165632	5.397126
1	3	1	119.99	10.45	3.48	1798.81	5.39	1560.16	0.005777	1.233066	5.395054
1	4	1	119.99	10.45	3.48	1803.27	5.43	1560.16	0.005786	1.12902	5.401341
1	5	1	119.99	10.45	3.48	1806.81	5.42	1560.16	0.00575	1.084874	5.400775
1	20	1	119.99	10.45	3.48	1807.86	5.42	1560.16	0.005776	1.105941	5.405787
10	5	1	119.99	10.45	3.48	1802.07	5.47	1560.16	0.005774	1.105567	5.408564
14	8	1	119.99	10.45	3.48	1803.49	5.47	1560.16	0.005769	1.104245	5.410275
15	12	1	119.99	10.45	3.48	1803.96	5.47	1560.16	0.005769	1.082103	5.413156
15	16	1	119.99	10.45	3.48	1803.94	5.47	1560.16	0.005768	1.080578	5.410377
16	1	1	119.99	10.45	3.48	1804.25	5.47	1560.16	0.005768	1.103978	5.41078
16	16	1	119.99	10.45	3.48	1804.18	5.47	1560.16	0.005768	1.066665	5.41078
21	20	1	119.99	10.45	3.48	1803.73	5.47	1560.16	0.005767	1.080186	5.41162
23	9	1	119.99	10.45	3.48	1804.62	5.47	1560.16	0.005764	1.062474	5.413836
23	17	1	119.99	10.45	3.48	1804.85	5.48	1560.16	0.005764	1.076116	5.412873
25	9	1	119.99	10.45	3.48	1803.85	5.48	1560.16	0.005763	1.074622	5.413377
40	4	1	119.99	10.45	3.48	1803.53	5.46	1560.16	0.005763	0.978869	5.413465
53	12	1	119.99	10.45	3.48	1803.02	5.47	1560.16	0.005761	1.002347	5.413818

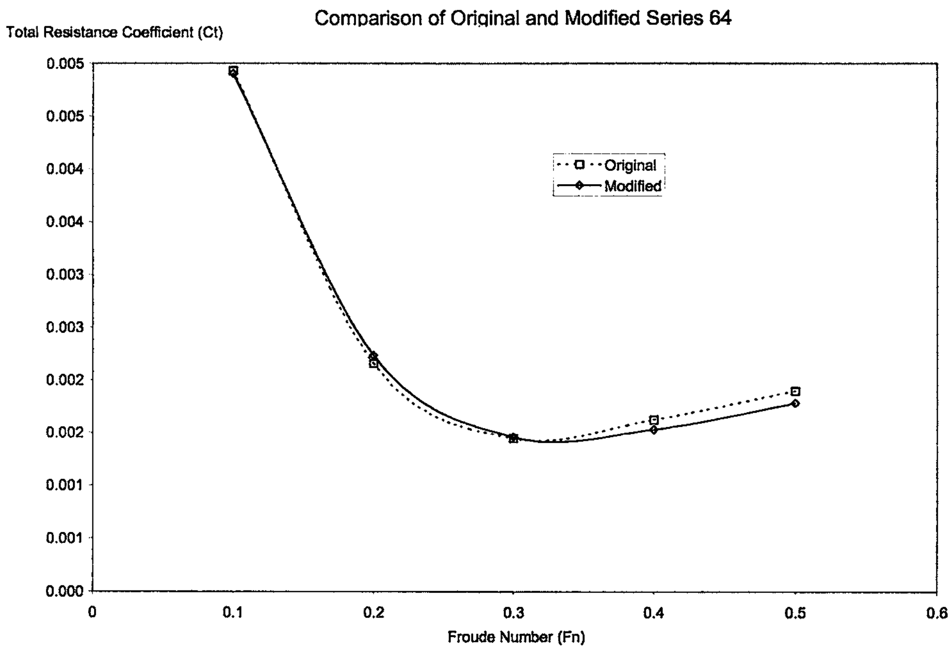

Figure 10.24 Comparison of Original and Modified Series64 Resistance Coefficients

The heave motion is shown in Figure 10.25 while pitch is shown in Figure 10.26. A reduction in heave is observed at all Froude numbers, however pitch is reduced at higher Froude numbers.

