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Sensitivity Analysis of Inland Water Transport Systems in Egypt

M. M.Moustafa[1,], L. B. Kamar[2], O. A. Harigy[3], and W. Yehia[4]*

[1]*Naval Architecture and Marine Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt,* moustafa3875@eng.psu.edu.eg

[2]*Naval Architecture and Marine Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt,* laila.kamar@eng.psu.edu.eg

[3]*Naval Architecture and Marine Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt,* harigy.omar@eng.psu.edu.eg.

[4]*Naval Architecture and Marine Engineering Department, Faculty of Engineering, Port Said University, Port Said, Egypt,* waleed.yehia@eng.psu.edu.eg

**M. M.Moustafa, moustafa3875@eng.psu.edu.eg,* *DOI: 10.21608/PSERJ.2022.140454.1186*

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ABSTRACT

Inland transport plays a significant role in the lives of the peoples of many countries since it offers many environmental, economic, and social benefits over other modes of transportation. Therefore, many studies have recently been carried out with the purpose of improving the infrastructure of the River Nile in order to increase the annual volume of transported cargoes over a huge network of inland waterways that connect most Egyptian cities. However, further research is required to select a suitable transport system capable of transporting the greatest amount of cargoes through River Nile's very shallow waterways. Thus, in this article, the distinctive characteristics of all river transportation modes employed in Egypt is analyzed and the pusher train barge system has been found to be the most appropriate method of transporting cargoes along waterways with limited water depth. Based on a technical and operational criterion termed transport efficiency, six possible configurations of a proposed pusher train barge system are compared in order to select the most economically feasible configuration to operate along the Cairo-Aswan waterway. For three different loading conditions, this study is carried out with the use of a computational fluid dynamics software package (CFD-Fluent) and the results are validated.

Keywords: Pusher Train Barge System, Shallow Water, River Nile, Transport Efficiency, Computational Fluid Dynamics

1. INTRODUCTION

Cairo, Egypt's capital and largest city, is a home to many kinds of inland water transportation. A vast network of inland waterways, covering over 3,200 kilometers, connects Cairo to most other Egyptian cities. Furthermore, River Nile is regarded as the most important inland waterway for transporting goods and passengers among Egyptian cities. Thus, the main priority of Ministry of Transport these days is significantly increasing freight transportation through the River Nile waterway. This will reduce traffic congestion, pollution, as well as the expense of road maintenance.

Many research efforts have focused on the factors that affect Egypt's inland waterways transportation sector [1]. As a result, the Egyptian government has recently begun to work on improving Egypt's inland navigation systems in order to meet the essential safety standards [2]. In addition, to increase the flow of goods through the River Nile, the feasibility of transporting containers throughout Cairo - Aswan waterway using self-propelled units was also studied [3]. Moreover, stern shape of heavily loaded inland cargo ships was studied theoretically and experimentally in order to improve operating performance for such ships [4].

The resistance of inland navigation units at different water depths was also predicted through theoretical and experimental study [5]. Through extensive research around the world, the pushed barge convoy system was proven it is the most successful and advanced mode of river transportation. Barge convoy technical and navigational standards were investigated [6]. Many studies also dealt with methods of calculating the resistance of the barge convoy systems, which represents the starting point for selecting the most appropriate configuration for the convoy [7, 8, 9].

For the case of the River Nile, S. M. Shenouda et al [10] established that the barge convoy system is the most suitable mode of inland water transportation in Egypt, based on previously published experimental results and empirical equations. Thus, this paper presents a sensitivity analysis for the pusher train barge system in order to determine the most economically feasible configuration capable of transporting the greatest quantity of heavy goods at the lowest water depth on the Cairo-Aswan waterway, which occurs in December and January [11].

This analysis is carried out with the use of a computational fluid dynamics software package (CFD-Fluent) for three different loading conditions (50%, 75% and 100%) and the results are validated with previously published results.

2. DESCRIPTION OF THE RIVER NILE NAVIGATION SYSTEM

Egypt really does have a vast network of inland waterways. The Nile River flows from Africa's heartland to the Mediterranean Sea. Its branches cover the country's most populous areas. Moreover, a huge system of constructed canals of various sizes exists in addition to the River Nile. So, Every city, town, and village lies on the River Nile, one of its branches, or one of the existing navigable canals. Egypt, in fact, is one of the few countries that manages such a vast inland waterways network. Egypt's inland waterways network includes a variety of waterways that are categorized into three classes. Table 1 illustrates the classification of Egypt's inland waterways according to the River Transportation Authority's criteria [2]. Egypt's three most important waterways are included in the First-Class inland waterways network; 980 km between Cairo and Aswan, 205 km between Cairo and Alexandria and 241 km between Cairo and Damietta.

