Mathcad model for the estimation of cost and main characteristics of Air-Cushion Vehicles in the preliminary design stage

by

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This work is dedicated to my parents and my grandfathers Georgios and Panagiotis for being the exemplars in my life.
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ABSTRACT

In the naval architecture terminology, the term ACV (Air Cushion Vehicle) refers to this category of vehicles, in which a significant portion of the weight (or all the weight) is supported by forces arising from air pressures developed around the craft, as a result of which they hover in close proximity to the sea. Major types are hovercrafts and SES (Surface Effect Ships).

A well-designed Air Cushion Vehicle (ACV) is superior to a conventional ship, because it has less drag and requires less horsepower to operate at the same speed. An ACV is much more fuel-efficient than a ship with similar capacity or size. Rising fuel prices and shortages will make ACVs a desirable form of transportation in the future.

In order to cover this future trend in marine transportation, a MathCAD model for the estimation of the main characteristics of Air Cushion Vehicles in the preliminary design stage is being developed.

This model is based on a statistical analysis of the various parameters of existing crafts. For this reason, a statistical database has been created using publicly available information. A regression analysis has been performed using the data collected and the trend lines for every case have been derived.

For the validation of the code, LCAC (Landing Craft Air Cushion) is used as the reference vehicle. The values of LCAC design parameters that are known, are input in the code and crosschecked with the outputs. Iterative procedures have been applied to the code in order to correct the trend lines according to the reference model.

The development of this MathCAD model is directly related to the lack of software dealing with the design of ACVs in the market. Conventional ship design tools are widespread and used even by students. On the other hand, ACV design programs are possessed by the companies that design this kind of crafts and are not widely available.

In the following pages, together with the analysis of the model developed, the associated theory is presented so that the reader has a complete image of what an ACV is and how it works. Hence, this thesis is not a manual of a program, but a combination of theory and application intended to help the reader-user understand the design process of ACVs.

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Nomenclature

ACV = Air Cushion Vehicle
SES = Surface Effect Ship
LCAC = Landing Craft Air Cushion
AUP = All Up Weight
TF = Transport Factor
Be = cushion beam
Le = cushion length
Se = cushion area
Uc = cushion pressure
Re = Reynolds number
Fr = Froude number
Vs = craft speed
Dw = wavemaking drag
Da = aerodynamic drag
Dm = momentum drag
Dw = wetting drag
g = gravity acceleration
Pa = air density
Ps = salt water density
Mathcad model for the estimation of cost and main characteristics of
Air-Cushion Vehicles in the preliminary design stage

1. Thesis Overview

The code developed is not intended to replace any tools that exist for the design of ACVs. It is mainly developed for use in the course of naval architecture to provide students with a tool for calculating the characteristics of ACVs in the initial iteration of the design spiral. In some cases simplifications and assumptions were made in order to maintain a level which is understood by the student who uses the model for the first time. The results of the code are approximate and for this reason a most thorough analysis with the aid of other more advanced tools has to be used in order to proceed to the final design stages.

Together with the analysis of the model developed, the associated theory is presented in a simple way so that the reader has a complete image of what an ACV is and how it works. Hence, this thesis is not just a manual of a program, but a combination of theory and application intended to help the reader-user understand the design process of ACVs. Moreover, many figures are used throughout the analysis so that the reader can visualize the mechanisms that govern ACVs.

The tool used for the code development is MathCAD 2001. MathCAD has the advantage that the user can see the formulas used, giving him the opportunity to better understand the theory. Another reason for choosing MathCad as the design tool was for compatibility with MIT 13A math model for conventional monohulls, a program estimating main characteristics of monohull ships using parametric analysis.
2. Definitions

*Air Cushion Vehicle* is any of the machines characterized by movement in which a significant portion of the weight or all the weight is supported by forces arising from air pressures developed around the craft, as a result of which they hover in close proximity to the earth or sea surface. It is this proximity to the surface that chiefly distinguishes such crafts from aircraft, which derive their lift from aerodynamic forces created by movement through the air.

Air Cushion Vehicles are divided in the following main categories:

*Hovercraft*, which is a fully amphibious vessel able to make the transition from water to land and vice versa.

*SES (Surface Effect Ship)*, which is effectively a catamaran with low displacement hulls and flexible structures forward and aft. Pressurized air is retained between the hulls which elevates the vessel thus reducing the drag through the water.

*WIG (Wing in Ground Effect)*, which is effectively an aircraft that utilizes the “ground effect” in which lift increases compared to a wing in free flight, if the distance to the surface measured from the trailing edge is less than 30% of the mean aerodynamic chord. This category of ACVs will not be analyzed in the present thesis.

In the following page the three representatives of Air Cushion Vehicles are presented in figures [1], [2], [3].
Figure 1: A hovercraft (LCAC of the US Navy)

Figure 2: A Surface Effect Ship (SES of the Norwegian Navy Skjold)
3. Historical Background

The idea of using an air-cushion as a means or aid to acceleration and reduction in (hydrodynamic) drag was first explored by Sir John Thornycroft, a British engineer, who, in the 1870's built some experimental models on the basis of an air cushion system that would reduce the drag of water on boats and ships. In 1877 he successfully patented the idea and his theory was that if a ship's hull was given a concave bottom, which could be filled - and replenished - with air, it would create significant additional lift. And so the air cushion effect was born.

Decades later scientists and inventors were still busy with his ideas but without any practical applications. With the coming of the airplane however, it was noticed that additional lift was obtained if the plane flew closer to land or water, creating a "funnel effect", a cushion of air. The air lift that this funnel effect created differed with the type of wing and its height above ground. The effect was strongest if this height was between one half and one third of the (average) front-to-rear breadth of the wing (chord).

After the Great War, which did increase technological interest, scientists and innovators again began exploring the advantages of air cushion vehicles and in the early 1920's some experimental models came to shape off the drawing board. The German-built Dornier Do-X flying boat proved the reality of Thornycroft's theory in 1929, when, during an Atlantic crossing, it flew much closer to the ocean's surface than was usual in order to take advantage of the air cushion effect. The trip time was significantly reduced
as a result and the aircraft's performance that much greater. Many flying boats were built during this era, and they formed the forefront and backbone of many aviation routes across the world, especially on the long haul destinations.

The successful use of the air cushion effect was not lost on engineers after World War 2 was over and in the early 1950's British, American and Swiss engineers started to rethink Sir John Thornycroft's problem.

The Englishman Christopher Cockerell, is considered as the father of the hovercraft. His theory was that, instead of using the plenum chamber - an empty box with an open bottom as Thornycroft had devised - air was instead pumped into a narrow tunnel circumnavigating the entire bottom, it would flow towards the center and form a more effective air cushion. This peripheral jet would cause the air to build up enough pressure to equal the weight of the craft and, as it would have nowhere to go, the pressure would force the craft up, clearing it off the ground altogether.

Cockerell successfully tested his theory and filed his first patent in 1955. The year after he formed a company called Hovercraft Ltd. Thinking that his air cushion vehicles would be eminently suitable as amphibious craft he approached the British Ministry of Supply, the government's defense equipment procurement authority with his findings. Soon after, in 1956, the air cushion vehicle was classified as "secret" and a construction contract was placed with a British aircraft and seaplane manufacturer. The result was the SR.N1 in 1959.

The first SR.N1 weighed four tons and could carry three men. Its maximum speed was 25 knots on calm water. It had a 15 cm rubberized skirt to make it easier to contain the air cushion on uneven ground ref [41].

Since then, the development was rapid. Today, there are about forty companies building hovercrafts in seventeen countries. There are hundreds of air-cushion-supported ferries around the world, and thousands of smaller patrol and recreational craft that can attain remarkable speeds in the range of 50-60 knots.
4. Typical Applications

Due to their characteristics Air Cushion Vehicles have a big variety of applications, some of which are listed below:

- Passenger Transport and tourism related excursions
- Commercial freight transportation
- Exploration
- Search & Rescue
- Patrol & Security
- Amphibious Assault
- Fast Attack
- Mine Counter Measures
- Policing & Customs
- Logistics
- Medical Evacuation
- Crash Rescue
- Hydrographic Survey
- Commando Missions
- Range Patrol
5. Comparison of ACVs

Since in the model developed the two basic representatives of ACVs are analyzed, it is expedient to examine the differences as well as the advantages and disadvantages of each type. The crucial difference, when comparing hovercrafts with other types of crafts, is the amphibious characteristics they have. Their amphibious capabilities give them significant advantages over any other vessel such as:

- travel over any surface such as sand, mud, ice etc.
- travel over sea mines
- shortcutting routes
- travel rivers up as fast as down, irrespective of the current
- travel in dry water-beds
- access to terrain, designated unreachable before
- no collision with debris, logs, rocks etc.
- access to 75% of littoral instead of only 5% with conventional vessels
- independent from dock, pier, harbor or dredged channel infrastructures

On the other hand SES have some significant advantages over hovercrafts which are summarized below:

- Reduced air pumping requirements
- More directionally stable
- Side walls contribute to the hydrostatic or hydrodynamic support of the craft allowing them to carry more payload than hovercrafts
6. General Principles and Description of ACVs

The basic working principle of ACVs can be explained with the aid of the sustention triangle. This triangle represents the three different types of lift found in naval architecture: buoyant, dynamic and powered lift. ACVs belong to the powered lift corner of the triangle; more specifically the lift of an ACV is categorized as active-hydro-static, since lift requires moving components of the craft (active), displaces water (hydro) and is generated without forward moving (static). The following figure from ref [17] illustrates the different categories of lift.

![Sustention Triangle Diagram](image)

**Figure 4: The sustention triangle**

The two types of ACVs, as previously defined, share the primary characteristic that nearly all their weight is supported by air forces. This air, which allows an ACV to float on a cushion, is pumped directly into the plenum through a compressor or a fan and some part of it escapes through a “daylight” gap at the lower edge of the cushion. There are different types of cushions as presented in the following four figures taken from ref [22].
The air pumped into the cushion causes the craft to rise or lift. This air is supplied to the cushion at an absolute pressure that is on the order of 5% above absolute atmospheric pressure. The amount of total weight that a hovercraft can raise is equal to the cushion pressure multiplied by the area of the hovercraft.
To make the craft function more efficiently, it is necessary to limit the cushion air from escaping, so the air is contained by the use of what is called a hovercraft skirt. The skirt is another vital component. All the different kinds of skirts are presented in the following figures and come from ref [22].

Figure 9: Bag and finger

Figure 10: Bag jetted

Figure 11: Bertin skirt
Figure 12: Convoluted skirt

Figure 13: Loop bag

Figure 14: Peri cell
The most common skirt in the modern designs is the bag and finger type. It is comprised of a bag that covers the bottom of the base and has holes in it to allow air to escape and push the craft off the ground. At the lower part of the bag the fingers are attached and retain the air coming out of the bag into the plenum. The big advantage of this type of skirt is that the fingers can be replaced after wearing out without having to replace the bag. The skirt is manufactured from fabric and allows a deep cushion or clearance of obstacles.

In the case of SES the same flexible structure described above is used at the stern and the bow of the craft, while at the sides the air is retained by the sidehulls. Thus, the skirt is replaced by the bow and stern seals.

Once "lifted" or "on cushion", thrust must be created to move the hovercraft forward. With many crafts, this is generated by a separate engine from the one used to create the lift, but with some, the same engine is used for both, like the one presented in
The engines used are mostly gasturbines since they combine high power with small weight and size. Moreover, water cooled engines cannot be used since there is no contact with the water.

As figure [19] indicates, the fan-generated air stream is split so that part of the air is directed under the hull for lift, while most of it is used for thrust. In most cases though, there is one fan for the generation of lift air and another fan or propeller for the generation of thrust as in figure [18]. Most commonly used thrust devices are the air propellers which are direct derivatives of the propellers used at the aircraft industry. In the case of SES the thrust generator can be either a water propeller, which in most cases is a supercavitating one, or a waterjet.
That which makes hovercrafts so efficient and different from other vehicles of the same size and capabilities is that very little force is required for it to move. This is achieved through the low friction interface between the flexible structure and the surface on which they move. Ideally, hovercrafts have no contact with the ground or the sea surface, therefore any resistance the ground may produce under other circumstances is now non-existent for the craft. As far as it concerns SES, we do not have total elimination of friction, but significant reduction, since the wetted surface of those crafts is very small. Of course the situation described is ideal since even in the case of hovercraft there is some friction resistance component as will be analyzed later.

When the hovercraft has lift and thrust, it requires steering capabilities. This is achieved through the use of rudders. The rudders are divided in two categories: the vertical ones and horizontal ones which are called elevons. Other maneuvering devices are the rotating ducted thrusters commonly known as bow thrusters and the puff ports which are not used in modern designs. A SES with water propellers uses conventional type rudders while if it powered by waterjets it does not need any additional steering device.
7. Introduction to the Code

The first thing before the setup of the code was to create a database in order to study the behavior of the characteristics that govern the design of Air Cushion Vehicles. The database was based on publicly available information obtained mainly from ref [1] and web research. As a result, a database with most of the available types of ACVs was created. In order to analyze in a better way the parameters of ACVs, the database was split in two parts; one for hovercrafts and another for SES.