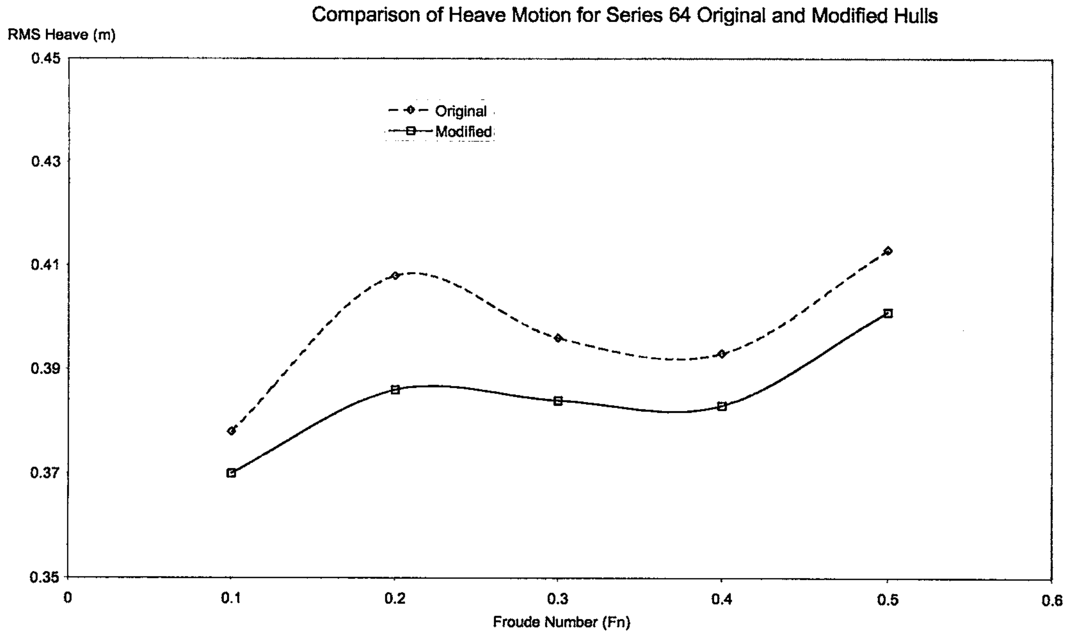

Figure 10.25 Comparison of Heave Motion for Original and Modified Series 64

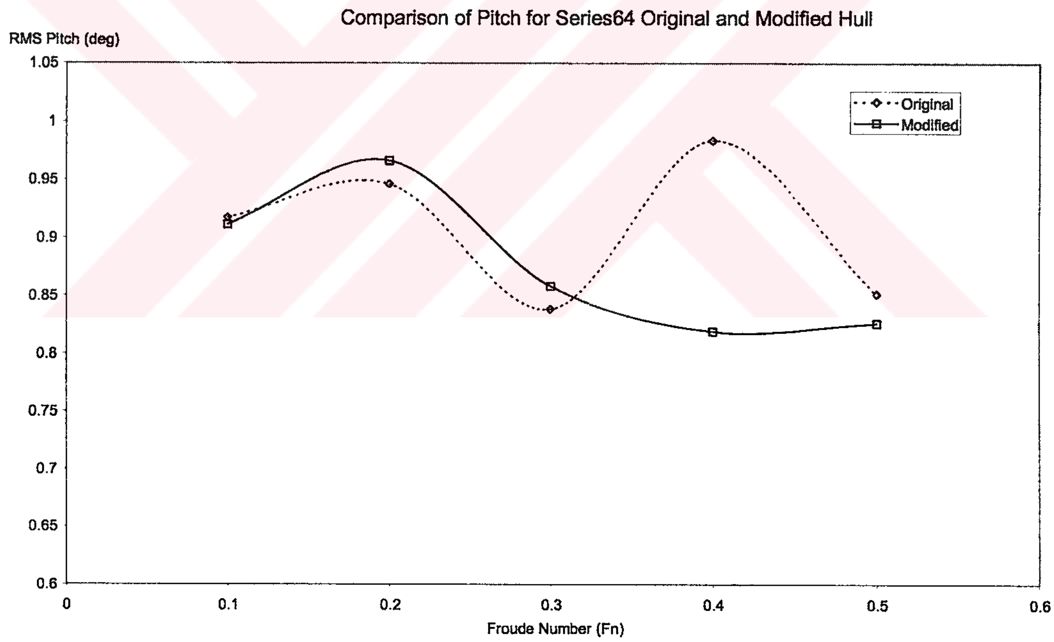

Figure 10.26 Comparison of Pitch for Series 64 Original and Modified Hull Form

10.8 A Typical Frigate

The hull model shown in Figure 10.27 is of a typical frigate. The hull is again fixed in dimension but the hull offsets are allowed to vary. Table 10.10 shows the performance objectives.