Table 1: Classification of the inland waterways in Egypt [2]

Class	Width (m)	Water depth (m)	Air Clearance (m)	Max. draft (m)	Length (km)
1st Class	35	2.5	13 for River Nile and it's branches	1.8	2191
			6 for other ways		
2nd Class	12	1.8	3.5	1.5	121
3rd Class	8	1.25	2.5	1.0	813
The total length of the Egyptian inland water ways =					3125

This research has been carried out on the Cairo-Aswan waterway. Fig. 1.a and Fig. 1.b show the Egyptian inland waterways network for Lower and Upper Egypt, respectively [2]

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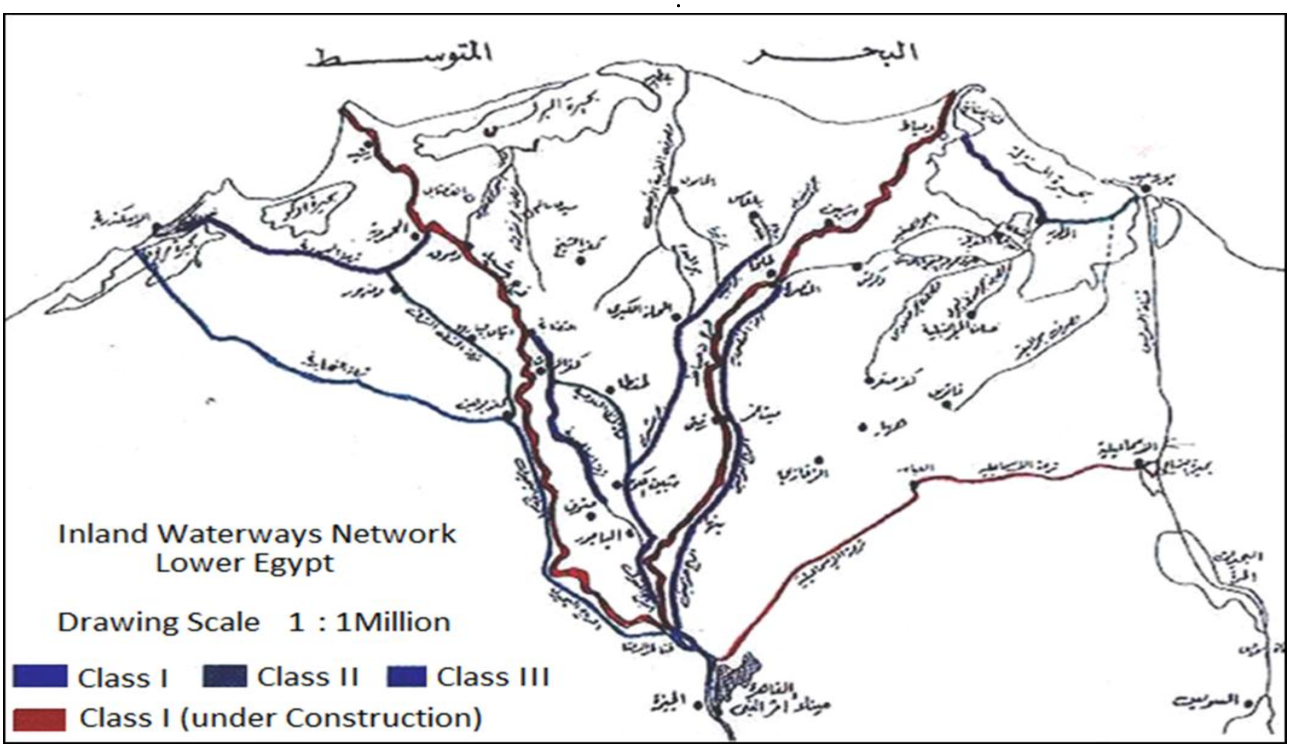

