1 Introduction

Inland navigation is a water-born transport mode whose specific characteristics make it an interesting alternative to both, land-born truck and rail transport modes. Although, Egypt is characterized by a vast network of waterways, the water-born transport mode has a very low position relative to the other transport modes as a consequence of numerous economical and political reasons.

According to the ministry of transport, in less than a decade, 600 million tons of goods will need to be transported inside Egypt annually. Therefore, the inland water transportation system has to be further developed if the country wants to cope with such a large rise in traffic of cargo.

The Egyptian government increased the investment in the field of inland water transportation to enable much higher utilization of the Egyptian waterways in the near future, and also to reduce the ever increasing congestion on Egyptian motorways.

The possible increase in the amount of goods, which will be transported through the River Nile, requires an increase in the volume of the inland water transportation fleet. The aim of the present work is to find out the optimum dimensions and speed of a new Container ship working between Cairo and Aswan through the River Nile.

2 Optimization problem

There are two principal ways to handle “multi-objective” problems, both leading to single objective optimization problems [1]:
1. One objective is selected and the other objectives are formulated as constraints.
2. A weighted sum of all objectives, forms the optimization objective function.

The rather arbitrary choice of weight factors makes the optimization model obscure and the first option is mostly preferred [1]. Therefore, in this study, the problem under consideration is handled as a single objective constrained optimization problem according to the first option.
This optimization problem can be formulated as follows [2]:

\[ \text{Find } X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix} \]  

which maximizes an objective function called \( f(X) \) subjected to the following constraints:

\[ g_j(X) \leq 0, \ j = 1, 2, \ldots, q \]  

and \[ l_j(X) = 0, \ j = q+1, q+2, \ldots, p \]  

where, \( g_j(X) \) and \( l_j(X) \) are the inequality and the equality constraints respectively.

2.1 Objective function

As the required freight rate (RFR) reflects the major goal of any commercial ship, it is decided upon as the objective function for this optimization process. In this work it is useful to define the minimum freight rate which must be charged to break even over the life of the ship. Practically, any freight rate above the required freight rate would lead to profits. Optimization is used to minimize the required freight rate (RFR) that is calculated as LE/TEU. The objective function for this optimization process can be formulated as follows:

\[ \text{RFR} = \frac{\text{AAC}}{\text{Transported Container Per Year}} \]  

2.2 Design variables

The problem under consideration involves five design variables. These variables are listed in Table 1. Most of these variables are for the ship principal dimensions with the exception of ship speed. The speed of the ship is the cruising speed. It is assumed that this speed is the average speed of the ship during its journey.

2.3 Design constraints

The constraints are functional relationship between the design variables. These constraints define the space of acceptable solutions (feasible region) from which the best solution has to be found.

2.3.1 Navigation constraints

The presence of locks and bridges along the waterway and shallow water nature of the River Nile, represent several constraints on the dimensions of the Nile ship. These constraints are formulated as follows:

1. The width and length of the Nile ship are dictated by the dimensions of Assiut lock. Where, its dimensions are smaller than the dimensions of other locks, see Table 2. These constraints can be formulated as follows:

\[ \text{(Loa} - 72.0) \leq 0 \]  

\[ (B - 14.4) \leq 0 \]  

The maximum ship length is obtained after subtracting 8.0 m from the length of Assiut lock to open the gates. While,
the maximum ship breadth is obtained after subtracting 1.6 m from the width of Assiut lock (for each side, 0.3 m fender and 0.5 m clearance).

2. The draught of the Nile ship is often dictated by the shallow water nature of the River Nile. This constraint can be formulated as follows:

\[( T - 1.5 ) \leq 0 \quad (6)\]

3. The air draught is often dictated by the existing bridges. This constraint restricts the number of container layers onboard inland container ships. It can be seen from Table 2 that the smallest air clearance is 10.0 m. Therefore, the maximum allowable number of container layers is 4.0 layers. This constraint can be formulated as follows:

\[( N_{\text{layer}} - 4.0 ) \leq 0 \quad (7)\]

4. The speed of Nile ship is often dictated by the shallow water nature of the River Nile.

\[ V_s \leq 18.0 \ \text{km/h} \]

The right choice of ship’s speed should be decided in the very early design stage based on the Froude depth number (\( F_{nh} \)) to avoid the critical region.

In this work the Froude depth number is taken equal to 0.7 [3]. This constraint can be formulated as follows:

\[ \left( \frac{V_s}{\sqrt{g * h_w}} - 0.7 \right) \leq 0 \quad (8)\]

2.3.2 Geometry constraints

The principal dimensions for 21 self-propelled inland ships has been collected in Table 3 and investigated to clarify the acceptable limits on the dimensional ratios (\( \text{Loa/D}, \text{Loa/B} \) and \( \text{B/T} \)) for such ships.