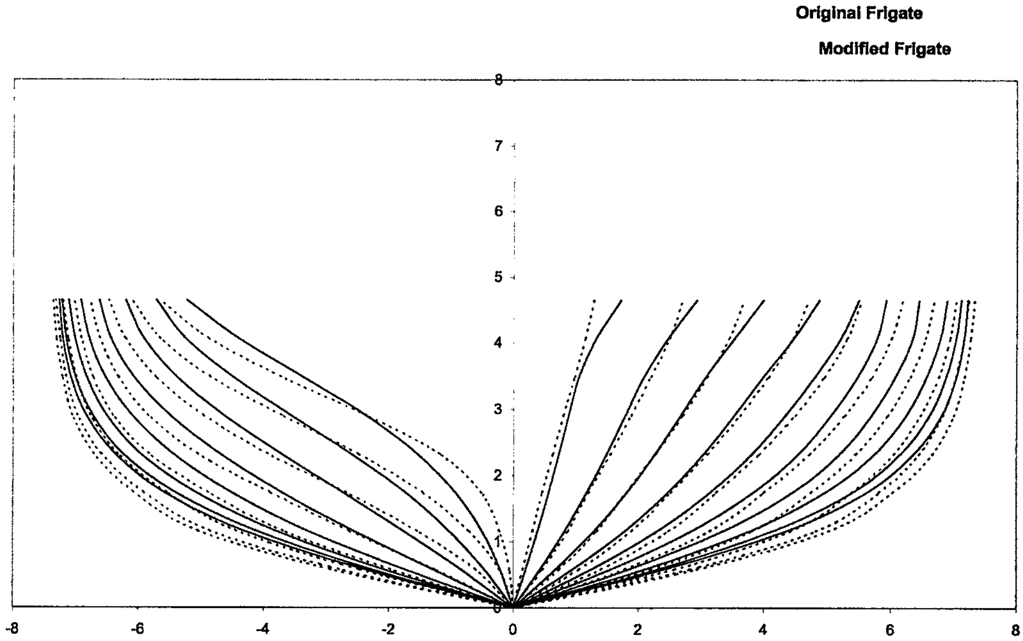

Figure 10.27 Frigate Original and Evolved Hull Forms

Table 10.10 Frigate Evolution of Performance Characteristics

Gen.	Pop.	Species	Length	Beam	Draft	Volume	GM	HV	RCI	SKI	STBX
1	2	1	123.27	14.77	4.65	4010.79	7.4	3206.65	0.004273	1.093669	6.905255
1	3	1	123.27	14.77	4.65	3996.14	7.32	3206.65	0.004099	1.034343	6.914766
1	4	1	123.27	14.77	4.65	4017.92	7.52	3206.65	0.005157	1.027177	6.924512
1	10	1	123.27	14.77	4.65	4013.2	7.34	3206.65	0.004228	1.027822	6.917637
1	13	1	123.27	14.77	4.65	4018.91	7.4	3206.65	0.004172	0.968706	6.921413
2	8	1	123.27	14.77	4.65	4018.54	7.41	3206.65	0.004172	0.991906	6.921562
3	9	1	123.27	14.77	4.65	4019.32	7.41	3206.65	0.004171	0.983354	6.922079
9	4	1	123.27	14.77	4.65	4024.46	7.45	3206.65	0.00417	0.982487	6.92511
10	2	1	123.27	14.77	4.65	4019.57	7.42	3206.65	0.004168	0.9775	6.923728
10	18	1	123.27	14.77	4.65	4024.01	7.43	3206.65	0.004166	0.972853	6.924345