These two databases are not as big as someone might expect. This is due to the limited number of vehicles in service comparing to other types of ships. ACVs’ history record is very small, comparing to conventional ships that date back to thousands of years ago, and the experience of naval architects is very limited (since 1959 when the first SR.N1 was constructed).

An effort was made to use craft that have some practical and commercial application. For this reason, although there is a large number of small ACVs, they were excluded from the database. Many of those small ACVs are used for recreational purposes; therefore, they are of no interest in our study.

The two databases are presented in appendices [1], [2]. A long time was spent to find and include as many characteristics as possible in order to make the database a powerful source of statistical analysis. As we can see in the databases, all the availability significant characteristics are included in order to derive the trend lines.

This database has been used in conjunction with theory for the creation of the code. Formulas found in the bibliography were used for the calculation of design parameters. In cases where theory was difficult to apply and be translated to a code, or when there was insufficient theory on a subject, a regression analysis based on the information collected for ACVs was used, providing the user with parametric results.

The code consists of the following eleven parts each of which is analyzed together with the background theory:

1. Constants
2. Inputs
3. Principal dimensions estimation
4. Total power estimation
5. Lift power estimation
6. Propulsion engine selection
7. Weights estimation
8. Area calculation
9. Volume calculation
10. Stability estimation
11. Cost estimation

Finally, all the databases gathered and used in the code (ACVs, engines, payload, cost etc.) are presented in the appendices section. Due to the fact that some of the tables are very long, some columns have been omitted and those with the most important parameters were kept. The reader can find the complete version of these tables – databases incorporated in the code as Excel worksheets.

8. Code Analysis

In the following paragraphs each part of the code is analyzed in detail together with the supporting theory.

8.1. Constants

This is a short part of the code that gives some constant values such as specific volumes, density, viscosity etc of fluids that are used in the design process (seawater, freshwater, lube oil, fuel etc).

8.2. Inputs

In this part of the code the user is required to give some input values. Next to the inputs there is a range helping the user to get a balanced design. In some cases there is also guidance concerning what limit of the range should be the starting point and what should be the goal. Apart from this section, the user will be prompted to choose some
other input values as he moves through the code. That happened in order to keep together parameters that belong to the same group of interest. However, the majority of input values have to be decided in the initial part of the code. Some of the most important design parameters are the following:

- Craft speed
- Range
- Cushion length to beam ratio
- Cushion density
- Skirt height ratio
- Sidewall depth ratio (SES)
- Relative thickness of sidewall (SES)
- Percentage of air support (SES)
- Initial estimation of All Up Weight

The last input that refers to the initial estimation of All Up Weight is very important since the user has to come back and reset the value until it matches the calculated total weight as it will be shown in the weight analysis section.

8.3. Principal dimensions estimation

The part following the inputs is the principal dimensions estimation. In this part, main dimensions, both for hovercrafts and SES are calculated from first principles. Some of these main outputs are:

- Cushion beam
- Cushion length
- Cushion pressure
- Skirt height
- Sidewall height
- Sidewall beam at the outer draft
• Cushion area

The user can refer to appendix [9] for the complete list of outputs of this section. Most of these outputs are later in the code used as inputs for the estimation of secondary parameters.

8.4. Total Power Estimation

This part of the code has to do with the general performance of ACVs. It is the most extended one because it is associated with the largest and most important part of theory governing ACVs. It was also the most lengthy in time, since there have been different approaches to the subject in order to decide the one with the most accurate outputs. The theoretical approach method that is first explained was tried in the beginning but didn’t have as good results as the statistical approach and for this reason it was abandoned.

8.4.1. Drag – Theoretical approach

The subject of the drag of ACVs is broken up to two parts: calculation of drag for a hovercraft and for a SES. The various components of drag, which apply to a hovercraft are as follows: wavemaking drag, aerodynamic profile drag, momentum drag and wetting drag (skirt drag); while for a SES the equivalent components are: wavemaking drag, aerodynamic profile drag, momentum drag, bow/stem seals drag, sidewall water friction drag, sidewall wavemaking drag and underwater appendage drag.

As we notice the first three components are the same for both types of crafts and for this reason they are analyzed at the same time.

The following analysis refers to calm water drag and for this reason the drag component due to the presence of waves is omitted. As yet no theoretical solutions are available for the estimation of the drag due to waves, values of the rough water drag are obtained from model and full scale test results by taking the difference between the calm and rough water drags.
8.4.1.1. Wavemaking drag

Wavemaking drag is the most thoroughly analyzed part of all drag components. Ref [7] gives a very intuitive description of the phenomena associated with wavemaking drag. “When an ACV is cushion-borne over water at zero forward speed, the cushion pressure distorts the water surface beneath the craft and causes a depression whose depth is given by:

\[ h = \frac{P_c}{\rho_{sw} \cdot g} \]

Where \( P_c \) is the cushion pressure,
\( \rho_{sw} \) is the salt water density,
and \( g \) is the acceleration of gravity.

Figure [20] taken from ref [8] shows the height of the depression caused by the cushion pressure and the subsequent creation of a two dimensional wave.

As soon as the craft moves forward it is apparent that the water surface at the front of the cushion will be subjected to cushion pressure for less time than that towards the rear of the craft. As a consequence, since the cushion pressure longitudinally is for all practical purposes uniform, the water surface will no longer be depressed by a constant amount but, owing to the inertia of the water will slope downwards towards the rear.
Further, the craft now aligns itself with the new surface so that the supporting cushion pressure is acting on an inclined craft base, hence producing a rearward component of the lift force. This inclination will reach a maximum, so producing what is known as the hump drag condition. Then, as speed is still further increased, the time for which cushion pressure will act on the surface of the water towards the rear of the craft will no longer be sufficient for the water surface depression to reach that equivalent to the cushion pressure. The water surface beneath the craft will therefore begin to approach the horizontal again and so will the craft attitude.” These situations are visualized in the following figure from ref [7].

Figure 21: Representation of hovercraft attitude change with forward speed
Crewe and Eggington, ref [18], propose the following formula for the calculation of the wavemaking drag.

\[
D_w = 2 \cdot \rho_c^2 \cdot \frac{S_c}{\rho_{sw} \cdot L_c \cdot g} \left( 1 - \cos \left( \frac{1}{Fr^2} \right) \right)
\]

where \( Fr \) is the Froude number given by the formula:

\[
Fr = \frac{V_s}{\sqrt{g \cdot L_c}}
\]

where \( V_s \) is the craft speed
and \( L_c \) is the cushion length

This result is similar to the formula for calculating the wavemaking drag derived in elementary marine hydrodynamics. If we consider two small disturbances, which generate waves of equal but opposite magnitude, situated at a distance \( l \), then the total free surface elevation resulting from the superposition of these two disturbances is:

\[
\eta = \text{Re} \left\{ a \cdot e^{i(k \cdot x)} \cdot \left( 1 - e^{ikl} \right) \right\}
\]

The total wave amplitude downstream is:

\[
A = 2 \cdot a \cdot \left| \sin \left( \frac{1}{2} \cdot k \cdot l \right) \right|
\]

And the associated wave resistance is given by:

\[
D = \rho \cdot g \cdot a^2 \cdot \sin^2 \left( \frac{1}{2} \cdot k \cdot l \right)
\]

where \( \rho \) is the water density,
a is the wave amplitude,
k is the wavenumber
and l is the distance between the two waves

By considering the deep water case for simplified results and by introducing the Froude number, the above equation can be rewritten in the following form:

\[ D = \rho \cdot g \cdot a^2 \cdot \sin^2 \left( \frac{1}{2 \cdot Fr^2} \right) \]

Plotting the above equation as in figure [21], the importance of interference effect is obvious especially for the lower speeds. Hence, for low speeds there is cancellation of the wavemaking drag component. In figure [22] the x axis represents the Froude number, while at the y axis the wavemaking drag is plotted.

![Figure 22: The general case of wavemaking drag vs Froude number](image)

In general the wavemaking drag is a function of the Froude number, the cushion length over beam ratio and the cushion pressure over length ratio. In figure [23] coming from ref [8], the wavemaking drag of an ACV vs Froude number is plotted. The similarities between the drag presented at figures [22] and [23] are obvious, meaning that
although the mechanism of wavemaking creation for ACVs is quite different from conventional ships, the results are practically the same.

Figure 23: Wavemaking drag vs Froude number for an ACV

Figure [24] coming from ref [3] presents the dependence of wavemaking drag on cushion length to beam ratio. As one can notice, there is a tradeoff on the selection of the L/B ratio. For small L/B ratios, the peak drag is high, but the drag at high speeds decreases substantially. On the other hand, a craft with high L/B ratio will experience low drag in low speeds (low hump drag) but the drag developed at high speeds will increase. Taking into account that ACVs operate mostly in high speeds (high Froude numbers) but they also have to overcome the hump speed as it will be developed in the next paragraph, the designer has to balance these two dimensions.
8.4.1.2. Hump speed

ACVs either do, or do not work at all due to the "hump" phenomenon. Hump speed, as mentioned earlier, is the speed at which the drag reaches a peak. It is this drag that the ACV has to overcome in order to reach its maximum speed. Hump speed usually occurs at low speeds of around 8-12 knots, depending on the weather and wave conditions. More specifically this happens when the term \(1 - \cos \left( \frac{1}{Fr^2} \right)\) in the Crewe and Eggington equation for the wavemaking drag equals two. To make this happen, the Froude number must have the value 0.56.

The Crewe and Eggington equation can also be rewritten in terms of the basic parameters discussed earlier:

\[
D_w = \frac{2 \cdot \left( \frac{p_c}{L_c} \right)^2 \cdot L_c^3}{\rho \cdot \rho \cdot \left( \frac{L_c}{B_c} \right) \left( 1 - \cos \left( \frac{g \cdot L_c}{V_s^2} \right) \right)}
\]
From the above equation we notice that the hump drag can be reduced if the cushion length to beam ratio is increased. In addition to that, the hump drag moves to greater Froude numbers when the cushion length increases.

It is obvious that special care has to be taken when calculations are made for the required power. The designer has to design for the hump speed in most cases. Numerous ACV designs failed to overcome hump speed even under moderate weather conditions despite engines running at full power. Hence, a hump thrust margin has to be allowed in order to have a successful design. At the same time, we do not want to have a craft with excessive power due to cost increases. For this reason a rational hump thrust margin has to be adopted. Mantle, ref [4], expresses this margin as a hump thrust margin of certain acceleration level and has the value of 0.025 g.

The following two figures show a well designed ACV and an ACV that fails to overcome hump speed.

![Figure 25: Satisfactory thrust margin](image)
8.4.1.3. Aerodynamic profile drag

The aerodynamic profile drag of the craft is usually referred to as body drag. The calculation of the aerodynamic drag is straightforward and is given by the formula:

\[ D_a = \frac{1}{2} \cdot C_a \cdot \rho_a \cdot S_a \cdot V_s^2 \]

where \( C_a \) is the coefficient for the aerodynamic profile drag and \( S_a \) the frontal projecting area of the hull above the water craft’s velocity.

\( C_a \) is highly sensitive to the aerodynamic profile of the craft’s hull, inclusive of the inflated skirt. Its value is generally obtained from wind tunnel tests for detailed
design. ACV aerodynamic drag is generally a significant proportion of total drag because of high design craft speed and the low water drag. It can reach values up to 30% of the total drag (see figure [27]) and therefore, it is very important to design the superstructure with care. In general, the $C_a$ can be taken as 0.4 – 0.6 for an ACV, with extreme values of 0.3 for fine lines and 0.75 for poor lines.

8.4.1.4. Momentum Drag

Unless the cushion is sealed to the surface as in the ideal case, a continuous supply of air is required to maintain it. The momentum drag is that force due to the rate of change of momentum of accelerating the cushion air and engine air to craft velocity. If air discharges uniformly through the air gap around the perimeter of a hovercraft, then the momentum drag in the direction of the relative air stream is given by the expression:

$$ D_m = Q \cdot \rho_a \cdot V_s $$

where $Q$ is the cushion air flow,
$\rho_a$ is the air density and
$V_s$ is the craft speed relative to ambient air

It has been found in some air cushion crafts that not all of this momentum is lost. If, for example, more air escapes in the direction of the relative wind than escapes forward, then the effective momentum drag is less than that given by the equation above. In those cases where it occurs, it is said that a cushion thrust is being experienced.