2.3.2.1 Constraint on (\( \text{Loa/D} \)) ratio

The value of (\( \text{Loa/D} \)) is significant in relation to the structural strength of the ship and in particular to the deflection of the hull girder under the bending moment imposed by waves and cargo distribution.

Figure 1 shows that the length to depth ratio of the River Nile ships varies between 14 and 26. This constraint can be formulated as follows:

\[( \text{Loa} - 26 \times D) \leq 0 \quad (9)\]

\[( 14 \times D - \text{Loa} ) \leq 0 \quad (10)\]

2.3.2.2 Constraint on (\( \text{Loa/B} \)) ratio

Inland container vessels should have full hull form, due to draught restrictions, but \( \text{Loa/B} \) ratio, long or beamy vessel, has yet to be clarified. Longer vessels should be advantageous from the wave resistance point of view, while the beamy vessels would be better in stability and hull weight considerations. Figure 2 shows that the length to breadth ratio of the River Nile ships varies between 4.5 and 6.5. This constraint can be formulated as follows:

\[( \text{Loa} - 26 \times D) \leq 0 \quad (9)\]

\[( 14 \times D - \text{Loa} ) \leq 0 \quad (10)\]
2.3.2.3 Constraint on \((B/T)\) ratio

It may be noted that for a fixed displacement, increasing the \((B/T)\) ratio will cause an increase in ship resistance and capital cost. Figure 3 shows that the breadth to draught ratio of inland navigation ships varies between 5 and 12. This constraint can be formulated as follows:

\[
( B - 12 \times T ) \leq 0 \tag{13}
\]

\[
( 5 \times T - B ) \leq 0 \tag{14}
\]

2.3.3 Weight balance constraint

This is the basic constraint in every ship. This equality constraint is handled to enforce the balance between ship weight and displacement. This constraint can be formulated as follows:

\[
L \times B \times T \times C_B = W_{\text{ship}} - D_{\text{wt}} = 0 \tag{17}
\]

2.3.3 Stability constraint \((GM_T)\)

The transverse metacentric height \((GM_T)\) of the inland container ship must be greater than 1.0 meters \([6]\). This constraint can be formulated as follows:

\[
(1.0 - GM_T) \leq 0 \tag{18}
\]

2.3.4 Freeboard constraint

The freeboard of the inland container ships must be greater than 0.5 meters \([6]\). This constraint can be formulated as follows:

\[
(0.5 - D + T) \leq 0 \tag{19}
\]

2.3.5 Rolling constraints

This inequality constraint depends on the minimum required rolling period \((T_{\text{roll}})\) criterion. It is regarded as a constraint to keep the transverse metacentric height \((GM_T)\) from getting too high. In this work the minimum rolling period is taken equal to 15 seconds \([7]\). The transverse rolling period can be calculated according to the following equation \([1]\):

\[
T_{\text{roll}} = \frac{2\pi \times K}{\sqrt{g \times GM_T}} \tag{20}
\]

The radius of gyration is taken equal to 0.385*B \([8]\). This constraint can be formulated as follows:

\[
(15 - \frac{0.77 \times B}{\sqrt{GM_T}}) \leq 0 \tag{21}
\]

3 Design modules

The first step in ship design is to use appropriate analytical and empirical relationships to obtain the geometry, weight and consequently the engine power. These relationships may be directly or indirectly proportional to the dimensions, vessel types, used materials, weight, etc.

3.1 Power module

In shallow water, vessel’s resistance is very much different than in deep water and may play the most important role in inland vessel’s design. There are some empirical methods developed for calculating the engine power in the early design stage of sea going ship \([9]\). These methods cannot be applied to inland ships.

\[
P_B = 0.02 \times \left( V^1_3 \Delta^{2/3} \right)^{0.841} \tag{22}
\]

In this work, equation (22) may be used in the early design stage to calculate the power of conventional self propelled inland units.
This equation has been developed by plotting the particulars of some existing inland units, as shown in Figure 4.