Figure 1.a: The Egyptian inland waterways network – Lower Egypt

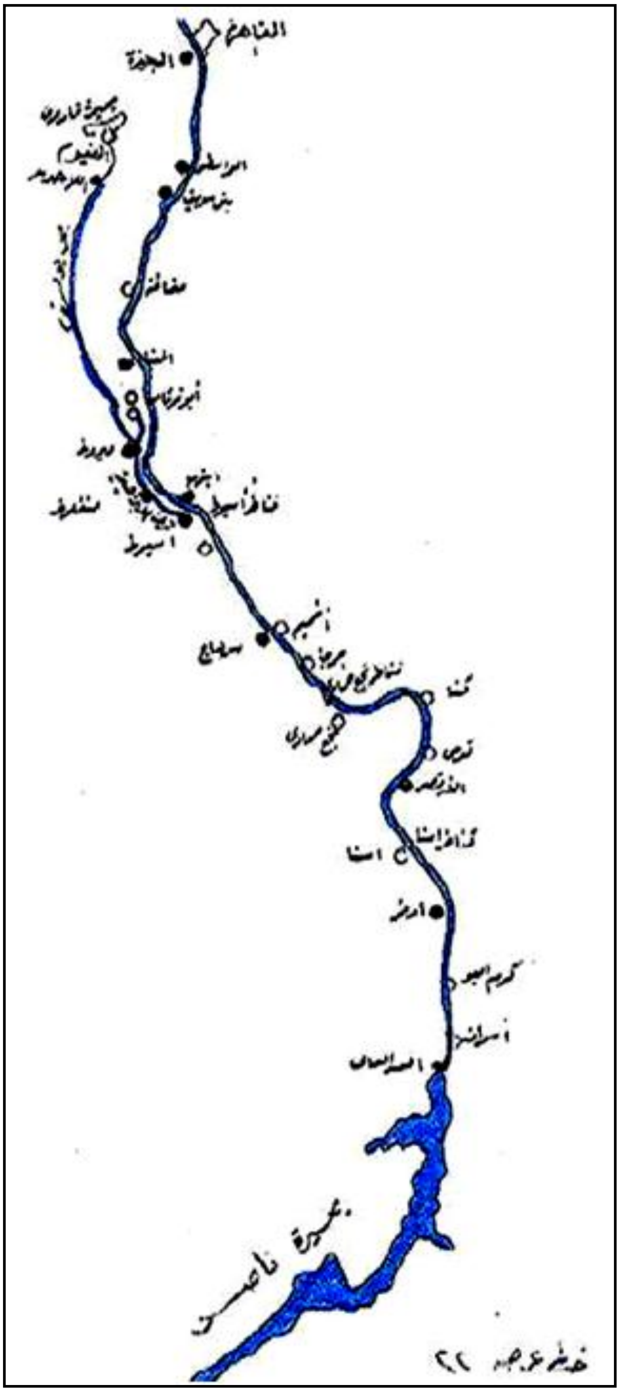

Figure 1.b: The Egyptian inland waterways network - Upper Egypt

3. FACTORS AFFECTING THE CHOICE OF INLAND TRANSPORTATION UNITS

The condition of the inland waterways has a significant influence on the selection of inland units. The main dimensions of such a type of vessel are influenced by the depth and width of the waterway, as well as the size of the locks and the applicable regulations. Due to the limited water depth, designing inland units, particularly the underwater form of these vessels, is difficult. If higher thrust is required, as in the case of a train barge convoy system, limited water depth leads to a multi-screw pusher unit. The condition of any inland waterway may be altered depending on the draught of the unit on which it is sailing, see Table 2 [6].

Table 2: Waterways Conditions as a Function of h/T

Condition	Range of h / T	Effect on ship
Deep Water	h / T > 4.0	No effect
Medium Deep	1.5 < h / T < 4.0	Noticeable
Shallow Water	1.2 < h / T < 1.5	Very Significant
Very Shallow Water	h / T < 1.2	Dominates Motion

When a ship enters a shallow waterway, the interaction between the ship and the seabed results in a number of hydrodynamic consequences. Under the ship's hull, there is a considerable increase in the backflow velocity and a reduction in water pressure, as well as significant sinkage and trim changes. This increases potential and skin friction resistance, as well as wave resistance. In terms of water depth, ship speed, and wave speed, these effects can be considered. The hydrodynamic behavior of any inland unit travelling in shallow waterways is characterized by the depth Froude number, see Fig. 2 [8].