Attempts to utilize cushion thrust as an aid to propulsion have not been successful. If the rear skirt is raised to generate cushion thrust, the craft pitches slightly nose down and the increased bow skirt drag normally nullifies the cushion thrust.
8.4.1.5. Wetting drag (skirt drag)

To date, there is no adequate completely theoretical treatment for the wetting drag in both calm and rough water. Because practically all the rough water resistance of an air cushion craft is attributable to the skirts, it means that there is still no adequate method of predicting the rough water performance of air cushion craft. As an alternative to a theoretical solution it is possible to obtain a value for wetting drag from the results of model and full scale tests. To do this we first obtain a total drag over calm water and then subtract the known components analyzed previously.

Wetting drag or skirt drag is a drag component accounting for the forces arising from contact with water, of those parts of the hovercraft normally above the water surface. In this term is included form drag and skin friction drag of skirt areas actually running through the water, skirt drag in the form of induced wave drag and drag forces due to the creation of spray ref [7].

Wetting drag is mainly a function of daylight clearance height over calm water cushion pressure and of the sea state. Moreover, the clearance height is a function of cushion air flow which determines the momentum drag as discussed earlier. Thus, by increasing the clearance height, the wetting drag is decreased, but the momentum drag is increased since the air flow rate is augmented. Therefore, it is obvious that when considering the total of momentum and wetting drag, the total of these two terms may indicate an optimal value of clearance height for a minimum total. Wetting drag is also a function of craft size, shape, skirt design and cushion pressure in that this will affect skirt stiffness, shape and spray generation.

Considerable care has to be taken during the design procedure since the wetting drag can be a significant quantity of total drag reaching values up to 30% as it is shown in figure [27].
Figure [28] taken from ref [8] presents empirical curves for wetting drag obtained from model and full scale trials, by the subtraction method discussed above. These are presented as wetting drag over weight $D_{wet}/W$ (y axis) against mean clearance height over cushion length $h/l$ (x axis). Because of the scatter of the test data the $D_{wet}/W$ results have been shown as bands. Thus, although $D_{wet}$ tends to increase with increase in speed, there is some evidence that it has a larger value at hump speed than at twice hump speed. It can be seen that $D_{wet}$ decreases with increase in $h/l$, as might be expected since physical contact becomes less likely and increases sharply at $h/l$ values below about 0.002.
8.4.1.6. SES drag components

The drag components described above and referred to as hovercraft drag components apply to SES as well. There are also some slight differences that will be developed in this section.

The wetting drag or skirt drag is replaced by bow/stem seals drag since SES do not have an “apron” running around the full periphery of the craft. This sides’ part of the hovercraft’s skirt is replaced by the rigid sidehulls and for this reason the rubber structure retaining the cushion air is limited only to the bow and stern of the craft. It is obvious that the value of this drag component is smaller comparing to the full skirt drag of a hovercraft. On the other hand, the rigid sidewalls create additional components of resistance in accordance with the full displacement vessels.

The first one is the sidewall water friction drag. This drag component takes large values in high speeds, especially if we take into account that the operational speeds of
these crafts are in the range of 50 – 60 kt. On the other hand the draft of the sidehulls is comparatively shallow and for this reason the wetted surface of a SES is smaller compared to a catamaran. Since the nature of this drag is identical to the friction drag for conventional ships, they share the same method of prediction of the resistance. For calculating the friction resistance one can use the ITTC method which gives the frictional coefficient from the formula:

\[ C_F = \frac{0.075}{(\log(Re)-2)^2} \]

where Re is the Reynolds number given by:

\[ Re = \frac{V_s \cdot L}{v} \]

where \( V_s \) is the craft speed,
L is the waterline length of the craft
And \( v \) is the kinematic viscosity of the water

The second sidewall drag component is the Sidewall wavemaking drag. The nature of this drag as well as the method for calculating it is the same as calculating the wavemaking drag of a high speed displacement hullform. One can use appropriate published series data such as “Series 62 methodical tests” or “Series 65” etc., in order to estimate the residual resistance (which is dominated by the wavemaking resistance). For more details the reader can go to ref [13].

The last drag component is the underwater appendage drag. These are drag forces arising from rudders, shafts, propellers, strut palms. Hovercrafts produce thrust with the aid of air propellers and maneuver using devices (rudders, elevons, bow thrusters) that are installed on the superstructure of the craft. SES unlike hovercrafts use waterjets or supercavitating propellers as main propulsors and submerged rudders for maneuvering, thus giving them this extra drag component.
8.4.2. Statistical method

The first attempt of calculating the total drag was made by considering a theoretical approach such as the one described earlier. However, the results of this method proved to be inaccurate due to the difficulty of calculating the wetting drag. For this reason a different approach was examined. The new approach is a statistical analysis of the power characteristics of the ACVS found in the database. The driving parameter was the power density of the vessels, which is the maximum available power per ton weight. The data was plotted in 2D graphs having as variables the power density (y axis) and the speed of the craft (x axis). Two different graphs were created, one representing hovercrafts and the other SES. The results obtained for the hovercraft type of ACVs were not of practical use, because the data was very scattered and could not be approached successfully by any function as it can be seen in the following figure.

![Figure 29: Power density vs speed for hovercrafts](image)

The action taken to resolve the problem of the "cloudy" data was to separate the hovercrafts in three different categories according to their use. As a result of this, we obtained three categories of power densities:

- High power density crafts, which include landing/military crafts
- Medium power density crafts, where we have large passenger crafts
- Low power density crafts, where we have small commercial crafts

By making this assumption the data plotted was able to be closely approximated by a series of polynomials and the results for the three categories are presented in the figures [30], [31], [32].

Figure 30: Power density vs speed for low power density hovercrafts

Figure 31: Power density vs speed for medium power density hovercrafts
Figure 32: Power density vs speed for high power density hovercrafts

In the case of SES, the derivation of power trendlines was easier since the data plotted followed a smooth line that was approximated by a polynomial of third order.

Figure 33: Power density vs speed for SES
The output values obtained by the statistical approach were more accurate than the theoretical method. Theoretical approach falls short because of difficulty to determine wetting drag. The only way to estimate wetting drag is model testing, something which is beyond the scope of our analysis.

In the code, the power output gives all the three possible values for a hovercraft. The user has to decide which value he will adopt according to the type of craft he wants to design. The value selected is taken into account for further calculations through the code. In the beginning of the power estimation section, the user will find another empirical graph taken from ref [4] that is used for a first approximation of the total power. This is an extra tool for comparing results between the two different empirical approaches.

8.5. Lift Power Estimation

The lift system of an ACV consists of the following parts: intakes, lift engines, lift fans, diffuser ducting, ride control elements and skirt system. The heart of the lift system, though, is the fans. The fans can be of axial, centrifugal or mixed flow type. All three types are used today since each one has unique advantages. The user has to select the suitable fan type according to the mission and the requirements of the craft.

The main characteristics and the advantages of each one of the three different types of fans are analyzed briefly below:

A centrifugal fan consists of the impeller, the volute casing and the motor. As the impeller rotates air is drawn into the ‘eye’ of the impeller through a central inlet opening in the side of the casing. The air is thrown from the blade tips centrifugally into the volute shaped casing. Finally, the air goes into the cushion chamber through the discharge opening. The volute shape of the casing helps to transform some of the velocity pressure of the air leaving the impeller into useful static pressure. Centrifugal fans can be used for static pressures (system resistances) up to about 750 Pa.

An axial fan works in the following way: air is drawn into the impeller from all directions and is discharged in a direction approximately parallel to the axis of the fan, but with a helical twist. Main use of axial fans is for moving large volumes of air against
low system resistances. They have the advantage of being less bulky than centrifugal fans for the same output, but for static pressures higher than 250 Pa their higher running speed makes them noisier than the centrifugal fans. To increase the performance against higher resistances two or more impellers can be used, forming a multi-stage fan.

A mixed flow fan combines the characteristics of the large volume of air moved by the axial fan and the higher pressure of the centrifugal fan. It can operate against static pressures up to about 750 Pa.

Some of the most important design parameters to be taken into account during the fan selection procedure are:

- Impeller diameter (mm, inch)
- Impeller RPM
- Tip speed (fpm, m/sec)
- Maximum horsepower (bhp, kW)
- Static pressure (in water, kPa)
- Airflow (cfm, cm/sec)

The user can find incorporated in the code an Excel spreadsheet containing a range of centrifugal and axial fans. The above mentioned characteristics of the fans are provided and are inputs to the code after the selection from the user.

The calculation of the lift power is easy providing we know the required pressure rise of the fan and the flow per fan. The lift power of an ACV is given by the following formula:

\[ N_{\text{lift}} = p_{c} \cdot \frac{Q}{n_{\text{fan}}} \]

As we can see the lift power is a function of cushion pressure, fan flow rate and fan efficiency.

For the estimation of the fan flow rate, ref [2] assumes that it equals the volume of cushion air swept per second and is a function of cushion beam, cushion height and the craft speed as it can be seen in the following formula:
8.6. Propulsion Engine selection

The propulsion system of an ACV can be either integrated or separated. By the term integrated we mean that the same engines are used for lift and thrust (i.e. same engine moves a fan and an air propeller) and by separated we mean that there are different engines dedicated to lift and thrust.

Due to the fact that ACVs hover on air, they have some restrictions concerning engine selection. Water cooled engines are not used due to the lack of effective water suctions. For this reason the most commonly used engines are gas turbines and air cooled diesel engines. Air cooled diesel engines are used only by small ACVs and they also have the disadvantage of being much heavier and bulkier compared with gas turbines of the same power. The above do not apply for SES since in this case there is contact with the water making the use of water cooled engines a feasible solution. Nevertheless, gas turbines are the most popular type of engines used in both categories of ACVs.

In the code, a database in Excel format is incorporated in order to allow the user to select the best engine according to power predictions and the requirements of the design. The most commonly used engines are provided together with the characteristics that affect the design. Some of these parameters that enter the code are the weight, the specific fuel consumption, the power, the dimensions etc.

8.7. Weights Analysis

The importance of the exact weight estimation as well as the position of every weight component is one of the most important tasks of a naval architect during the design stage. Miscalculation of the weights can have as a result the failure of the produced ship. For the purposes of the weight analysis the following categories were adopted according to US Navy standards:

- W100 - Structure
For a detailed analysis of the exact components that comprise every category, the reader can go to ref [4].

Summing up the above categories we obtain the lightship weight of the craft. In order to get the full displacement or All Up Weight, we have to add the weight of fuel and other liquids (fresh water, ballast water, oil etc.), the weight of the crew and finally the disposable payload weight which can be passengers, vehicles, military equipment etc.

The value of the total weight that the user gets in this section of the code has to be iterated until it matches the value of the initial estimation of All Up Weight. Some of the equations used come from refs [3], [4] and some others were derived based on the weight breakdown of other crafts pulled out of the database.

The propulsion weight group, W200 of the code estimates the weight of all the machinery components apart from the lift and skirt system of the craft. Because of their great significance those two systems are calculated separately. In addition to the main propulsion weight, an estimation of the weight of the lift fans, as well as weight estimation for the two different types of air propellers is given. The air propellers given are of the free and the shrouded type and the material used is aluminum.

For the Command and Surveillance group W400, it was difficult to derive a specific trendline since there can be large variations according to the mission of the craft. For this reason, the user can choose how heavily the craft will be equipped in order to fulfill the mission needs. Thus, the basic group is subdivided in the following subcategories: Command and Control, Navigation, Interior Communications, Exterior Communications, Surface Surveillance, Underwater Surveillance, Countermeasures, Fire control. The user can choose among the following levels for each subcategory: none, light, medium, high and full.
A similar approach was followed in the Armament group W700. A craft can have no armament if it is intended for commercial use or can be heavily armed if it participates in landing operations in a hostile environment. Again, the main group was divided in three subgroups each one representing the three different types of threats: surface, air and submarine warfare. The levels of equipment used in this group are the same as those used in group W400.

In the case of the estimation of the disposable payload the value of 25% of the total weight that ref [3] proposes has been increased to 35%. This is justified by averaging the payloads of ACVs given in the database. The values presented here are initial estimations only. The user has to define the appropriate payload that the craft is intended to carry. There is another Excel spreadsheet incorporated in the code which includes some indicative military payloads. The equipment found there refers to the vehicles that are used by the US Marine Corps. Similarly the user can define whatever payload he wants and add it in the table. For the purposes of this model military payload was used since the validation craft was the LCAC, which is a military amphibious vessel.

8.8. Area calculation

The goal of this section is not to calculate in detail all the areas on an ACV. It is rather intended to prove if the produced design is balanced as far as it concerns the space allocation. Assuming a RO-RO configuration of the vessel, similar to LCAC, it is checked if the cushion area, which is approximately equal to the deck area, can accommodate all the necessary parts of the design, mainly the superstructure and the cargo. In such a vessel, the superstructure, apart from the crew and the combat spaces, must be able to accommodate the propulsion and lift system, which occupies the biggest part of the superstructure. At the same time for such a vessel combat spaces are not vital and for this reason do not exist, while the personnel is minimal and does not need living spaces since most of the amphibious crafts operate from a mothership.