### 3.2 Trip module

The total trip time (TTd) is consisting of the time spent at sea and time spent at ports. The annual sea and port time may be calculated after calculating the annual number of trips (Tn) as follows:

\[
Tn = \frac{350}{TTd} \tag{23}
\]

\[
TTd = STd + PTd \tag{24}
\]

\[
STd = \frac{(1 + Ra)Ru}{12 * V_s} \tag{25}
\]

\[
PTd = \frac{2 * (1 + Pa)N_c}{24 * C.H.R} \tag{26}
\]

River Nile ships are prevented from sailing at night as a result of the currently improper navigational conditions on the waterway itself. Therefore, sailing time is taken equal to 12 hours per day. However, containers handling operations can be continued for 24 hours per day in the River Nile terminals.

The fuel and diesel consumption per trip (FCT) may be calculated according to the following equations:

\[
FCT = FCS + FCP + DCS \tag{27}
\]

\[
FCS = \frac{SFC * P_a * (STd + 12.0)}{10^6} \tag{28}
\]

For self-loading and unloading ships, it is possible to take the daily diesel oil consumption at port and sea equal to 5 and 2 ton respectively [10]. For inland container ships, loading and unloading operations are carried out by the containers handling equipment of the river terminals. Therefore, in the present study, the daily diesel oil consumption is taken as follows:

\[
FCP = 2.0 * PTd \tag{29}
\]

\[
DCS = 2.0 * STd \tag{30}
\]

### 3.3 Weight module

#### 3.3.1 Light ship weight

The lightship weight (W\textsubscript{light}) may be calculated according to the following equation:

\[
W_{\text{light}} = W_{\text{steel}} + W_{\text{out}} + W_{\text{m/c}} + \text{Margin} \tag{31}
\]

#### 3.3.1.1 Steel weight

Some empirical methods are available for calculating ship steel weight in the early design stage of sea going ship [1 and 9]. These methods cannot be applied to inland ships.

In the present work, ship steel weight is estimated using Equation (32). This equation has been specially developed on the basis of the steel weights of some existing inland ships and the computed steel weights obtained from construction drawings produced specially for this reason as shown in Figure 5.

\[
W_{\text{steel}} = 0.097 * [C * E^{1.36}]^{0.831} \tag{32}
\]

\[
C = [1 + 0.05 * (C_n - 0.7)] \tag{33}
\]

\[
C_n = [C_n + (0.8D - T)] / ST \tag{34}
\]

\[
E = Loa * (B + T) + 0.85Loa * (D - T) \tag{35}
\]

#### 3.3.1.2 Outfit weight

Schneckluth [1] gave the following formula for the calculation of outfit weight (W\textsubscript{outfit}):

\[
W_{\text{outfit}} = k_iLB \tag{36}
\]

where \(k_i\) is a coefficient based on ship types; \(k_i\) is taken as 0.028 tons/m² for inland container ships [11].

#### 3.3.1.3 Machinery weight

The first step towards assessing the machinery weight (W\textsubscript{m/c}) is the calculation of the required power to drive a ship. The second step involves taking a decision on the type of machinery best suited to the service conditions of the ship under consideration.
In the absence of manufacturers’ specifications, a value between (0.012 – 0.02 t/kW) can be used as approximate unit weight for medium speed diesel engines [1]. In this study a value of 0.02 t/kW is used for the determination of machinery weight.

3.3.1.4 Margin

The purpose of this margin is giving an allowance to ensure the attainment of the specified deadweight in case of underestimating the lightship weight, and also to compensate for possible departures from the initial weight design during construction.

The extent of the margin on the hull weight depends on the type and size of the ship, and importantly, on the penalty which may be exacted for non-compliance with the specific deadweight. A margin of 2% of the lightweight is recommended by Watson [9] as a margin for merchant ships.

3.3.2 Ship deadweight

The deadweight (Dwt) is a notation of the ship carrying capacity. The deadweight includes the following items:

- Cargo weight (payload or useful load). For container ships, it is the weight of transported containers. The average weight for TEU can be assumed to be around 12 tons [12].

\[
\text{Payload} = 12.0 \times N_C
\]  

(37)

- Other weights such as fuel, feed water, fresh water, stores, provisions, ballast other than permanent ballast, lubricating oil, etc.

3.4 Stability module

This module deals with the calculations of the ship’s vertical center of gravity and the transverse metacentric height to evaluate the initial stability. The transverse metacentric height (\(G M_T\)) can be calculated as follows:

\[
G M_T = KB + BM_T - KG
\]  

(38)

The vertical center of buoyancy (\(KB\)) for the Nile ships can be calculated according to the following equation [13]:

\[
KB = 0.535 \times T
\]  

(39)

In the preliminary design stage, the transverse metacentric radius (\(BM_T\)) can be calculated according to the following formula [6]:

\[
BM_T = \left[\frac{1}{12.5 - \left(\frac{T}{D}\right)}\right] \times \frac{B^2}{T}
\]  

(40)

The vertical center of gravity (\(KG\)) can be calculated according to the following equation:

\[
KG = \frac{(W \times KG)_\text{light} + (W \times KG)_\text{Dwt}}{\Delta}
\]  

(41)

It is advisable to create a margin of stability with the weight margin by placing the center of mass of the margin weight at around 1.2 KG above the keel [1].