11	20	1	123.27	14.77	4.65	4023.69	7.43	3206.65	0.004166	0.972043	6.92464
16	14	1	123.27	14.77	4.65	4021.12	7.44	3206.65	0.004165	0.968411	6.924984
28	10	1	123.27	14.77	4.65	4015.32	7.4	3206.65	0.004157	0.963797	6.925808
29	20	1	123.27	14.77	4.65	4015.23	7.4	3206.65	0.004157	0.968241	6.92571
35	10	1	123.27	14.77	4.65	4014.82	7.41	3206.65	0.004156	0.963978	6.926158

The comparison of resistance is shown in Figure 10.28. In this case the resistance shows an improvement in the modified hull at higher speeds.

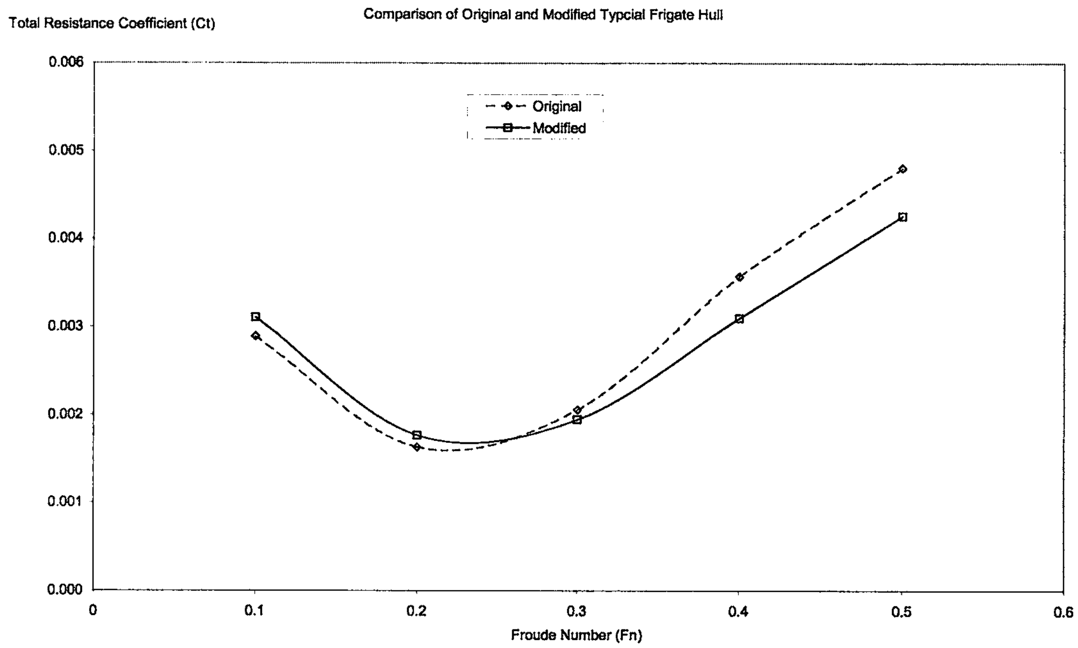

Figure 10.28 Comparison of Resistance Coefficients for Original and Modified Frigate

In terms of motion, Figure 10.29 shows the heave motion for the typical Frigate hull and the modified version. Over the full range of Froude numbers, a slight improvement in shown. Figure 10.30 shows a similar reduction for the pitch motion that has a larger scale to shown the reduction more clearly.