The superstructure is assumed to run the whole length of the deck with a width that it is dictated by the dimensions of the machinery box, thus the engine that has been selected previously. Then, the total machinery area is calculated taking into account
engine dimensions, lift fans, shafts and propellers. By subtracting the machinery space from the total superstructure space, we get the available crew spaces.

The total cargo space will be determined by the payload selected previously and its dimensions. Finally, adding the superstructure area and the disposable payload area must be smaller than the deck area in order for the vessel to be balanced.

8.9. Volume calculation

If the area part of the design is balanced, then the volume is usually balanced too. For the volume balance the total fuel and other liquids loads (water, oil etc.) is calculated. Adding the margin left for the structural elements within the hull, the total required volume that has to be fitted in the hull is estimated. This volume has to be smaller than the total hull volume, something which is usually the case, since those craft have a lot of void compartments in their hulls.

8.10. Stability estimation

Both intact and damaged stability analysis is included in the code as it is described in the following two sections.

8.10.1. Intact Stability

When we refer to transverse and longitudinal stability we mean the stability in roll and pitch respectively. These two terms of stability are quite different for ACVs since they float in a mixture of air and water with proportions ranging from 100% air to 50% air and 50% water. Hence, the restoring moment for a hovercraft is provided by the air displaced.

The most common method for ensuring the stability of a hovercraft is to adopt a compartmented skirt design. The compartmentation can be transverse, longitudinal or a combination of both. The main principle is that when the hovercraft rolls, the cushion pressure at the side that heels down increases while the cushion pressure at the opposite
side decreases since the air gap underneath the skirt gets bigger. This difference of pressures provides the necessary restoring moment for the ACV.

Direct application of this principle is the skirt type developed by Bertin which was presented earlier. There, the compartments form individual “jupes” or conical cushions as can be seen in figure [11]. Other methods used to ensure stability are the skirt lifting or shifting systems and the transverse shift of the center of pressure. All these methods follow the same principle analyzed above for the creation of a restoring moment.

In the case of SES the above methods do not apply, since a large part of the restoring moment comes from the sidehulls. Important factors for the stability of a SES are the outer deadrise angle of the sidewall and the relative thickness of the sidewall. Apart from the geometry of the sidewalls that is most important for the stability behavior of the craft, other important parameters are the fan flow rate and the inner draft of the sidewalls.

Having presented the factors that affect stability we must define some measures of this stability. A hovercraft or SES requires a minimum positive intact stability moment arm in roll and pitch while floating or hovering statically and while moving. This intact stability is expressed in terms of cushion height, cushion beam, transverse and longitudinal metacenteric heights.

In the various rules and regulations available at present, requirements are often not specific to dynamically supported and high speed craft, the category which includes ACVs. A large amount of information from model experiments and craft trials is already available which allows us to propose criteria for the safe operation of ACVs.

The criteria used in the code come from ref [3] and are summarized in the following ratios:

- Cushion height or skirt height over cushion beam must be less than 0.2
- Transverse metacenteric height over cushion beam must be in the range 0.35 – 1.2
- Longitudinal metacenteric height over cushion beam must be in the range 1.0 – 2.4
From general naval architecture it is known that the metacentric height \( GM \) is the sum of the center of buoyancy \( KB \), plus the metacentric radii \( BM \), minus the center of gravity \( KG \) both for longitudinal and transverse calculations.

In the case of hovercrafts there is no immersed volume and for this reason a rather “risky” simplification was adopted in order to estimate the metacentric height. The center of buoyancy (KB) was replaced by a virtual value, the center of cushion (KC) in order to ease the calculations. This method was found to give a good estimate of the metacentric height.

As mentioned above in order to calculate the metacentric height, it is necessary to estimate first the center of gravity. In the model, the center of gravity is estimated by averaging the center of gravities of the main components of the craft, which are the skirt, the main hull, the superstructure and the payload.

Concerning the stability of ACVs in the off cushion mode, they behave exactly the same as the conventional ships. The hovercrafts like monohulls and the SES like catamarans. Hovercrafts due to their barge like hull construction, exhibit a very high transverse stability. The length over beam ratio is usually in the range of 2 – 2.8 with an average value at 2.2. The same is valid for SES as well. The length to beam ratio is in the range of 3.5 - 5.5. On the other hand, the very small length to beam ratio that all ACV designs show, has the disadvantage of decreased longitudinal stability.

8.10.2. Damaged Stability

Damaged condition is an emergency situation caused by multiple reasons such as fire, flooding, explosion, collision etc. The most important factor in such a situation is the reserve buoyancy or reserve dynamic stability. Loss of reserve buoyancy will finally result in sinking of the vessel. In the case of ACVs, it is assumed that in a damaged condition caused from the above mentioned reasons, a partial or total loss of the air cushion will occur. If that is the case, the damaged stability analysis can be performed in a similar way to conventional ships.

The damaged stability and buoyancy criteria of ACVs used in the code were done according to ref [11]. In this part of the code the user is asked to provide a value for the
extent of transverse damage of the craft. A multiple “if” loop programming is used according to the criteria that follow, in order to calculate the permissible floodable length.

The construction of ACVs usually consists of honeycomb-like network of small compartments. The conventional ship requirements that ships under 100 ft withstand flooding of one compartment, or two compartments for ships between 100 ft and 300 ft, cannot reasonably apply to this type of construction. Another factor to consider is the lightweight shell construction and the great possibility of sustaining rip damage.

“The following assumed damages apply for ACVs less than 100 ft in length. The worst of the following two cases of damage must be used:

- Longitudinal shell opening of 10% of the flotation box length, or 8 ft, whichever is greater, with transverse damage up to the centerline. Damage should be selected in that part of the craft which results in the poorest stability.
- Longitudinal shell opening of 15% of the flotation box length, or 8 ft, whichever is greater, with the transverse damage extending up to, but not including, longitudinal bulkheads located more than 20% of the beam inboard of the shell at maximum beam of the hard structure. As in above damage is located to produce the poorest stability.

For air cushion types with over 100 ft in length, the worst of the following two cases of damage must be used:

- Longitudinal shell opening equal in length of 15% of the design waterline length (including seals) or the length-of-hit for the counterpart monohull, whichever is greater, with transverse extent to the centerline.
- Longitudinal damage of the side shell equal to 50% of the design waterline length (including seals) with a transverse extent to the first longitudinal bulkhead inboard of the shell. The transverse penetration shall be no less than 10% of the beam.
For SES types with a length of approximately 200 ft, the 15% length-of-hit above will generally result in at least a two-compartment capability. This compares with the two-compartment requirement for conventional ships of 100 to 300 ft. SES types of greater length will generally require a length-of-hit similar to equivalent conventional ships of over 300 ft.” ref [11]

8.11. ACV Economics

8.11.1. General description of ACV economics and market trends

Trends within the passenger ferry market show that the need for higher ferry speeds has been steadily increasing over the years and we now see catamarans that can achieve cruise speeds of 40 knots. As ferry operators try to satisfy the passenger’s needs for reduction of the trip duration, cruise speeds for new ferries will continue to increase.

Given these market trends, ACVs might well see a bloom in interest worldwide. ACVs and especially Surface Effect Ships have been in passenger service primarily in Europe and Asia for about 40 years. Twenty years ago, the SES appeared to be well positioned to dominate the fast ferry market. The catamaran industry, though, has shown that catamarans can achieve the relatively modest transit speeds of 30 to 40 knots with far better operational costs. Ref [16]

At this speed range the complexity and the cost associated with the lift system is responsible for the inability of ACVs to economically compete with other hullforms such as slender catamarans. However, in the range of 50 knots and above, ACVs become more attractive since they can achieve those speeds more efficiently than competing hullforms.

There are also situations where ACVs compete directly with air transportation instead of other types of water transportation. A good example is the Greek water transportation industry. The Aegean Sea has a large number of islands in proximity with the mainland as well with each other. Although there is no ACV operating on those routes, the use of hydrofoils and catamarans has been proved to be competitive with air transportation. The introduction of ACVs with a simultaneous increase of cruise speed of the order of 15 knots would definitely earn a big share of the market.
Another important issue associated with high speeds is the wash or wake that is produced at high speeds. Conventional ships like catamarans often have to slow down on waterways because of the amount of wash or wake they produce. ACVs on the contrary produce virtually no wake at high speeds, thus reducing further the journey time.

The following examples justify the latter opinions and trends: The British company “Hovertravel” was established in 1965 and since then it has carried more than twenty million passengers. “Hovertravel” now provides service between the Isle of Wight and Portsmouth. “Hoverwork”, a subsidiary of “Hovertravel” was the operator of the legendary SR.N4 hovercrafts that were connecting the English Channel at a maximum speed of 65 knots. Those crafts retired from service in year 2000 after 30 years of successful operation at the English Channel.

Another country that has applied successfully the use of ACVs on a variety of routes is China. Type 7211 SES operates in the route Shekou – Hong Kong since 1992 replacing two other ACVs of the type HM218. Another illustration of the unique characteristics of ACVs is the Type 7215 SES that is operated on the upper reaches of the Yangtze River.

Finally, the “Techno-Superliner “ project is a Japanese program of an ocean going ACV cargo vessel with a speed of 50 knots, a payload of 1000 tonnes and a range of 500 nautical miles. TSL-A140 (a derivative of the program) was ordered in the beginning of 2003 for delivery in 2005. The craft will operate between Tokyo Ogasawara reducing the trip duration from 26 to 17 hours.

Concluding, we are already seeing interest in ACVs as potential hull forms for fast sealift and commercial RO/RO services. Once transit speeds exceed 50 knots, it can be very difficult for other hull forms to compete with ACVs.

8.11.2. Cost Analysis

Before a ship enters production a thorough analysis of alternatives as well as the feasibility of the design has to be examined. The parameters examined before the final selection are the cost estimates, the risks associated with alternatives and assessing performance of alternatives. The model developed deals with the cost estimates and the
assessing of performance but it does not cover the topic of risk assessment during the design process.

The cost estimation is based in the calculation of the partial components of the final cost while the performance of the alternatives is measured with the aid of the transport factor that will be analyzed below. The trendlines presented in the code are based on a weight-cost regression analysis.

The currency used in the cost calculations is the US dollar. The cost analysis is mostly based on ref [6], [2]. Unfortunately the information presented in those sources is outdated but ACV's manufacturers were reluctant to provide any information concerning their crafts' costs.

Almost all of the crafts presented in ref [6] have retired from service and for this reason the results of the cost analysis should be considered with concern, since they do not incorporate any new designs. On the contrary ref [2] has some designs that are still in service but the information provided is in some cases incomplete. Nevertheless, the code is a good source of comparison and determination of the overall measure of effectiveness of different designs.

Ref [6] examines in detail the economics of 14 different crafts ranging from 430 kg to 64326 kg. The study was published in 1974 and for this reason it is assumed that the prices quoted belong to 1972. Those prices are adjusted to account for inflation. In order to adjust the prices to 2004 levels, an inflation calculator from ref [19] was used. 1$ in 1972 is equivalent to 4.52$ in 2004. Thus, every price has been increased by a factor of 4.52.

Ref [2] mentions that the prices found there, refer to 1984 levels. Similarly, the prices are adjusted to 2004 levels by increasing them by a factor of 1.82.

The procedure used for the cost estimates refers to commercial vehicles. This analysis does not apply to military cost estimations. Almost all the crafts that this analysis was based on are or were used for commercial purposes.

The crafts used in the analysis are constructed using aluminum as the main material and for this reason new crafts that are in service and use composite materials (Finish T2000, Norwegian Skjold) may not apply to this analysis.
Finally, a nominal figure of 1500 annual operating hours is used to calculate equivalent hourly costs. The cost is broken down to the following components:

![Cost Breakdown Diagram](image)

**Figure 34: Cost breakdown**

### 8.11.2.1. Acquisition cost

Acquisition cost is the cost related with the initial purchase of the craft. The acquisition cost approach was made with the use of weight as the leading parameter. The values presented in appendix [9] were plotted in an acquisition cost versus total weight graph.

### 8.11.2.2. Spares cost

Spares must be held by the owner or operator representing an additional capital cost. The spares cost is taken to be 15% of the total acquisition cost. This is the average.
value of the spares cost found from the data presented in appendix [4]. The range is from
8% to a maximum of 31% of acquisition cost. Ref [8] agrees to the calculated value for
the spares cost of 15%.

8.11.2.3. Fixed costs

Fixed costs are the costs that are independent of the operating hours of the craft
and consist of depreciation, interest and insurance.

Depreciation is a non cash expense and it is important only because it reduces
taxable income. There are two kinds of depreciation: straight line depreciation and
accelerated depreciation. For this type of crafts the kind of depreciation used is the
accelerated with a depreciation period in the range of seven to ten years.