The center of gravity of each weight components can be calculated according to the following equations [1]:

\[
KG_{\text{steel}} = 0.70 \times D
\]  

(42)

\[
KG_{\text{out}} = 1.20 \times D
\]  

(43)

\[
KG_{\text{m/c}} = 0.60 \times D
\]  

(44)

3.5 Cost module

Many attempts and approximations have been previously proposed for the economic evaluation of ships under construction. The most famous of these attempts were the formulae proposed by Benford [14]. Although these formulae were derived during the 60s, they still nowadays represent a good guidance, if some of the involved parameters are re-adjusted. These formulae have been used after some modifications in the FIRST project conducted in the Aerospace and Ocean Engineering Department at Virginia University and have proven their validity [7].

In this project, the man-hours assumed by Benford [14] have been multiplied by 0.4 for the technological enhancements in the yard standards and the price of materials. Labour costs were updated according to the current market price in USA at that time. In this work, the number of man-hours is kept as assumed by Benford [14] and the labour cost is considered 20 LE/hr according to the current market price in Egypt [11].

3.5.1 Capital cost estimation

Ship capital Cost (\(P\)) is broken down into steel cost (\(C_{\text{steel}}\)), outfitting cost (\(C_{\text{out}}\)) and machinery cost (\(C_{\text{m/c}}\)). Each of these constitutes costs for material and labour.

\[
P = C_{\text{steel}} + C_{\text{out}} + C_{\text{m/c}}
\]  

(45)

The ship capital cost can be converted to uniform annual amounts using the capital recovery factor (CR).

3.5.1.1 Steel cost

Hull steel cost (\(C_{\text{steel}}\)) is calculated by multiplying the steel weight by a fixed value for manufacturing of one ton of steel. An average value of 8000 LE has been taken for the evaluation in the FIRST project conducted

\[
C_{\text{steel}} = C_{\text{nh}} \times f_{\text{steel}} \times \left(\frac{W_{\text{out}}}{100}\right)^{0.9}
\]  

(46)

\[
C_{\text{out}} = f_{\text{out}} \times W_{\text{out}}
\]  

(47)

3.5.1.3 Machinery cost

The machinery costs (\(C_{\text{m/c}}\)) may be divided into machinery labour cost and machinery material cost.
These costs can be estimated using the following formulae [7]:

\[ C_{\text{melb}} = C_{\text{nh}} * f_{\text{melb}} * \left[ \frac{\text{SHP}}{1000} \right]^{0.6} \]  
(48)

\[ C_{\text{mcmat}} = f_{\text{mcmat}} * \left[ \frac{\text{SHP}}{1000} \right]^{0.6} \]  
(49)

### 3.5.2 Annual operating costs

In the present work, the annual operating costs \( (C_{ao}) \) are allowed to escalate with a rate of 5\% throughout the life span and projected again to the first year of ship’s life using the present value techniques as follows:

\[ \left[ C_{ao} \right]_n = C_{ao} * 1.05^{n-1} \]  
(50)

\[ C_{an} = \sum_{n=1}^{N_c} \left( \left[ C_{ao} \right]_n * (pw - i \% - n) \right) \]  
(51)

\[ (pw - i \% - n) = \left( \frac{1}{(1+i)} \right) \]  
(52)

#### 3.5.2.1 Crew cost

The two major factors which determine crew costs today are crew numbers and the nationality of different sections of the officers and crew. The crew cost \( (C_{\text{wages}}) \) may be calculated according to the following formula:

\[ C_{\text{wages}} = N_{\text{crew}} * (12 * A_{\text{wage}}) \]  
(53)

#### 3.5.2.2 Victualling cost

Victuals are usually bought locally at the ship’s trading ports and the annual cost is calculated on a per-person per day basis. Victualling cost \( (C_{\text{Vict}}) \) may be calculated according to the following equation:

\[ C_{\text{Vict}} = C_{\text{day}} * N_{\text{crew}} * 350 \]  
(54)