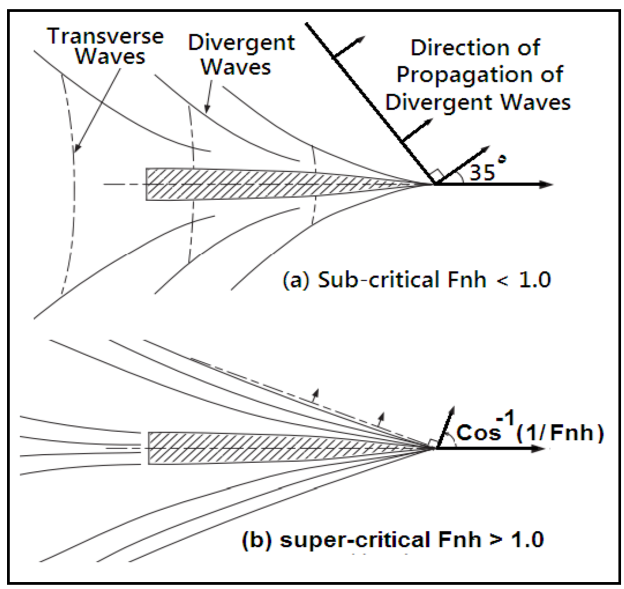

Figure 2 Sub-critical and super-critical wave patterns

At the subcritical speed range (Fnh ≤ 1.0), the wave system will be as shown in Fig. 2.a, with a transverse wave system and a diverging wave system propagating at an angle of roughly 35 degrees away from the ship. The wave angle approaches 0 degree (perpendicular to the ship's track) when the ship speed approaches the critical speed, Fnh = 1.0. The diverging wave system returns to a wave propagation angle of roughly cos-1(1/Fnh) at speeds greater than the critical speed and no transverse waves are present, Fig. 2.b. To avoid the critical region of ship resistance, the proper choice of ship speed should be based primarily on the Froude depth number (Fnh). Thus, most inland units usually sail at a speed that corresponds to a Fnh value of less than 0.7 [12].

4. THE PROPOSED PUSHER TRAIN BARGE SYSTEM

The River Nile and its associated navigable canals are vital transportation routes, particularly for heavy goods. However, the extremely low water depths on the Nile River, especially during the winter session, necessitate an economical transport mode. Therefore, in the present study, a pusher train barge system is proposed to help with transportation development. This system is characterized by its ability to transport the largest amount of goods with minimal number of crew members. Furthermore, the ability to separate the propulsion unit from the goods-carrying barges provides the most efficient use of the system's most expensive component.

The proposed system will run along the Cairo-Aswan waterway, which is a very shallow waterway with a h/T ratio of 1.47. This route is primarily used for cargo and tourist transportation, and it is constrained by locks, bridges, and limited water depth. Based on a technical and operational criterion termed transport efficiency (E_T), six possible configurations of a pusher train barge system are compared in order to select the most economically feasible configuration to operate along the Cairo-Aswan waterway. Every configuration of the proposed pusher train barge system is named in a specific style, see Fig.3.

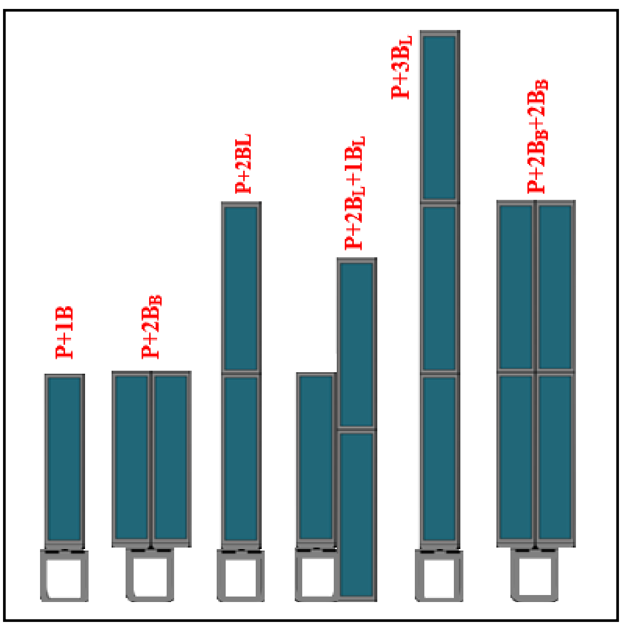

Figure 3: Configuration of the Proposed Pusher Train Barge System

5. NUMERICAL INVESTIGATION

This study is carried out with the use of a computational fluid dynamics software package (CFD-Fluent). This calculation is performed with h/T = 1.47, assuming no waves and no propeller effects. It is also assumed that the proposed pusher train barge system moves in a linear motion at a constant speed and its free surface is adapted. Importing the geometry of the Pusher Train, creating the domain, meshing, defining boundary conditions, setting solver parameters, running the simulation, getting the results, and finally model validation are all used in the CFD-Fluent code simulations.

5.1. Hull Geometry, Mesh, and Boundary Conditions

The geometries of the pusher tug and pushed cargo barge have been chosen to comply with the aforementioned restrictions, which are located in the Cairo-Aswan waterway, which has been chosen as the study's target route. Table 3 lists the dimensions of the pushed cargo barge and the pusher tug. Figs. 4 and 5 illustrate the geometries of the pusher tug and pushed cargo barge, respectively. The Pusher Tug and Pushed Barge models are created with Rhinoceros-3D modelling software.