In the code the ten year depreciation period is used and the values presented are
taken from ref [10]. The user can choose the year for which he wants to calculate the cash
flows by selecting the appropriate value from the depreciation matrix.

In the case that the owner has taken a loan from a financial institution in order to
cover the craft capital costs, then an interest amount has to be included in the cash flow
calculations. Annual interest charges are calculated at a rate of 5% of the craft capital
cost.

Insurance rates may vary according to the craft type and the operation. SES
insurance rates are comparable to conventional ships like catamarans since they resemble
them in many respects. For this reason, a hovercraft may exhibit a higher insurance rate,
but for the purpose of our analysis a flat insurance rate equal to 2% of the acquisition cost
was assumed.

8.11.2.4. Fuel

Posted prices for fuel vary considerably throughout the world as a function of
distance from the refinery, local taxes, method of supply and quantity ordered.
Approximate estimates of fuel cost may be calculated by using the specific fuel
consumption values for the power plants operating in the craft, appropriate to the
maximum continuous power level.
In the model the fuel cost is calculated as a function of total installed power, specific fuel consumption of engines, price of fuel used and the amount of annual operating hours. The user is given the prices of marine diesel oil (MDO) and marine gas oil (MGO) in the beginning of the cost section. For an update in prices of fuel and oil the user can go to ref [20]. There, apart from the prices of MDO and MGO, one can find prices for other fuels such as IF180, IF380 depending on the engine type.

ACVs are mostly powered by gas turbines and for this reason the quality of fuel has to be of high level. Gas turbines use fuels of lower viscosity and higher purity than diesel engines especially those that are installed in large commercial vehicles. Moreover, the fuel consumption of a gas turbine is higher than an equivalent diesel engine. For this reason the fuel cost for such a craft is a significant portion of the operating costs.

8.11.2.5. Engine overhaul - Maintenance

Both engine overhaul and maintenance analyses are conducted in the same way. Cost values are plotted against crafts’ All Up Weight and the approximations are made with the use of first order polynomials.

As mentioned earlier, the main engines of ACVs are gas turbines. Gas turbine propulsion, although it has the advantages of low weight and volume compared to diesel propulsion, is less reliable and presents a lower MTBF (Mean Time Between Failure). The required maintenance is more frequent – i.e. the air compressor of a LM 2500 has to be washed every 24 hours of operation – resulting in high operating costs.

However, part of the maintenance can be conducted by the crew – as the example mentioned above – but for more serious works, the service has to be conducted by authorized personnel or the manufacturer.

Another serious factor that affects the maintenance is the marine environment. The marine environment for this category of crafts has a more significant impact than other ship categories. ACVs require high efficiency filtration systems for the air intakes because the air contains large amounts of sand, salt and water. Air intakes for those crafts are comparatively low and near the sea level and thus they are subjected to the water spray generated by the air cushion. These effects are more serious in the case of military
landing crafts since they often use sandy beaches for mooring and not prepared places as with commercial vehicles.

A big difference that ACVs and especially hovercrafts have compared to conventional ships is the existence of the flexible parts that retain the cushion air, the skirt. Skirts or bow/stern seals when referring to SES are sensitive and are easily destroyed by contact with rough surfaces. The different types of skirt damage are delamination, tearing, abrasion and corrosion. The bag and the loop components of a skirt can last for many thousands hours, but the segments and fingers need replacement after approximately 1500 hours of operation. This number coincides with assumed annual operating hours, meaning that replacement has to be done in an annual basis. It is of great importance to monitor the condition of the fingers because uneven wear can result in drag increase.

8.11.2.6. Crew

Crew salaries do not necessarily follow ferry boat levels since no sleeping accommodation or catering for crew members is likely to be provided. The number of personnel being employed depends upon the number of crafts operated and the utilization. Under some circumstances a single crew might be able to run a single craft for a low utilization but in general it is safe to say that each craft should have two crews.

For the purposes of this study the number of crew is calculated in the manning section that is included in the estimation of the All Up Weight. It covers the cases of a single crew as well as the two shifts mentioned above. Since the military aspect of those vehicles is taken into account, an estimation of crew based on three shifts is calculated. This is the standard number of personnel manning a craft that is required to operate on a 24 hours basis. As for the case that the ACV is a landing vehicle operating from a mothership, then the single crew applies.

For the calculation of the crew salaries the table given in appendix [3] was the basis. The values of the table have been updated as explained earlier and an approximation line was derived as seen in appendix [9].
8.11.2.7. Cost Learning Curves

The code has the capability of calculating the total fleet craft capital cost taking into account the number of units to be produced and the experience gained (learning) from the construction of the leading ship.

It is often, but not universally accepted that multiple products benefit from a learning curve. That is, it is anticipated that for a series of ships, each ship labor cost should decrease from continued improvements introduced over time in the build strategy and manufacturing processes and refinements in production engineering.

Therefore, when the estimator has developed the cost estimate for the lead ship of the series and copies this estimate for each of the follow ships, the learning curve factors can be applied to each of the follow ship estimates ref [2].

In the model a cost learning curve of 95% slope has been used. There are other types of learning curves with different slopes, but this depends on the shipyard, its labor and the equipment used. Figure [35] taken from ref [2] provides an example of two different learning curves one for 90% and 95% respectively.

**Cost Learning Curves**

![Cost Learning Curves graph](image)

**Figure 35: Cost learning curves**

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8.11.2.8. Transport Factor

Another means for estimating the overall measure of effectiveness when someone examines different designs is the transport factor or transport efficiency. The Transport Factor compares competing designs to relate the utility of each design when performing its transport task. In general, there is a unique non-dimensional characteristic called TF for each design, given by:

\[ TF = \frac{W_p \cdot V_s}{SHP_{TI}} \]

where:
- \( W_p \) = payload weight
- \( SHP_{TI} \) = total installed power (lift power + propulsion power for dynamically supported concepts)
- \( V_s \) = average ship speed for a voyage (i.e., sustained or service speed)

There are also different definitions of the transport factor, where the payload weight is replaced by the weight of empty ship or the weight of fuel. However, the payload weight is the most common expression of transport factor and that’s why it has been used in the code.

The following table taken from ref [14] presents the transport factors for a variety of high speed marine vessels. Some of the ships presented are actual crafts, while some others are conceptual designs.
<table>
<thead>
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<th>Ship</th>
<th>Ship Type</th>
<th>Ship (S) or Design (D)</th>
<th>Speed (kt)</th>
<th>Power (hp)</th>
<th>Full Load Disp (Iton)</th>
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<td>Speed (kt)</td>
<td>Power (hp)</td>
<td>Full Load Disp (iton)</td>
<td>TF</td>
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Table 1: Transport Factors for high speed vessels
The transport factors for hovercrafts lie in the range of 2.4 – 7.8 while for SES 3 - 25.1. Comparing with other fast ships, SES demonstrate a high transport factor contrary to hovercrafts. SES support part of their weight – including payload – hydrostatically due to the use of sidehulls. For this reason, they are more efficient in carrying loads comparing to hovercrafts. Only semi planning monohulls demonstrate a higher transport factor.

On the other hand hovercrafts exhibit a low transport factor which is superior only to planning monohulls. This happens because the carried payload cannot be as heavy as the other crafts in the table. Currently the heaviest payload that can be carried by a hovercraft is 130 tonnes and the craft with this capability is the Russian “Zubr”. This craft is designed for landing operations and is currently the largest hovercraft in service.

The following table summarizes the above conclusions.

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Table 2: Transport Factors summary
9. Future Considerations

Nowadays, we see more and more ACVs being built both for commercial and military applications. New technologies, as well as the experience gained this half century that these crafts are in service, will allow those vessels to operate with lower costs, making them an attractive means of transportation. The great diversity of applications and missions that ACVs can take over makes them unique in the marine environment. If the advantage of high speed will manage to be combined with heavier payloads and reasonable costs, then those crafts are the future in the marine transportation sector.

As we see more and more crafts of the type produced, the market for designing software of ACVs will grow and this software will be more accessible for use by students in the naval architecture major. The code presented herein is a step in this direction. As every study, there are improvement margins and additions that one can make. Such an addition could be a seakeeping performance analysis of ACVs.

A valuable source of results and conclusions in such a case is always the model testing. The code presented is based only on literature and does not include any experiments due to various reasons. However, model testing for ACVs is a more complicated procedure than conventional ships. Scaling is more difficult and there are more parameters entering the similitude process than conventional ships.

For a conventional ship the two most crucial non dimensional numbers are the Froude number related to the wave generation and the Reynolds number related to the friction. In the case of ACVs there are more factors that affect the scaling. The reader can find in ref [3] a complete analysis of the scaling laws and criteria. Here, indicatively we will mention the Euler number that is required for simulating the cushion pressure and the Strouhal number for the simulation of the elastic aerodynamic characteristics of the skirt. These non dimensional parameters are given in the following equations:

\[ Eu = \frac{\rho_a}{0.5 \cdot \rho_a \cdot V_a^2} \]

where \( \rho_a \) is the air density
and \( V_a \) is the velocity of the cushion air
\[ S = \frac{f \cdot L_c}{V_{\text{soo}}} \]

where \( f \) is the vibration frequency of skirts
and \( V_{\text{soo}} \) is the velocity of sound in skirts

As it can be seen in the above formulas, the Euler and Strouhal numbers are not directly related to the Froude and Reynolds numbers since the velocity in the latter case refers to the velocity of the craft and not to the velocity of the cushion air.
List of References

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27. http://www.hoverwork.co.uk/
30. http://www.jameshovercraft.co.uk/
40. http://www.hovertravel.co.uk/info.stm
41. http://www.links999.net/Science/hovercraft/hovercraft_history.html
## Appendix 1: Hovercraft database

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</tbody>
</table>

Selected fan

<table>
<thead>
<tr>
<th>Power (BHP)</th>
<th>Diameter (m)</th>
<th>Static Pressure (in WG)</th>
<th>Static Pressure (Pa)</th>
<th>Airflow (cfm)</th>
<th>Airflow (cm/sec)</th>
<th>rpm</th>
<th>Tip Speed (fpm)</th>
<th>Tip Speed (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>540.9</td>
<td>1.98</td>
<td>29</td>
<td>7202.44</td>
<td>82000</td>
<td>38.6997</td>
<td>976</td>
<td>19998.24</td>
<td>101.5911</td>
</tr>
</tbody>
</table>
# Appendix 7: Air propellers

<table>
<thead>
<tr>
<th>No of blades</th>
<th>max Diameter (m)</th>
<th>max. Power (hp)</th>
<th>max. RPM</th>
<th>weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTV-4</td>
<td>4</td>
<td>2.5</td>
<td>600</td>
<td>2700</td>
</tr>
<tr>
<td>MTV-14</td>
<td>4</td>
<td>1.95</td>
<td>500</td>
<td>2700</td>
</tr>
<tr>
<td>MTV-16</td>
<td>4</td>
<td>2.8</td>
<td>1000</td>
<td>2700</td>
</tr>
<tr>
<td>MTV-22</td>
<td>4</td>
<td>1.75</td>
<td>210</td>
<td>2800</td>
</tr>
<tr>
<td>MTV-5</td>
<td>5</td>
<td>2.15</td>
<td>600</td>
<td>2700</td>
</tr>
<tr>
<td>MTV-8</td>
<td>5</td>
<td>6</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>MTV-25</td>
<td>5</td>
<td>1.8</td>
<td>350</td>
<td>2700</td>
</tr>
<tr>
<td>MTV-27</td>
<td>5</td>
<td>2.8</td>
<td>1250</td>
<td>220</td>
</tr>
<tr>
<td>MTV-28</td>
<td>5</td>
<td>6</td>
<td>2720</td>
<td>670</td>
</tr>
</tbody>
</table>
# Appendix 8: Marine Corps disposable payload