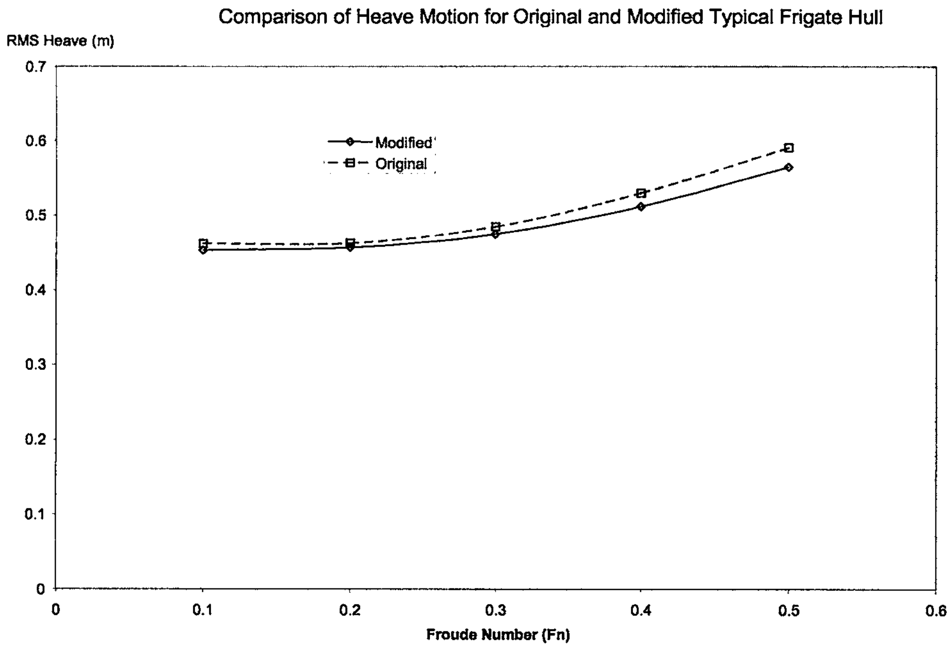

Figure 10.29 Heave Motion for Original and Modified Typical Frigate

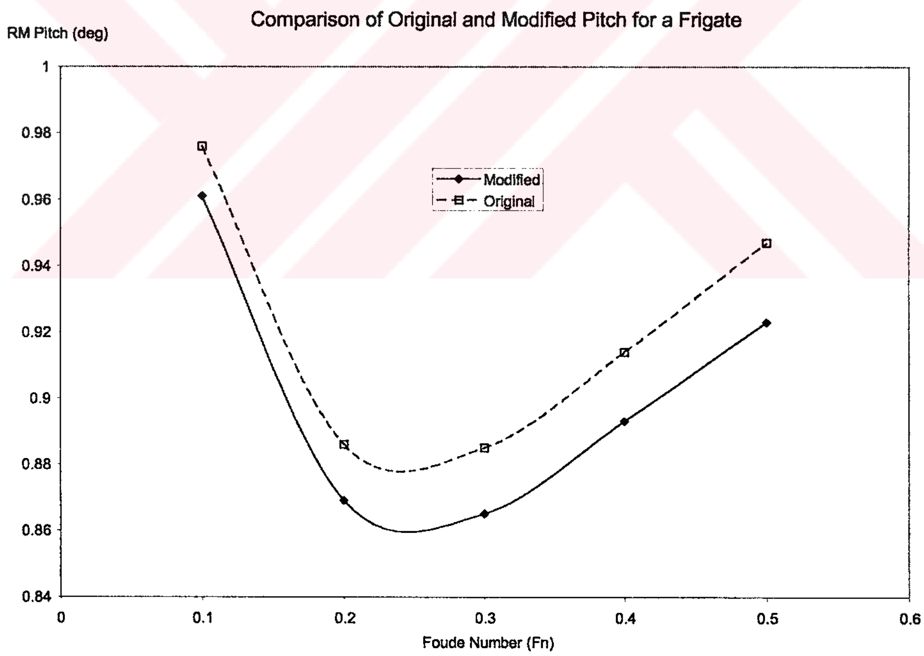

Figure 10.30 Pitch Motion for Original and Modified Frigate

11. CONCLUSIONS

11.1 Thesis Objectives and Goals

The main objective of the thesis was to investigate the use of the evolutionary algorithms for hull form optimization. Some researchers have studied hull form optimization for optimizing resistance or other specific tasks. This thesis investigates the scope of evolutionary algorithms to design hulls based on the performance of the hull in terms of resistance, seakeeping and stability which are fundamental to naval architecture.

The performance of the hull is measured through hydrodynamic analysis and hydrostatics rather than through database derived regression formulations. The optimization is conducted by creating a population of design variants and through the process of the evolutionary algorithm, candidates are chosen that perform better in each of the performance objectives. Candidates that perform better are then combine with other leading candidates through genetic operators to create new populations.

The objective is to be able to evaluate the candidates leading to an optimal design in terms of the design requirements and performance objectives. In developing the methodology a number of goals are achieved. The first is that a practical tool for generating different hulls was developed. The hull forms can be varied by length, beam and draft as well as by changing the hull form through alteration of the hull offsets. By this means the hull form can be adapted to use for completely different displacements to suit the purpose.

Normally the principal parameters are developed from the concept design and the hull is designed to suit the parameters determined at that stage. While that methodology is still useful, the current methodology allows an optimal hull form can be determined simultaneously. That is to say, the optimal hull form should also include the optimal length, beam, draft and displacement in order to create and optimal design. Regression analysis can still be utilized if convenient, as shown in Chapter 5 for the design requirements, but the focus is on the development of the hull form satisfying the design requirements.

The optimal hull forms demonstrate the main objective of the thesis, but many aspects of the methodology have yet to be investigated. The method could only be considered as the development of a prototype design tool as only a few design requirements for fishing vessels were utilized. For ships only displacement was required. These have demonstrated the potential of the methodology as a first step towards a more capable design tool.