Table 3: Dimensions of the pushed cargo barges and the pusher tug

Items	Pusher Tug	Pushed Barge
Length (L)	19 (m)	70 (m)
Breadth (B)	9.5 (m)	9.5 (m)
Draft (T)	1.1 (m)	1.7 (m)
Depth (D)	2.47 (m)	3.2 (m)

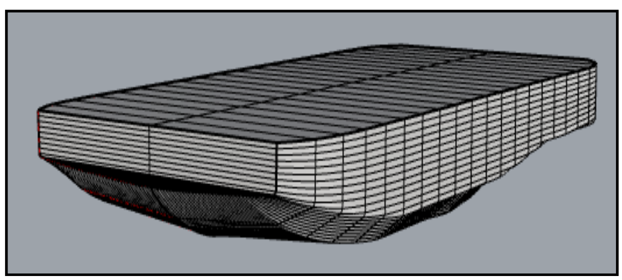

Figure 4: Pusher Tug - 3D Hull Model

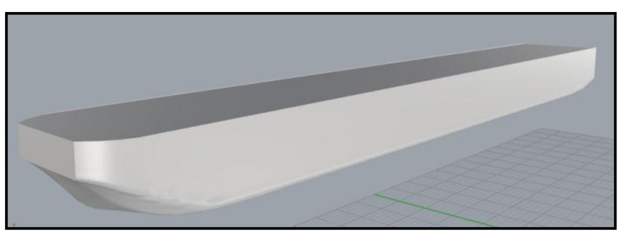

Figure 5: Pushed Cargo Barge - 3D Hull Model

The portion of space where the solution of the Computational Fluid Dynamics (CFD) simulation is calculated is known as a CFD domain. To solve the discretized equations of fluid flows, the computational domain must be discretized into a computational grid (or mesh). The International Towing Tank Conference recommends computational domain dimensions as a function of ship length [13]. The majority of the flow computations used domain sizes with an upstream boundary of roughly 1L from the bow, a downstream boundary of roughly 2L from the stern, a side boundary of 1L from the plane of symmetry, and a bottom boundary of 1L from the keel [13]. However, modifying the domain size to match the width and depth of the towing tank in which the model scale hull will be measured is recommended [13]. This is useful for validation scenarios requiring a precise comparison with measurements. In this study, the P+2B_B+2B_B pusher train barge system is used as a validation example, and the results are compared to previously published experimental results [14]. Figure 6 shows the computational domain of such a system, while Table 4 lists its size.

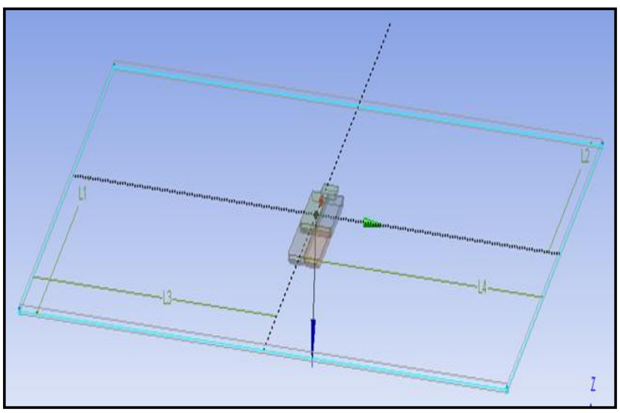

Figure 6: Computational Domain of the P+2B_B +2B_B Pusher Train Barge System

Table 4: Size of the computational domain of the P+2B_B +2B_B Pusher Train Barge System

Items	Size (m)
Upstream Boundary	159
Downstream Boundary	159
Side Boundary	142.5
Bottom Boundary	0.8

The mesh is generated using ANSYS-Fluent meshing software, which supports both structured and unstructured meshing. Because the domain is complicated and there are localized areas of the pusher train barge system that require higher resolution mesh, the unstructured mesh is used in this study. Fig. 7 shows mesh of the P+2B_B +2B_B Pusher Train Barge System.