<table>
<thead>
<tr>
<th>type</th>
<th>weight (tn)</th>
<th>length (m)</th>
<th>width (m)</th>
<th>height (m)</th>
<th>area (sq m)</th>
<th>volume</th>
<th>No of components</th>
<th>total area</th>
<th>total volume</th>
<th>total weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1A1</td>
<td>67.7</td>
<td>9.78</td>
<td>3.66</td>
<td>2.89</td>
<td>35.7948</td>
<td>103.447</td>
<td>2</td>
<td>71.5896</td>
<td>206.89394</td>
<td>135.4</td>
</tr>
<tr>
<td>M60A1AVLB</td>
<td>14.61</td>
<td>9.75</td>
<td>3.81</td>
<td>0.94</td>
<td>37.1475</td>
<td>34.91865</td>
<td>2</td>
<td>74.295</td>
<td>69.8373</td>
<td>29.22</td>
</tr>
<tr>
<td>M88A1E1</td>
<td>70</td>
<td>8.27</td>
<td>3.43</td>
<td>3.12</td>
<td>28.3661</td>
<td>88.50223</td>
<td>2</td>
<td>56.7322</td>
<td>177.00446</td>
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<tr>
<td>AAAV</td>
<td>33.792</td>
<td>9.098</td>
<td>3.65</td>
<td>3.18</td>
<td>33.2077</td>
<td>105.6005</td>
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<tr>
<td>LAV-25</td>
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<td>42.97275</td>
<td>1</td>
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<td>12.802</td>
</tr>
<tr>
<td>AAVP7A1</td>
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<td>3.11</td>
<td>25.8844</td>
<td>80.50048</td>
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<td>25.8844</td>
<td>80.50048</td>
<td>25.738</td>
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<tr>
<td>HMMWV(M998)</td>
<td>2.35</td>
<td>4.57</td>
<td>2.16</td>
<td>1.83</td>
<td>9.8712</td>
<td>18.0643</td>
<td>1</td>
<td>9.8712</td>
<td>18.06426</td>
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</tr>
<tr>
<td>Mk48-14</td>
<td>18.28</td>
<td>11.58</td>
<td>2.43</td>
<td>2.59</td>
<td>28.1394</td>
<td>72.88105</td>
<td>1</td>
<td>28.1394</td>
<td>72.881046</td>
<td>18.28</td>
</tr>
<tr>
<td>Mk48-15</td>
<td>22.93</td>
<td>11.27</td>
<td>2.43</td>
<td>2.59</td>
<td>27.3861</td>
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<td>70.929999</td>
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<tr>
<td>Mk48-16</td>
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<td>10.1</td>
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<td>2.59</td>
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<td>63.56637</td>
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<td>63.56637</td>
<td>18.393</td>
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<tr>
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<td>21.41</td>
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<td>2.43</td>
<td>2.59</td>
<td>28.1394</td>
<td>72.88105</td>
<td>1</td>
<td>28.1394</td>
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<td>21.41</td>
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<tr>
<td>Troops</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>totals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>428.9707</td>
<td>1086.7327</td>
<td>494.107</td>
</tr>
</tbody>
</table>
Appendix 9: The MathCAD model
A Mathcad model for the estimation of the cost and the main characteristics of Air Cushion Vehicles in the preliminary design stage

Legend:

user has to give a value to the boxes with this colour  output values

chapters 1  subchapters 1  subchapters 2

1) Constants:

\[ \text{nmile} = 1852 \text{m} \quad \text{kt} = \frac{\text{nmile}}{\text{hr}} \quad \text{kPa} = 1000 \text{Pa} \]

Seawater Temp: \[ T_{SW} = 15 \]

Seawater Viscosity: \[ \nu_{sw} = 1.19 \frac{\text{m}^2}{\text{sec}} \]

Seawater Density: \[ \rho_{sw} = 1025.86 \frac{\text{kg}}{\text{m}^3} \]

Air Density: \[ \rho_a = 1.226 \frac{\text{kg}}{\text{m}^3} \]

Seawater Specific Volume: \[ \gamma_{sw} = 0.975 \frac{\text{m}^3}{\text{tonne}} \]

Endurance Fuel Specific Volume: \[ \gamma_{fuel} = 1.198 \frac{\text{m}^3}{\text{tonne}} \]

2) Inputs:

\[ \text{craft type: use 1 for ACVs and 2 for SES} \]

\[ \text{craft speed: } V_s = 40 \text{kt} \]

\[ \text{range: } 250 \text{-nmile} \]

\[ \text{cushion length to beam ratio: } L_c/B_c = 1.8 \quad \text{L}_c \quad \text{B}_c \]

- 2-2.5 (2.5 for large crafts) for ACV
- 3-5 with most usual 3.5-4.5 for SES

\[ \text{cushion pressure to length ratio: } \]

\[ pc/L_c = 14 \frac{\text{kg}}{\text{m}^3} \]

- 10-15 kg/m^3 for ACV (low density craft)
- 15-20 kg/m^3 for ACV (high density craft)
- 13-30 kg/m^3 for SES
skirt height ratio: \( \frac{H_{sk}}{B_{c}} := 0.123 \)  
- range: 0.11-0.18  
- start with high value and decrease

sidewall depth ratio for SES: \( \frac{H_{sw}}{B_{c}} := 0.25 \)  
- range 0.25 - 0.333  
- start with 0.25 then check stability and if fine deepen the cushion

relative thickness of sidewall for SES: \( \frac{B_{sw}}{B_{c}} := 0.09 \)  
range: 0.08 - 0.13

Sidewall prismatic Coefficient for SES: \( C_p := 0.60 \)

Sidewall maximum Section Coefficient for SES: \( C_X := 0.80 \)

percentage of air support for SES: \( \text{per} := 0.8 \)

initial estimation of all-up weight: \( W := 150\text{-tonne} \)

### 3) Principal dimensions estimation:

**cushion beam:**  
\[
B_c := \left[ \frac{W}{(\frac{p_c}{L_c}) (L_c/B_c)^2} \right]^{\frac{1}{3}}
\]  
\( B_c = 14.898 \text{ m} \)

**cushion length:**  
\( L_c := B_c \cdot (L_c/B_c) \)  
\( L_c = 26.817 \text{ m} \)

**cushion pressure:**  
\[
p_c := \frac{W}{(B_c \cdot L_c)}
\]  
\( p_c = 375.439 \frac{\text{kg}}{\text{m}^2} \)

**skirt height (cushion depth):**  
\( H_{sk} := (H_{sk}/B_c) \cdot B_c \)  
\( H_{sk} = 1.833 \text{ m} \)

**sidewall height:**  
\( H_{sw} := (H_{sw}/B_c) \cdot B_c \)  
\( H_{sw} = 3.725 \text{ m} \)

**sidewall beam at the outer draft:**  
\( B_{sw} := (B_{sw}/B_c) \cdot B_c \)  
\( B_{sw} = 1.341 \text{ m} \)

**cushion area:**  
\[
S_c := \frac{W}{p_c}
\]  
\( S_c = 399.532 \text{ m}^2 \)

**SES weight of submerged sidewalls:**  
\[
W_{sw} := (W - \text{per} \cdot p_c \cdot S_c)
\]  
\( W_{sw} = 30 \text{ tonne} \)
SES volume of submerged sidewalls: \[ V_{sw} = W_{sw} \gamma_{sw} \quad V_{sw} = 29.25 \text{ m}^3 \]

Sidewall Block Coefficient for SES: \[ C_B := C_p \cdot C_X \quad C_B = 0.48 \]

SES sidewall outer draft: \[ T_o := \frac{2}{C_B \cdot L_c \cdot B_{sw}} \quad T_o = 0.847 \text{ m} \]

4) Total power estimation:

First approximation:

This is an approximation for the power estimation proposed by Mantle

\[ K_4 := 165 \text{ hp} \text{ tonne}^{-8} \quad \frac{7}{8} \quad N_{est} := K_4 \cdot (1.102 W)^{\frac{7}{8}} \quad N_{est} = 1.074 \times 10^4 \text{ kW} \]

\[ W_{estim} := 10^7 \text{ to } 10^8 \quad N_{estim}(W_{estim}) := K_4 \cdot (1.102 W_{estim})^{\frac{7}{8}} \]
\[
V := \text{regrass}(V_{\text{max}_{\text{ACV}}}, \frac{\text{power}}{\text{tn}_{\text{ACV}}}, 1)
\]

\[
t_2 := 0 \ldots 100
\]

\[
P/\text{tn}_{\text{ACV}} := \text{interp}(v, V_{\text{max}_{\text{ACV}}}, \frac{\text{power}}{\text{tn}_{\text{ACV}}}, \frac{V_s}{kt})
\]

\[
P/\text{tn}_{\text{ACV}} = 54.39
\]

\[
\text{ACV}_{\text{power}} := W\left(\frac{P/\text{tn}_{\text{ACV}}}{\text{tonne}}\right)
\]

\[
\text{ACV}_{\text{power}} = 8.158 \times 10^3 \text{ kW}
\]
Low power density ACV propulsion estimation

\[
v_{ldACV} := \text{regress}(V_{\text{max}_{ldACV}}, \text{power/tn}_{ldACV}, 2)
\]
\[
t_3 := 0..80
\]
\[
P/\text{tn}_{ldACV} := \text{interp}\left(v_{ldACV}, V_{\text{max}_{ldACV}}, \frac{\text{power/tn}_{ldACV}}{\text{tonne}}\right)
\]
\[
P/\text{tn}_{ldACV} = 35.074
\]

Power/tn_{ldACV}

Medium power density ACV propulsion estimation

\[
v_{mdACV} := \text{regress}(V_{\text{max}_{mdACV}}, \text{power/tn}_{mdACV}, 2)
\]
\[
P/\text{tn}_{mdACV} := \text{interp}\left(v_{mdACV}, V_{\text{max}_{mdACV}}, \frac{\text{power/tn}_{mdACV}}{\text{tonne}}\right)
\]
\[
P/\text{tn}_{mdACV} = 54.108
\]

IdACVpower := W \left(\frac{\text{power/tn}_{ldACV}}{\text{tonne}}\right)

IdACVpower = 5.261 \times 10^3 \text{ kW}
\[ \text{mdACVpower} := W_{\text{P/tn\text{mdACV}}} \left( \frac{\text{kW}}{\text{tonne}} \right) \]
\[ \text{mdACVpower} = 8.116 \times 10^3 \text{ kW} \]

**High power density ACV propulsion estimation**

\[ V_{\text{hdACV}} := \text{regress}\left(V_{\text{max\_hdACV}}, \frac{\text{power/tn\_hdACV}}{V_{\text{max\_hdACV}}}, 1\right) \]

\[ P/\text{tn\_hdACV} := \text{interp}\left(V_{\text{hdACV}}, V_{\text{max\_hdACV}}, \frac{V_s}{0.514 \text{ UnitsOf}(V_s)}\right) \]

\[ P/\text{tn\_hdACV} = 84.42 \]
hdACVpower := \( P/tn_{hdACV} \times \frac{\text{kW}}{\text{tonne}} \)  

\[
\text{hdACVpower} = 1.266 \times 10^4 \text{ kW}
\]

choose power value:  
\[ N_{ACV} := \text{hdACVpower} \]

\[ N_{ACV} = 1.266 \times 10^4 \text{ kW} \]

**SES propulsion estimation:**

\[ v_{SES} := \text{regress}(V_{\text{max SES}}, \text{power/tn}_{SES}, 3) \]

\[ t_6 := 0 \ldots 60 \]

\[ P/tn_{SES} := \text{interp}\left(v_{SES}, V_{\text{max SES}}, \text{power/tn}_{SES}, \frac{V_s}{0.514 \text{UnitsOf}(V_s)}\right) \]

\[ P/tn_{SES} = 24.685 \]

\[ N_{SES} := \text{W.}\left(\frac{P/tn_{SES}}{\text{tonne}}\right) \times \frac{\text{kW}}{} \]

\[ N_{SES} = 3.703 \times 10^3 \text{ kW} \]

\[ N := \begin{cases} N_{ACV} & \text{if type } = 1 \\ N_{SES} & \text{if type } = 2 \\ 0 & \text{otherwise} \end{cases} \]

\[ N = 1.266 \times 10^4 \text{ kW} \]
5) Lift power estimation:

\[ Q := B_c \cdot V_s \cdot H_{sk} \cdot V_s \]

\[ Q = 561.801 \frac{m^3}{s} \]

\[ n_{fan} := 0.8 \]

\[ N_{el} := \left( \frac{p_c \cdot Q}{n_{fan}} \right) \frac{kgf}{kg} \]

\[ N_{el} = 2.586 \times 10^3 kW \]

\[ N_{prop\_ACV} := N_{ACV} - N_{el} \]

\[ N_{prop\_ACV} = 1.008 \times 10^4 kW \]

\[ N_{prop\_SES} := N_{SES} - N_{el} \]

\[ N_{prop\_SES} = 1.117 \times 10^3 kW \]

6) Propulsion engine selection:

\[
\begin{pmatrix}
W_{eng} \\
P_{eng} \\
SFC \\
L_{eng} \\
B_{eng} \\
H_{eng} \\
D_{fan}
\end{pmatrix}
\]

\[ A_{eng} := L_{eng} \cdot B_{eng} \cdot m \]

\[ Vol_{eng} := A_{eng} \cdot H_{eng} \cdot m \]

number of engines: \( N_{no\_eng} := 4 \)

Mechanical Efficiency: \( \eta := .97 \)

\[ W_{tot\_eng} := N_{no\_eng} \cdot W_{eng} \cdot \text{tonne} \]

\[ P_{tot} := N_{no\_eng} \cdot P_{eng} \cdot kW \]

\[ P_s := \eta \cdot P_{tot} \]

\[ P_s = 1.302 \times 10^4 kW \]