#### 3.5.2.3 Maintenance and repair costs

The maintenance and repair costs \( (C_{\text{mar}}) \) may be calculated according to the following equations [7]:

\[ C_{\text{mar}} = C_{\text{hmar}} * C_{\text{mmar}} \]  
(55)

\[ C_{\text{hmar}} = 600000 * \left( \frac{L * B * D}{100000} \right)^{2/3} * 1.4 \]  
(56)

\[ C_{\text{mmar}} = 60000 * \left( \frac{\text{SHP}}{1000} \right)^{2/3} * 1.4 \]  
(57)

#### 3.5.2.4 Insurance cost

Insurance cost is directly related to the capital cost of the ship with the insurance history of the managing company exercising it as a secondary effect. The insurance costs \( (C_{\text{insu}}) \) may be calculated according to the following equation [11]:

\[ C_{\text{insu}} = 0.11 * P \]  
(58)

#### 3.5.2.5 Administrative cost

Administrative cost is a contribution to the office expenses of a shipping company or the fees payable to a management company plus a considerable sum for communications and sundries. It can be taken equal to 10\% of the annual operating costs [11].

#### 3.5.2.6 Fuel cost

The annual fuel cost \( (C_{\text{fuel}}) \) may be calculated according to the following equation:

\[ C_{\text{fuel}} = FCT * F_{\text{price}} * Tn \]  
(59)

#### 3.5.2.7 Port expenses

The port expenses are directly related to the amount of cargo transported per year. The port expenses \( (C_{\text{port}}) \) may be calculated according to the following equation [11]:

\[ C_{\text{port}} = W_{\text{cargo}} * Tn * f_{\text{port}} \]  
(60)

#### 3.5.2.8 Container handling cost

Container handling cost is directly related to the number of containers which are handled each year. Container handling cost \( (C_{\text{ch}}) \) may be calculated according to the following equation:

\[ C_{\text{ch}} = 2 * TNC * Tn * C_{\text{loc}} \]  
(61)

where, the ship carrying capacity is handled two times (loading and unloading) in each trip leg.

### 4 Developed computer program (CACSO)

The present optimization problem is carried out by using a specially developed Visual Fortran computer program (CACSO). This program is illustrated by the flow chart shown in Figure 6. In this program the design variables \( (L, B, D, T, V_s) \) are varied in a sequential manner over a range of different step sizes. Thus, this program deals with a multi-dimensional problem whose size is a function of the number of variables, the step size and the specified range of each variable.
Table 4: Input Data – developed program (CACSO)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth (hw)</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Round trip distance (Ru)</td>
<td>1960 km</td>
</tr>
<tr>
<td>River allowance (Ra)</td>
<td>0.05</td>
</tr>
<tr>
<td>Port allowance (Pa)</td>
<td>0.25</td>
</tr>
<tr>
<td>Ship life (N)</td>
<td>25 years</td>
</tr>
<tr>
<td>Scrap value (Sv)</td>
<td>0.10</td>
</tr>
<tr>
<td>Interest rate (i)</td>
<td>10%</td>
</tr>
<tr>
<td>Double bottom height (Hdb)</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Max. container layer (Nlaym)</td>
<td>4 layers</td>
</tr>
<tr>
<td>Cost of handling one container (Choc)</td>
<td>50 LE/TEU</td>
</tr>
<tr>
<td>Port expenses per ton of cargo (Fport)</td>
<td>1.0 LE/ton</td>
</tr>
<tr>
<td>Man hour cost (Cmh)</td>
<td>20 LE/h</td>
</tr>
<tr>
<td>Number of crew (Ncrew)</td>
<td>8 crews</td>
</tr>
<tr>
<td>Average wage per person (A wage)</td>
<td>1500 LE/month</td>
</tr>
<tr>
<td>Fuel price per ton (Fprice)</td>
<td>1200 LE/ton</td>
</tr>
<tr>
<td>Specific fuel consumption (SFC)</td>
<td>150 gr/hp/h</td>
</tr>
<tr>
<td>Accommodating cost per person (Cday)</td>
<td>20 LE/day</td>
</tr>
<tr>
<td>Minimum required freight rate (RFRmin)</td>
<td>2300 LE/TEU</td>
</tr>
</tbody>
</table>

Table 5: Output Results – developed program (CACSO)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFR (LE/TEU)</td>
<td>1198.385</td>
</tr>
<tr>
<td>Loa (m)</td>
<td>65.90</td>
</tr>
<tr>
<td>B (m)</td>
<td>13.70</td>
</tr>
<tr>
<td>D (m)</td>
<td>3.00</td>
</tr>
<tr>
<td>T (m)</td>
<td>1.50</td>
</tr>
<tr>
<td>V5 (km/h)</td>
<td>12.34</td>
</tr>
<tr>
<td>CNL (TEU)</td>
<td>7.0</td>
</tr>
<tr>
<td>CNB (TEU)</td>
<td>5.0</td>
</tr>
<tr>
<td>NC (TEU)</td>
<td>70.0</td>
</tr>
<tr>
<td>Nlaym (Layers)</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Figure 6a: The developed computer program (CACSO)
5 Analysis of the output results