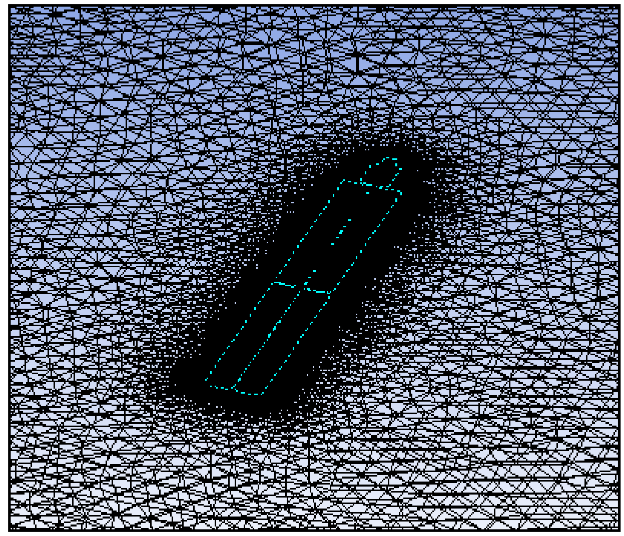

Figure 7: Mesh of the P+2B_B +2B_B Pusher Train Barge System

A mesh independence study is conducted based on the ITTC uncertainty analysis guidelines to define mesh resolution and the optimum number of mesh cells for the P+2B_B+2B_B pusher train barge system. The results are listed as shown in Table 5.

Table 5: The results of mesh independence study for P+2B_B+2B_B pusher train barge system

Mesh Resolution	Coarse Mesh	Medium Mesh	Fine Mesh
Number of Elements	274152	852346	1680147
Estimated Resistance (kN)	192.11	189.23	186.14

To simulate the shallow water towing tank condition, boundary conditions are being used. Uniform flow is usually imposed at the inlet, which is located in front of the hull, and the velocity of the inlet boundary condition is usually equal to the velocity of the model used in experiments. Zero gradient pressure is imposed at the outlet, which is placed behind the hull. The sides and bottom should always be treated as moving boundaries when simulating shallow water. Table 6 lists the conditions for all of the study's boundaries.

Table 6: Boundary Conditions

Boundary	Condition
Inlet	Constant velocity and turbulence quantities
Outlet	Constant static pressure
Hull	No-slip wall
Top	Symmetry
Bottom	Symmetry
Side	Symmetry

The distance to the wall, where $y^+ \leq 1$ for near-wall boundary conditions and $30 < y^+ < 100$ for logarithmic wall functions, should be estimated to capture the boundary layer effects near the hull, see Eq. 1 [12].

$$y = \frac{y^+}{\left(Rn \, . \sqrt{\frac{C_F}{2}}\right)} \, . \, L_{pp} \qquad (1)$$

Where y is the first required cell height, y^+ is a non-dimensional parameter, C_F is the skin friction coefficient, Rn is the Reynolds number and L_{pp} is length between perpendiculars. For the purpose of this study, y^+ is taken to be equal to 50. Thus, for the $P+2B_B+2B_B$ pusher train barge system, the first required cell height is calculated and found to be equal to 1.52371×10^{-7} m.

5.2. Computational Simulation and Results Validation

The accuracy of the CFD-Fluent code's calculation results is dependent on the turbulence model employed. As a result, one is forced to select the best model for each application. There are two types of turbulence models k-ε and k-ω. These models, which have been demonstrated to be capable of accurate prediction in ship hydrodynamics, are by far the most widely used. The resistance of the $P+2B_B+2B_B$ pusher train barge system at a speed of 11.5 km/hr is calculated in this study using both the k-ε and k-ω models, and the results are compared to previously published experimental results, as shown in Table 7.

Table 7: Results of the Turbulence Model and Validation

Turbulence Model		CFD P_D (kW)	Exp P_D (kW)	Error %
k-ε	Standard	210.52	200	4.99
	RNG	225.06	200	12.53
	Realizable	226.36	200	13.18
k-ω	Standard	225.06	200	12.53
	BSL	227.5	200	13.75
	SST	228.68	200	14.34

According to Table 7, the k-ε standard turbulence model has the lowest error of 4.99%, which is acceptable. So, it is used to simulate the other configurations of the proposed pusher train barge system.

6.CHOOSING THE MOST ECONOMICAL CONFIGURATION

In this section, the most cost-effective configuration of the proposed pusher train barge system operating on the Cairo-Aswan waterway is determined by comparing six possible configurations. This comparison is based on transport efficiency (E_T), which is one of the most widely used technical and operational measures in the maritime transport sector. Eq. 2 can be used to calculate E_T in tons-kilometers per kilowatt-hour [15].

$$E_T = \frac{Dwt \, . \, V}{P_B} \qquad (2)$$

Eq. 2 illustrates that in addition to the required power, the weight of the transported cargo and the time required to move that weight are considered. Using a computational fluid dynamics software tool (CFD-Fluent), the resistance of each configuration is determined for three different loading conditions (50%, 70%, and 100%). Fig. 8 depicts the cargo carrying capacity of each configuration, with draughts ranging from 1.0 to 1.7 m.