was utilized and showed only marginal improvements in the resistance at upper Froude numbers, and better improvement in the seakeeping. The frigate showed a similar result although a larger improvement in resistance and in seakeeping was observed.

In all cases the results show that the optimal hulls tend to have somewhat narrower offsets as the body plans show the optimal sections to be inside the original lines, especially near midsections. Whether this is truly due to the optimization process or is a result of using the offsets as control points in a B-spline surface is less apparent, however the latter is more likely to be the case.

11.4 Further Research

The current program can only be considered to be in the initial stage of development as a practical design tool. For each type of ship or vessel being considered, substantial numbers of design requirements are necessary before these can be incorporated into the current methodology. For example in this thesis the fishing boat design is represented by a GM requirement for stability, a fish hold volume, and later a requirement for a displacement. While these might be similar to other concept designs the full concept design stage would make use numerous other methods and regression formulas for weights, arrangements, and mission requirements. Therefore the current program should not be considered as a fully developed concept design tool.

As shown by some of the cases especially those in which the dimensions are fixed, small changes in the offsets can lead to some improvements in resistance in particular. This means that for the more traditional approach to hull form optimization, it would probably be beneficial to develop and incorporate a better resistance prediction program, such as a 3-Dimensional potential flow model. The problem with incorporating this method is the substantial computation requirement. One idea is to incorporate mixed evaluations of thin ship theory and 3-D theory similar to the hybrid search programs in other evolutionary programs. This idea would differ in that it would have two methods for evaluating the fitness of the population in terms of resistance. However the merit of having a 3-D resistance evaluation may be that that the evolution of the population changes and is more accurately represented in terms of the resistance performance than by thin ship theory alone.

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