From the output results of the developed computer program, one can conclude that:
1. RFR reaches its optimum value when the ship length has reached a suitable point to allocate seven containers longitudinally.
2. RFR reaches its optimum value when the ship breadth has reached a suitable point to allocate five containers transversely.
3. RFR reaches its optimum value at the lower bound of the ship depth. Any increase in the depth would increase the hull steel weight of the ship resulting in greater building costs. This might further increase the objective function.
4. RFR reaches its optimum value at the upper bound of the ship draught. However, the optimum value of the draught is achieved...
by the weight balance constraint. Any increase in the draught would increase ship resistance, and this would consequently increase the required power to drive the ship at the same speed. This might further increase the objective function.

5. RFR reaches its optimum value at an intermediate point for ship speed. Figure 7 shows the variation of RFR with ship speed. This figure indicates that RFR reaches its minimum value at the lowest point in the curve. However, the optimum value of speed is achieved by Froude depth number (Fnh) constraint.

![Figure 7 Variation of RFR with ship speed](image)

From the above mentioned points, one can conclude that the ship breadth can be increased by increasing the width of side tanks. This will cause the following effects:

- Increasing ship steel weight will consequently increase ship capital cost.
- Providing additional buoyancy will decrease ship draught and consequently, decrease the required power. Finally, the annual operating cost will be decreased.
- If the ship draught remains constant, increasing ship speed will increase the number of round trips and consequently, will increase the number of transported containers each year. From the other side, increasing ship speed will increase fuel consumption which consequently, will increase the annual operating cost.

Figure 8 indicates that the RFR reaches its minimum value at the lowest point in the curve. This point is taken as the optimum design point.

![Figure 8 Variation of RFR with side tank width](image)

Table 6: Effect of side tanks width on the optimum design point

<table>
<thead>
<tr>
<th>Design</th>
<th>S. T. Width (m)</th>
<th>Loa (m)</th>
<th>B (m)</th>
<th>T (m)</th>
<th>D (m)</th>
<th>Vₕ (km/h)</th>
<th>RFR (LE/TEU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.50</td>
<td>65.9</td>
<td>13.70</td>
<td>1.50</td>
<td>3.0</td>
<td>12.34</td>
<td>1198.385</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>65.9</td>
<td>13.95</td>
<td>1.50</td>
<td>3.0</td>
<td>12.46</td>
<td>1202.149</td>
</tr>
<tr>
<td>3</td>
<td>2.00</td>
<td>72.0</td>
<td>14.2</td>
<td>1.50</td>
<td>3.0</td>
<td>12.42</td>
<td>1127.335</td>
</tr>
<tr>
<td>4</td>
<td>2.25</td>
<td>72.0</td>
<td>14.45</td>
<td>1.50</td>
<td>3.0</td>
<td>12.42</td>
<td>1131.366</td>
</tr>
<tr>
<td>5</td>
<td>2.50</td>
<td>72.0</td>
<td>14.7</td>
<td>1.50</td>
<td>3.0</td>
<td>12.38</td>
<td>1136.089</td>
</tr>
<tr>
<td>6</td>
<td>2.80</td>
<td>72.0</td>
<td>15.0</td>
<td>1.40</td>
<td>3.0</td>
<td>12.42</td>
<td>1140.411</td>
</tr>
</tbody>
</table>

Table 6 indicates that the increase of the width of the side tanks does not only affect the value of the objective function, but it also affects the ship design variables. From this table, design number three can be taken as an optimum design for self propelled container ships working between Cairo and Aswan through the River Nile.

Table 7 illustrates the main particulars of the optimum self propelled Cairo – Aswan container ship.