Machinery Box Size:

Dimensions:

\[ B_{MB} = 1.275 m \]

\[ L_{MB} = 1.25B_{eng} \cdot m \]

\[ H_{MB} = 2.5 \cdot H_{eng} \cdot m \]
Area: \( A_{MB} := L_{MB} \cdot B_{MB} \quad A_{MB} = 4.188 \, \text{m}^2 \)

Volume: \( V_{MB} := H_{MB} \cdot A_{MB} \quad V_{MB} = 8.9 \, \text{m}^3 \)

### Weights estimation

#### Structural weight (Group 100):

\[
W_{100/W} := 0.25 \left( \frac{W}{\text{tonne}} \right)^{1/3} + 0.04 \left( \frac{W}{\text{tonne}} \right)^{1/3} \left( \frac{0.062 \, \text{pc}/\text{Lc}}{\text{kg}^3/\text{m}^3} \right)^{1/3}
\]

\( W_{100/W} = 0.27 \)

\( W_{100} := W_{100/W} \cdot W \)

\( W_{100} = 40.478 \, \text{tonne} \)

#### Propulsion System weight (Group 200):

Lift and skirt system are calculated separately from the rest components of \( W_{200} \)

1) Main propulsion:

\[
W_2/P := \left( 1.25 + \frac{74}{\sqrt[7]{\text{N}} \, \text{hp}} \right) \quad W_{200} := W_2/P \cdot N \quad W_{200} = 14.002 \, \text{tonne}
\]

2) Propulsors:

\[
T_s := \frac{N_{\text{prop,ACV}}}{V_s} \quad T_s = 4.897 \times 10^5 \, \text{N}
\]

give number of propulsors: \( N_{\text{prop}} := 2 \quad T_{\text{prop}} := \frac{T_s}{N_{\text{prop}}} \)
Thrust/Horsepower: \[ TP := \frac{T_{\text{prop}}}{1.341 \times 10^{-3} N_{\text{prop ACV}}} \] 
UnitsOf\(T_{\text{prop}}\) UnitsOf\(N_{\text{prop ACV}}\)

\[ TP = 4.077 \]

Diameter Parameter for shrouded air propellers: \[ D_P := \left( \frac{TP}{1.08} \right)^{\frac{3}{2}} \]

\[ D_P = 7.334 \]

Diameter Parameter for free air propellers: \[ D_P := \left( \frac{TP}{0.86} \right)^{\frac{3}{2}} \]

\[ D_P = 10.321 \]

\[ D_{\text{props}} := \left( \frac{1.341 \times 10^{-3} N_{\text{prop ACV}}}{1000} \right)^{0.305} \]

\[ D_{\text{props}} = 8.223 \text{ m} \]

\[ D_{\text{propf}} := \left( \frac{1.341 \times 10^{-3} N_{\text{prop ACV}}}{1000} \right)^{0.305} \]

\[ D_{\text{propf}} = 11.573 \text{ m} \]

*The above formulas for calculation of the propeller diameter do not give accurate results for high power and number of propellers = 2* 

aluminum free propeller weight: \[ W_{\text{pf}} := 5.40 \cdot D_{\text{propf}}^2 \text{ lb ft}^2 \]

\[ W_{\text{pf}} = 3.531 \text{ tonne} \]

aluminum shrouded propeller weight: \[ W_{\text{ps}} := 16 \cdot D_{\text{props}}^2 \text{ lb ft}^2 \]

\[ W_{\text{ps}} = 5.282 \text{ tonne} \]

3) Lift system:

total lift system weight calculation:

\[ \frac{W_{\text{LS}}}{W} := 0.044 + \frac{0.08}{\left( \frac{W}{\text{tonne}} \right)^3} \]

\[ \frac{W_{\text{LS}}}{W} = 0.059 \]

\[ W_{\text{LS}} := \frac{W_{\text{LS}}}{W} \cdot W \]

\[ W_{\text{LS}} = 8.858 \text{ tonne} \]
fan calculations:

select number of fans: \( \text{No}_{\text{fan}} : 4 \)

Centrifugal fanweight calculation:

\[
\begin{align*}
D_{\text{fan}} &= \text{D}_{\text{fan}} \text{m} \\
W_{\text{fan}} &= 1.98 \left( \frac{D_{\text{fan}}}{\text{ft}} \right)^{2.42} \text{lb} \\
A_{\text{fan}} &= \pi \frac{D_{\text{fan}}^2}{4} \\
W_{\text{fan}} &= 0.083 \text{ tonne} \\
A_{\text{fan}} &= 3.079 \text{ m}^2
\end{align*}
\]

4) Skirt system:

skirt system weight calculation

\[
\begin{align*}
K_{SK} &= 0.02 \text{ if type } = 1 \\
&= 0.023 \text{ if type } = 2 \\
&= 0 \text{ otherwise} \\
W_{SK} &= K_{SK} (L_c + B_c) H_{sk} P_c 9.807 \text{ if type } = 1 \\
&= K_{SK} B_c H_{sw} P_c 9.807 \text{ if type } = 2 \\
&= 0 \text{ otherwise}
\end{align*}
\]

\( W_{SK} = 5.629 \text{ tonne} \)

Electrical System weight (Group 300):

\[
\begin{align*}
W_{300}/W &= 0.00034 \left( \frac{W}{\text{tonne}} \right)^2 + 0.10 \left( \frac{W}{\text{tonne}} \right)^{1/2} \\
W_{300}/W &= 0.012 \\
W_{300} &= W_{300}/W \cdot W \\
W_{300} &= 1.849 \text{ tonne}
\end{align*}
\]

Command and Surveillance weight (Group 400):

choose how well equipped is each command & surveillance group on the ship:

\[
K_{\text{size}} = \begin{cases} 
0 & \text{none} \\
0.25 & \text{light} \\
0.5 & \text{medium} \\
0.75 & \text{high} \\
1 & \text{full}
\end{cases}
\]

Assumption: each group assigned an equal value of 12.5%
Command and Control  \[ K_{CC} := 0.125 \cdot K_{size_0} \]

Navigation  \[ K_{Nav} := 0.125 \cdot K_{size_1} \]

Interior Communications  \[ K_{IC} := 0.125 \cdot K_{size_0} \]

Exterior Communications  \[ K_{EC} := 0.125 \cdot K_{size_0} \]

Surface Surveillance  \[ K_{SS} := 0.125 \cdot K_{size_0} \]

Underwater Surveillance  \[ K_{US} := 0.125 \cdot K_{size_0} \]

Countermeasures  \[ K_{Count} := 0.125 \cdot K_{size_0} \]

Fire control  \[ K_{FC} := 0.125 \cdot K_{size_0} \]

\[ K_{400} := K_{CC} + K_{Nav} + K_{IC} + K_{EC} + K_{SS} + K_{US} + K_{Count} + K_{FC} \]

\[ W_{400/W} := \frac{K_{400}^{1.15}}{3} \left( \frac{W}{\text{tonne}} \right)^4 \]

\[ W_{400} = 1.64 \text{ tonne} \]

Auxiliary systems weight (Group 500):

\[ (W_{500}-WLS)/W := 0.0024 \left( \frac{W}{\text{tonne}} \right)^3 + 0.06 \left( \frac{W}{\text{tonne}} \right)^{1.1} \]

\[ (W_{500}-WLS)/W = 0.024 \]

\[ W_{500} := (W_{500}-WLS)/W \cdot W + W_{LS} \]

\[ W_{500} = 12.465 \text{ tonne} \]

Outfit and Furnishings (Group 600):

\[ W_{600/W} := 0.003 \left( \frac{W}{\text{tonne}} \right)^{1.1} + 0.07 \left( \frac{W}{\text{tonne}} \right)^{1.1} \]

\[ W_{600/W} = 0.029 \]

\[ W_{600} := W_{600/W} \cdot W \]

\[ W_{600} = 4.367 \text{ tonne} \]
choose how heavily armed is each warfare group on the ship: 
\[ K_{\text{size}} := \begin{pmatrix} 0 \\ 0.25 \\ 0.5 \\ 0.75 \\ 1 \end{pmatrix} \]
- none
- light
- medium
- high
- full

Assumption: in a fully armed multirole ship
45% is assigned to ASUW, 35% to AAW and 20% to ASW

Surface War coefficient 
\[ K_{\text{ASUW}} := 0.45 \cdot K_{\text{size}} \]

Anti-airwarfare coefficient
\[ K_{\text{AAW}} := 0.35 \cdot K_{\text{size}} \]

Anti-submarine coefficient
\[ K_{\text{ASW}} := 0.2 \cdot K_{\text{size}} \]

\[ K_{\text{mission}} := K_{\text{ASUW}} + K_{\text{AAW}} + K_{\text{ASW}} \]

\[ W_{700/W} := \frac{0.5 \cdot K_{\text{mission}}}{\left( \frac{W}{\text{tonne}} \right)^3} \]

\[ W_{700} := W_{700/W} \cdot W \]

\[ W_{700} = 1.588 \text{ tonne} \]

**Lightship:**

\[ W_{\text{lightship}} := W_{100} + (W_{200} + W_{LS} + W_{SK}) + W_{300} + W_{400} + W_{500} + W_{600} + W_{700} \]

\[ W_{\text{lightship}} = 90.878 \text{ tonne} \]
\[ M := \text{round} \left( 0.35 \cdot \left( \frac{W}{\text{tonne}} \right)^{\frac{3}{4}} \right) \]

\[ M(\text{shift}) := \begin{cases} M & \text{if shift} = 3 \\ \text{round} \left( \frac{M}{3} \right) & \text{if shift} = 1 \\ \text{round} \left( \frac{M}{2} \right) & \text{if shift} = 2 \\ 0 & \text{otherwise} \end{cases} \]

Craft operates independently having 3 shifts
Craft operates from a mothership and has only 1 shift
Craft operates having 2 shifts

\[ M(\text{shift}) = 5 \quad W_M := M(\text{shift}) \cdot 0.75\text{kg} \quad W_M = 0.375 \text{ tonne} \]

Weight of fuel and oil:

oil and water consumption coefficient: \( K_{\text{fuel}} = 1.07 \)

\[ W_{\text{fuel}} := \left( \frac{\text{SFC} \cdot \text{kg}}{\text{kW} \cdot \text{hr}} \right) \cdot 0.5 \cdot \text{range} \cdot \frac{1}{V_s} \cdot K_{\text{fuel}} \quad W_{\text{fuel}} = 13.138 \text{ tonne} \]

Liquid Load:

\[ W_{\text{LL}} := 0.004 \cdot W \quad W_{\text{LL}} = 0.6 \text{ tonne} \]

Disposable payload:

\[ K_{\text{payload}} := \begin{pmatrix} 0.20 \\ 0.25 \\ 0.35 \\ 0.25 \\ 0.35 \end{pmatrix} \]

- for small ACV \( W<10 \text{ ton} \)
- for medium ACV \( W<40 \text{ ton} \)
- for large ACV \( W<50 \text{ ton} \)
- for small SES \( W<60 \text{ ton} \)
- for large SES \( W<80 \text{ ton} \)

\[ W_{\text{dpayload}} := K_{\text{payload}} \cdot W \quad W_{\text{dpayload}} = 52.5 \text{ tonne} \]

Total weight:

\[ W_{\text{full}} := W_{\text{lightship}} + W_{\text{fuel}} + W_{\text{LL}} + W_{\text{dpayload}} + W_M \quad W_{\text{full}} = 157.491 \text{ tonne} \]
8) Payload selection:

\[
\begin{align*}
A_{\text{payload}} \\
V_{\text{ol, payload}} \\
W_{\text{payload}} \\
(KG_{\text{payload}})
\end{align*}
\]

Worksheet

Selected payload must be smaller than the calculated disposable payload

\[W_{\text{payload}} := W_{\text{payload, tonne}} \quad W_{\text{payload}} = 28.2 \text{ tonne}\]

9) Area calculation:

assuming a RoRo configuration like LCAC with engines on the main deck

\[A_c := L_c \cdot B_c \quad A_c = 399.532 \text{ m}^2\]

choose width of superstructure:

\[B_{\text{sup}} := 2 \text{ m} \quad B_{\text{sup}} := \begin{cases} B_{\text{sup}} & \text{if } B_{\text{sup}} \geq B_{\text{MB}} \\ B_{\text{MB}} & \text{otherwise} \end{cases} \quad B_{\text{sup}} = 2 \text{ m}\]

superstructure area:

\[A_{\text{sup}} := 2 \cdot L_c \cdot B_{\text{sup}} \quad A_{\text{sup}} = 107.268 \text{ m}^2\]

machinery area:

choose length of shaft:

\[L_{\text{shaft}} := 2 \text{ m} \quad L_{\text{volute}} := 1.5 \cdot D_{\text{fan}}\]

\[A_{\text{mach}} := N_{\text{eng}} \cdot A_{\text{MB}} + N_{\text{fan}} \cdot D_{\text{fan}} \cdot L_{\text{volute}} + N_{\text{prop}} \cdot L_{\text{shaft}} \cdot B_{\text{MB}} \quad A_{\text{mach}} = 45.376 \text{ m}^2\]

area for troops, bridge and living:

\[A_{\text{crew}} := A_{\text{sup}} - A_{\text{mach}} \quad A_{\text{crew}} = 61.893 \text{ m}^2\]

total area on main deck:

\[A_{\text{tot}} := (A_{\text{payload, m}^2}) + A_{\text{sup}} \quad A_{\text{tot}} = 225.723 \text{ m}^2\]

area index := 1 if \(A_{\text{tot}} \leq A_c\) \quad area index = 1 \quad rearrange the area if area index equals 0
(10) Volume calculation:

Avg Deck Height: \( H_{Dkh} := 2.6 \) m

ship depth: \( D := 1.3 \) m

Propulsion Fuel Tank Volume: (allow 2% for tank structure and 5% for expansion)

\[
V_{fuel} := 1.02 \cdot 1.05 \cdot V_{fuel} \cdot W_{fuel} \quad V_{fuel} = 16.857 \text{ m}^3
\]

\[
V_{LL} := 1.02 \cdot V_{fw} \cdot W_{LL} \quad V_{LL} = 0.614 \text{ m}^3
\]

\[
V_{hull} := A_c \cdot D \quad V_{hull} = 519.391 \text{ m}^3
\]

inner hull structural volume \( V_{str} := 0.1 \cdot V_{hull} \)

\[
H := \begin{cases} 
H_{Dkh} & \text{if } H_{Dkh} \geq H_{MB} \\
H_{MB} & \text{otherwise}
\end{cases}
\]

\[
V_{sup} := 2 \cdot (L_c \cdot H \cdot B_{sup}) \quad V_{sup} = 278.898 \text{ m}^3
\]

\[
V_{tot} := V_{sup} + V_{hull} \quad V_{tot} = 798.289 \text{ m}^3
\]

volume_index := 1 if \( V_{fuel} + V_{LL} + V_{str} \leq V_{hull} \)

volume_index = 0 otherwise

volume_index = 1 rearrange the volume if volume_index equals 0

(11) Stability estimation:

KG calculation:

\[
KG := \frac{W_{SK} \cdot \frac{H_{sk}}{2} + V_{hull} \cdot W_{100} \left( \frac{H_{sk} + D}{2} \right) + V_{sup} \cdot W_{100} \left( \frac{H_{sk} + D + H}{2} \right) + W_{payload} \left( KG_{payload} \cdot m + H_{sk} + D \right)}{W_{100} + W_{SK} + W_{payload}}
\]

KG = 3.329 m
ACV intact stability calculations:

\[ l_x := \frac{L_c \cdot B_c^3}{12} \]

\[ KC_{ACV} := \frac{H_{sk}}{2} \]

\[ CM_{x,\ ACV} := \frac{l_x}{S_c \cdot H_{sk}} \]

\[ GM_{x,\ ACV} := KC_{ACV} + CM_{x,\ ACV} - KG \]

\[ GM_{x,\ ACV} = 7.681 \text{ m} \]

\[ l_y := \frac{B_c \cdot L_c^3}{12} \]

\[ CM_{y,\ ACV} := \frac{l_y}{S_c \cdot H_{sk}} \]

\[ GM_{y,\ ACV} := KC_{ACV} + CM_{y,\ ACV} - KG \]

\[ GM_{y,\ ACV} = 30.291 \text{ m} \]

Righting moment calculation:

\[ \phi := \frac{\pi}{12} \cdot 0 \ldots \pi \]

\[ RM(\phi) := W \cdot GM_{x,\ ACV} \cdot \sin(\phi) \]

\[ h_\theta := \frac{GM_{x,\ ACV}}{B_c} \]

\[ h_\theta = 0.516 \]

\[ h_\psi := \frac{GM_{y,\ ACV}}{L_c} \]

\[ h_\psi = 1.13 \]

\[ \text{stability} := \begin{cases} 1 & \text{if } 0.35 \leq h_\theta \leq 1.2 \land 1 \leq h_\psi \leq 2.4 \land H_{sk}/B_c \leq 0.2 \\ 0 & \text{otherwise} \end{cases} \]

\[ \text{stability} = 1 \quad \text{if stability} = 1 \text{ then the stability criteria are satisfied} \]
\[ \text{stability} = 0 \quad \text{if stability} = 0 \text{ then not} \]
**SES intact stability calculations:**

sidewall length: \( L_{sw} := L_c \)

waterplane area of one sidewall: \( A_{sw} := L_{sw} \cdot B_{sw} \)

cushion height: \( H_c := H_{sk} \)

\[
I_{x_{sw}} := \frac{\left( L_{sw} \cdot B_{sw} \right)^3}{12} \quad I_{x_{totsw}} := 2 \cdot \left[ I_{x_{sw}} + \left( \frac{B_{sw}}{2} + \frac{B_c}{2} \right)^2 \cdot A_{sw} \right] \quad I_{x_{SES}} := I_{x_{totsw}} + I_x
\]

\[
KC_{SES} := \frac{H_c}{2} \quad CM_{x_{SES}} := \frac{I_{x_{SES}}}{2 \cdot A_{sw} \cdot T_0 + S_c \cdot H_c}
\]

\( GM_{x_{SES}} := KC_{SES} + CM_{x_{SES}} - KG \quad GM_{x_{SES}} = 12.897 \text{ m} \)

\[
I_{y_{sw}} := \frac{\left( B_{sw} \cdot L_{sw} \right)^3}{12} \quad I_{y_{totsw}} := 2 \cdot I_{y_{sw}} \quad I_{y_{SES}} := I_{y_{totsw}} + I_y
\]

\[
CM_{y_{SES}} := \frac{I_{y_{SES}}}{2 \cdot A_{sw} \cdot T_0 + S_c \cdot H_c} \quad GM_{y_{SES}} := KC_{SES} + CM_{y_{SES}} - KG \quad GM_{y_{SES}} = 33.213 \text{ m}
\]

\[
h_\theta := \frac{GM_{x_{SES}}}{B_c + 2 \cdot B_{sw}} \quad h_\theta = 0.734
\]

\[
h_\psi := \frac{GM_{y_{SES}}}{L_c + 2 \cdot B_{sw}} \quad h_\psi = 1.126
\]

stability := \[
1 \quad \text{if } 0.35 \leq h_\theta \leq 1.2 \land 1 \leq h_\psi \leq 2.4 \land \text{Hsk/Bc} \leq 0.2
\]

\[
0 \quad \text{otherwise}
\]

\[\text{stability} = 1 \quad \text{if} \quad \text{stability} = 1 \text{ then the stability criteria are satisfied}
\]

\[\text{if} \quad \text{stability} = 0 \text{ then not} \]
Damaged Stability Analysis:

According to DDS 079-1
give the extent of transverse damage: \( B_{\text{flood}} := 5 \text{m} \)

\[
L_{\text{floodable}} := \begin{cases} 
\text{if } L_c < 100 \text{ft} \\
\max(0.1 \cdot L_c, 8 \text{ft}) \text{ if } B_{\text{flood}} \leq 0.5 \cdot B_c \land B_{\text{flood}} > 0.2 \cdot B_c \\
\max(0.15 \cdot L_c, 8 \text{ft}) \text{ if } B_{\text{flood}} \leq 0.2 \cdot B_c \\
0 \text{ otherwise} \\
\end{cases}
\]

\[
\begin{cases} 
\text{if } 100 \text{ft} < L_c < 470 \text{ft} \\
0.15 \cdot L_c \text{ if } B_{\text{flood}} \leq 0.5 \cdot B_c \land B_{\text{flood}} > 0.1 \cdot B_c \\
0.5 \cdot L_c \text{ if } B_{\text{flood}} \leq 0.1 \cdot B_c \\
0 \text{ otherwise} \\
\end{cases}
\]

\[
L_{\text{floodable}} = 2.682 \text{ m}
\]

Cost Analysis:

for an update in prices go to: http://www.ship.gr/bunkers/index.htm

USD := 1

Marine Diesel Oil: \( \text{MDO} := 361 \frac{\text{USD}}{\text{tonne}} \)

Marine Gas Oil: \( \text{MGO} := 400 \frac{\text{USD}}{\text{tonne}} \)

annual\_operating\_hours := 1500\text{hr}

fleet\_size := 5

Acquisition Cost Analysis

\( v_{\text{cost}} := \text{regress}(A\text{UW}, \text{acq\_cost}, 1) \)

\( \text{acquisition\_cost} := \text{interp}\left( v_{\text{cost}}, \text{A\text{UW}}, \text{acq\_cost}, \frac{W}{\text{tonne}} \right) \)

\( t_7 := 0..300 \)
**Crew Salaries Analysis**

\[
\begin{align*}
\text{crew size} &:= 
\begin{cases} 
3 \\
4 \\
5 \\
6 \\
18
\end{cases} \\
\text{salary} &:= 
\begin{cases} 
152516 \\
185276 \\
218036 \\
276640 \\
732368
\end{cases}
\end{align*}
\]

\[v := \text{regress(crew size, salary, 1)}\]

\[\text{crew salaries} := \text{interp}(v, \text{crew size, salary, M(type)})\]

\[t_8 := 0 .. 100\]

**Engine Overhaul Cost Analysis**

\[v_{\text{eng}} := \text{regress(AUW, eng_overhaul, 1)}\]

\[\text{engine overhaul} := \text{interp}(v_{\text{eng}}, \text{AUW, eng_overhaul, } \frac{W}{\text{tonne}})\]
Other Maintenance Cost Analysis

\[ v_{\text{maint}} := \text{regress}(\text{AUW}, \text{other maint}, 1) \]

\[ \text{other maintenance} := \text{interp}\left(v_{\text{maint}} \cdot \text{AUW}, \text{other maint}, \frac{W}{\text{tonne}}\right) \]

\[ t_{10} := 0..300 \]

Depreciation Table

\[
\begin{array}{cccccccc}
& 0 & 0.1 & 0.18 & 0.144 & 0.1152 & 0.0922 & 0.0737 & 0.0655 \\
\text{depreciation}_{10\text{y}} := & 0.0655 & 0.0655 & 0.0655 & 0.0655 & 0.0655 & 0.0329 \\
\end{array}
\]

Assume 10 years depreciation period
**Craft capital cost:**

\[
\text{acquisition\_cost} = 2.34 \times 10^7
\]

\[
\text{spares\_cost} := 0.15 \times \text{acquisition\_cost} \quad \text{spares\_cost} = 3.51 \times 10^6
\]

\[
\text{craft\_capital\_cost} := \text{acquisition\_cost} + \text{spares\_cost} \quad \text{craft\_capital\_cost} = 2.691 \times 10^7
\]

**Operating costs:**

**Fixed annual costs:**

\[
\text{depreciation} := \text{depreciation\_10y} \times \text{acquisition\_cost} \quad \text{depreciation} = 2.34 \times 10^6
\]

\[
\text{interest} := 0.05 \times \text{craft\_capital\_cost}
\]

\[
\text{insurance} := 0.02 \times \text{acquisition\_cost} \quad \text{insurance} = 4.68 \times 10^5
\]

\[
\text{fixed\_cost} := \text{depreciation} + \text{interest} + \text{insurance}
\]

**Variable costs:**

\[
\text{crew\_salaries} = 2.274 \times 10^5
\]

\[
\text{fuel} := 0.8 P_{\text{tot}} \left( \frac{\text{SFC}}{\text{kg/\text{kW}\text{hr}}} \right) \times \text{MDO} \times \text{annual\_operating\_hours} \quad \text{fuel} = 1.702 \times 10^6
\]

\[
\text{engine\_overhaul} = 7.745 \times 10^5
\]

\[
\text{other\_maintenance} = 1.035 \times 10^6
\]

\[
\text{variable\_cost} := \text{crew\_salaries} + \text{fuel} + \text{engine\_overhaul} + \text{other\_maintenance}
\]

\[
\text{annual\_operating\_cost} := \text{fixed\_cost} + \text{variable\_cost} \quad \text{annual\_operating\_cost} = 7.893 \times 10^6
\]
Transport Factor:

\[ W_{\text{payload}} := W_{\text{payload}} \frac{\text{kgf}}{\text{kg}} \]

\[ TF := \frac{(W_{\text{payload}} \cdot V_s)}{N_{\text{ACV}}} \]

\[ TF = 0.449 \]
Transport Factor:

\[ W_{\text{payloadf}} := \frac{W_{\text{payload}} \text{ kgf}}{\text{kg}} \]

\[ TF := \frac{(W_{\text{payloadf}} \cdot V_s)}{N_{\text{ACV}}} \]

\[ TF = 0.449 \]