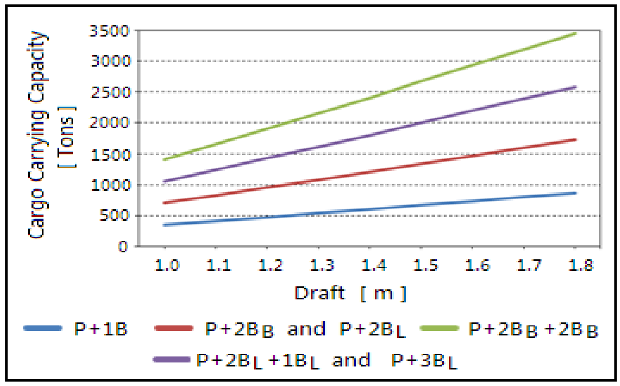

Figure 8: Cargo Carrying Capacity

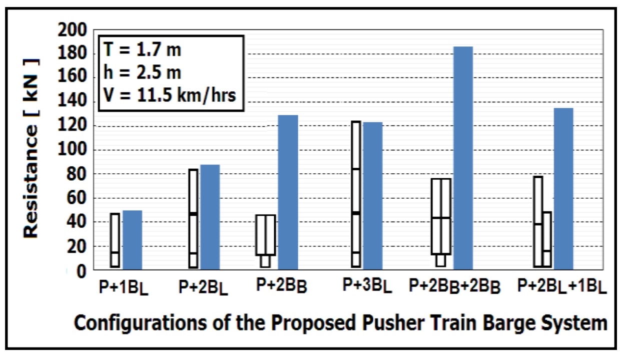

Figure 9: Resistance for Configurations of the Proposed Pusher Train Barge System - 100% Loaded

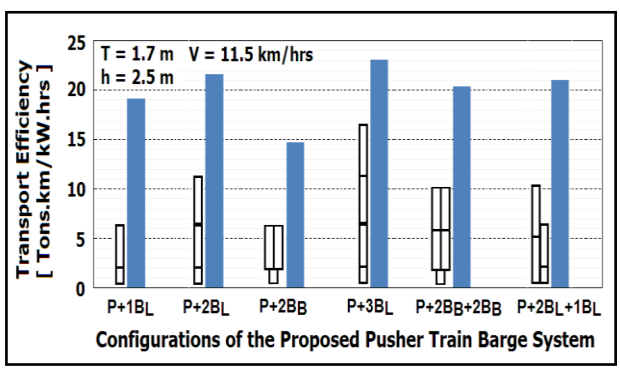

Figure 10: Transport Efficiency for Configurations of the Proposed Pusher Train Barge System – 100% Loaded

For full load (100% cargo carrying capacity), resistance and transport efficiency for all configurations of the proposed pusher train barge system are calculated and presented as shown in Figs. 9 and 10, respectively. The water resistance of all configurations of the proposed pusher train barge system varies greatly, as shown in Figure 9. However, the transport efficiency values of configurations $P+2B_L$, $P+3B_L$ and $P+2B_L+1B_L$ are found to be quite similar, see Fig. 10. Furthermore, although having the highest transport efficiency, configuration $P+3B_L$ is excluded from the comparison because of the maneuvering and steering difficulties that would be encountered while sailing through the Cairo-Aswan waterway due to its large length of up to 222 m. As a result, the comparison is limited to the two configurations $P+2B_L$ and $P+2B_L+1B_L$, which have roughly similar transportation efficiency values. Moreover, the configuration $P+2B_L+1B_L$ is chosen to be the most economical configuration of the proposed pusher train barge system for the full load condition because it can transport a larger quantity of goods than the other configuration.

It is not reasonable to transport a quantity of goods using a configuration consisting of a group of partially loaded cargo barges. As a result, a comparison is made between configuration $P+2B_B+2B_B$, which can transport 2323.8 tons of cargoes in 75% partially loaded cargo barges, and configurations $P+3B_L$ and $P+2B_L+1B_L$, which can transport the same quantity of cargo in fully loaded cargo barges. For these configurations, the transport efficiency is determined, and the results are presented in Fig. 11.

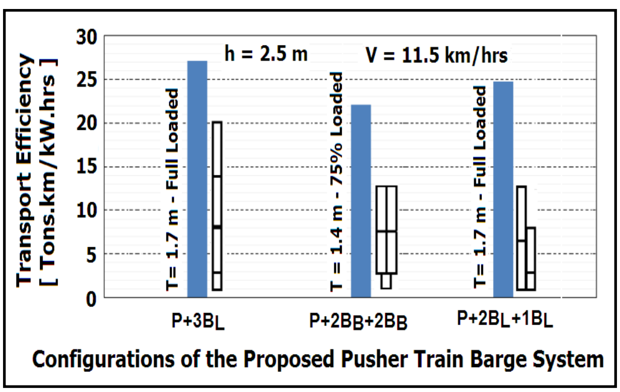

Figure 11: Transport Efficiency for 75% and 100% Loaded Conditions at a Constant Cargo Carrying Capacity