### Table 7: Main particulars of the optimum self propelled Cairo–Aswan container ship

<table>
<thead>
<tr>
<th>Objective Function:</th>
<th>RFR (LE/TEU)</th>
<th>1127.335</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design variables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loa (m)</td>
<td>72.0</td>
<td></td>
</tr>
<tr>
<td>B (m)</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>D (m)</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>T (m)</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>Vₕ (km/h)</td>
<td>12.42</td>
<td></td>
</tr>
<tr>
<td>Block Coefficient Cₐ</td>
<td>0.896</td>
<td></td>
</tr>
<tr>
<td>Brake Power Pₜ (hp)</td>
<td>643.28</td>
<td></td>
</tr>
<tr>
<td>Light Weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wₘₜ (tons)</td>
<td>301.74</td>
<td></td>
</tr>
<tr>
<td>Wₘₑ (tons)</td>
<td>27.20</td>
<td></td>
</tr>
<tr>
<td>Wₑₑ (tons)</td>
<td>9.46</td>
<td></td>
</tr>
<tr>
<td>Margin (tons)</td>
<td>6.77</td>
<td></td>
</tr>
</tbody>
</table>

Table 8 and Figure 9 illustrate the distribution of containers onboard the optimum self propelled Cairo – Aswan container ship during the first and second legs for each trip.
6 Sensitivity study

The developed computer program (CACSO) has been used to investigate the sensitivity of the objective function (RFR) to a variety of factors to which the objective function may be sensitive.

6.1 Sailing time

The results of the developed program show that increasing sailing time per day will increase the annual number of round trips, which consequently increases the number of annually transported containers and finally decreases the required freight rate.

Figure 10 shows that if the sailing time increases from 12 to 24 h/day and the number of crew doubles, the required freight rate will decrease for about 25% approximately. Therefore, this navigation route must be developed to be suitable for night navigation.

6.2 Container handling rate

Port time for a container ship is inversely proportional to the efficiency of container handling equipment. It is true that the time spent in ports during which the ship is not operating in containers handling represents a loss to the ship owner.

Figure 11 shows that if the container handling rate increases, the required freight rate will decrease for about 25% approximately. Therefore, the ship owner may consider investing in more efficient handling equipment to reduce costs.
It is shown from the results of the developed program that at a constant port allowance, the increasing of the container handling rate will increase the economical utility of the ship, which consequently decreases the required freight rate.

Figure 11 shows that the container handling rate has a considerable effect on the required freight rate. Therefore, the River Nile terminals must be provided with highly efficient container handling equipment.

6.3 Fuel price

The results of analyses performed using the developed program prove that at a constant fuel consumption rate, the increasing of the price of fuel will increase the operation cost, which consequently increases the total annual cost and finally increases the required freight rate.

Figure 12 shows that fuel price has a significant effect on the required freight rate. Thus, if fuel price increases 10%, the required freight rate will increase for about 4% approximately. Considering the instability of fuel prices, due to political controversies, it has been realized that fuel cost sensitivity study should have an important role in the final choice of the optimum design.

6.4 Building cost

The results of analyses made using the developed program have proved that at a constant man hour cost, the increasing of the cost of building one ton of steel will increase the ship capital cost, which finally increases the required freight rate.

Figure 13 shows the relation between the required freight rate and the steel building cost at different man hour costs. This figure shows that the building cost has a considerable effect on the required freight rate.

7 Conclusions

1. Inland navigation offers reduction in the congestion on the Egyptian motorways and a decrease in the air pollution and overall transport cost.
2. Inland container vessel design differs significantly not only from the design of seagoing ship, but also from one waterway to another.
3. The presence of locks and bridges along the considered route, and the shallow water nature of the River Nile affect the dimensions and speed of the Nile container ships.
4. The proposed formulae for the estimation of ship steel weight and power prediction can be simply used in the preliminary design stage of conventional self-propelled inland container ships.
5. The developed computer program (CACSO) represents an accurate tool for finding out the optimum characteristics of any container ship operating between Cairo and Aswan through the River Nile.
6. The output results of the developed program may be taken as standard dimensions for any new inland container ship operating through the same navigation route.
7. The developed program (CACSO) may be simply modified to suit not only the other navigation routes but also the other River Nile ship types.
8. To enable much higher utilization of the waterways, further technical improvement and therewith further attraction for inland navigation should be created.
9. Increase in the sailing time per day through the River Nile and the use of efficient container handling equipment in river terminals will highly encourage the transportation companies to shift their activities to the River Nile transportation mode.
10. Fuel price and steel building cost have considerable effects on the required freight rate. Therefore, these costs have important roles in the final choice of the optimum design.
11. From the economical point of view, inland water transportation (IWT) mode generally remains a competitive mode of transportation even after adding the cost of secondary handling by trucks.

8 References


### Nomenclature:

- \( AAC \): Average annual cost, LE/year
- \( A_{\text{wage}} \): Average wage per person, LE/month
- \( B \): Ship breadth, m
- \( BM_T \): Transverse metacentric radius, m
- \( CHR \): Cargo handling rate, TEU/h
- \( CNB \): Number of containers abreast, TEU
- \( C_{\text{nl}} \): Number of containers along ship, TEU
- \( CR \): Capital recovery factor
- \( Choc \): Container handling cost, LE/TEU
- \( C_{\text{admin}} \): Administration cost, LE/year
- \( C_{\text{annual}} \): Annual operating cost, LE/year
- \( C_{\text{cb}} \): Container handling cost, LE/year
- \( C_{\text{day}} \): Accommodating cost, LE/day/person
- \( C_{\text{fuel}} \): Fuel cost, LE/year
- \( C_{\text{c}} \): Container handling cost, LE/TEU
- \( C_{\text{insu}} \): Insurance cost, LE/year
- \( C_{\text{maintenance}} \): Hull maintenance and repair costs, LE/year
- \( C_{\text{machinery}} \): Machinery cost, LE
- \( C_{\text{lab}} \): Machinery labour costs, LE/year
- \( C_{\text{material}} \): Machinery material costs, LE/year
- \( C_{\text{man}} \): Man hour cost, LE/h
- \( C_{\text{manual}} \): Machinery maintenance and repair costs, LE/year
- \( C_{\text{outfitting-lab}} \): Outfitting labour cost, LE
- \( C_{\text{outfitting-mat}} \): Outfitting material cost, LE
- \( C_{\text{outfitting}} \): Outfitting cost, LE
- \( C_{\text{port}} \): Port expenses, LE/year
- \( C_{\text{prov}} \): Provisions cost, LE/year
- \( C_{\text{steel}} \): Hull steel cost, LE
- \( C_{\text{total}} \): Total annual operating cost, LE
- \( C_{\text{crew}} \): Crew cost, LE/year
- \( D \): Ship depth, m
- \( DCS \): Diesel oil consumption at sea, tons/trip
- \( Dw \): Dead weight, tons
- \( E \): Lloyd’s numeral
- \( FCS \): Fuel consumption at sea, tons/trip
- \( FCT \): Total fuel consumption, tons/trip
- \( FCP \): Fuel consumption at port, tons/trip
- \( F_{\text{h}} \): Froude number depth
- \( F_B \): Freeboard, m
- \( F_{\text{price}} \): Fuel price, LE/ton
- \( f_{\text{lab}} \): Factor for machinery labour cost
- \( f_{\text{mat}} \): Factor for machinery material cost
- \( f_{\text{port}} \): Factor for port expenses, LE/ton
- \( GM_T \): Transverse metacentric height, m
- \( g \): Gravity acceleration, m/sec\(^2\)
- \( Hdb \): Double bottom height, m
- \( h_w \): Water depth, m
- \( I_T \): Transverse moment of inertia, m\(^4\)
- \( i \): Interest rate
- \( K \): Radius of gyration, m
- \( K_B \): Vertical center of buoyancy, m
- \( K_G \): Vertical center of gravity, m
- \( LE \): Egyptian pound
- \( Loa \): Length over all, m
- \( N \): Ship life, years
- \( N_c \): Number of containers
- \( N_{\text{crew}} \): Number of crew
- \( N_{\text{layer}} \): Number of container layers
- \( P \): Ship capital cost, LE
- \( P_{\text{td}} \): Port time, days/trip
- \( Pa \): Port allowance
- \( P_b \): Brake power, hp
- \( pw \): Single present worth factor
- \( RFR \): Required freight weight, LE/TEU
- \( Ru \): Round trip distance, km
- \( Ra \): Sea allowance
- \( SFC \): Specific fuel consumption, gr/hp/h
- \( SHP \): Shaft power, hp
- \( STd \): Sea time, days/trip
- \( Sv \): Scrap value
- \( T \): Ship draught, m
- \( T_{\text{nc}} \): Number of transported containers per year, TEU
- \( T_{\text{td}} \): Total trip time, days
- \( TEU \): Twenty feet equivalent unit
- \( Tn \): Number of trips per year
- \( T_{\text{roll}} \): Rolling period, sec
- \( V_{\text{km}} \): Ship speed, km/h
- \( W_c \): Cargo weight, tons
- \( W_{\text{light}} \): Light ship weight, tons
- \( W_{\text{machinery}} \): Machinery weight, tons
- \( W_{\text{outfitting}} \): Outfitting weight, tons
- \( W_{\text{steel}} \): Net steel weight, tons
- \( Y_{\text{nc}} \): Number of transported containers per year, TEU/year
- \( \Delta \): Ship displacement, tons
- \( \gamma \): Specific weight of water, tons/m\(^3\)