In this case, for the same reasons mentioned above, the configuration $P+2B_L+1B_L$ is chosen to be the most economical configuration of the proposed pusher train barge system. Another comparison is carried out to compare both the $P+2B_B+2B_B$ configuration, which can transport 1549.2 tons of cargo in 50% partially loaded cargo barges, and the $P+2B_L$ and $P+2B_B$ configurations, which can transport the same quantity of cargo in fully loaded cargo barges. In this case, the $P+2B_L$ configuration is considered the most economical configuration for the proposed push-train barge system as it has the highest transport efficiency, see Fig. 12.

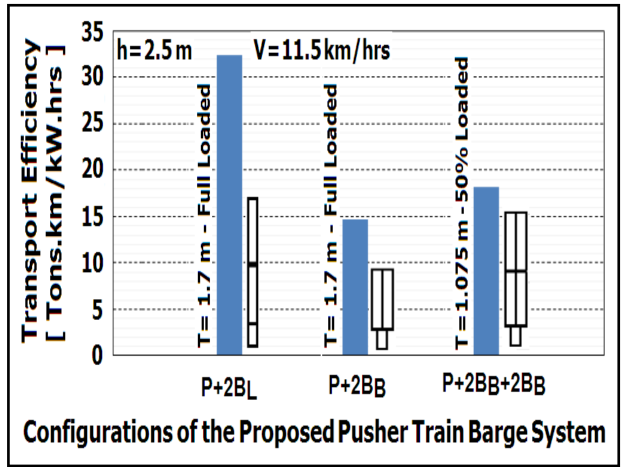

Figure 12: Transport Efficiency for 50% and 100% Loaded Conditions at a Constant Cargo Carrying Capacity

7. CONCLUSIONS

Egypt has great potential for inland transportation, but it is not effectively utilized, requiring a significant amount of effort to achieve a boom in cargo transport over the River Nile. The River Nile's shallow water depth is also regarded as one of the most significant navigational obstacle to this development. As a result, it is important to expand goods transportation throughout the Nile River by utilizing the pusher train barge system, which can transport the maximum amount of goods through very shallow waterways in an economical and safe manner.

In the present study, six possible configurations of a proposed pusher train barge system are compared in order to select the most economically feasible configuration to operate along the Cairo-Aswan waterway. This research is carried out with the help of the Computational Fluid Dynamics (CFD-Fluent) software package, which is found to be accurate when compared to previously published experimental data. Moreover, this comparison is based on transport efficiency (E_T), which is one of the most widely used technical and operational measures in the maritime transport sector.

The most economically feasible configuration of the proposed pusher train barge is determined for three different loading conditions (50%, 70%, and 100%). For the full load condition, the configuration $P+2B_L+1B_L$ is chosen as the most economical configuration of the proposed system. In comparison to configuration $P+2B_B+2B_B$ at 75% of its maximum loading capacity, configuration $P+2B_L+1B_L$ proven to be the most economical configuration consisting of three fully loaded cargo barges. Furthermore, when compared to configuration $P+2B_B+2B_B$ at 50% of its maximum loading capacity, configuration $P+2B_L$ has proven to be the most economical configuration consisting of two fully loaded cargo barges.

Finally, while going through the existing locks on the Cairo-Aswan waterway, components of the utilized cargo-transporting configuration will have to be dismantled, and thus this passage will take place on multiple runs.

Credit Authorship Contribution Statement

M. M. Moustafa: Conceptualization, Methodology, Writing review & editing, Supervision. **L. B. Kamar:** Conceptualization, Methodology, Writing review & editing, Supervision. **O. A. Harigy:** Methodology, Writing original draft. **W. Yehia:** Conceptualization, Methodology, Writing review & editing, Formal analysis, Supervision.

Declaration of Competing Interest

The authors state they have no idea of conflicting financial interests or personal relationships that may affect the work presented in this article.

Symbols and Abbreviations

B	Breadth, m
CFD	Computational Fluid Dynamics
C_F	Skin Friction Coefficient, --
D	Depth, m
Dwt	Deadweight, tons
E_T	Transport Efficiency, tons.km/(kW.h)
Fnh	Depth Froude Number, --
h	Water Depth, m
L_{pp}	Length Between Perpendiculars, m
P_B	Brake Power, Kw
P_D	Developed Power, kW
Rn	Reynolds's Number, --
T	Draft, m
V	Speed, km/h
y	The First Required Cell Height, m
y^+	Non-dimensional Parameter, --

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