# THE FEASIBILITY AND PERFORMANCE OF A TRIMARAN YACHT CONCEPT EQUIPPED WITH A HULL VANE®

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## SUMMARY

The Hull Vane® consists of a foil situated below the waterline, near the aft of a vessel. It is aimed at reducing the pressure resistance of the vessel. Like the Hull Vane®, trimarans offer beneficial resistance characteristics at higher speeds. The addition of a Hull Vane® to a trimaran could thus prove to be beneficial.

This paper presents a study into the advantages and disadvantages of the application of this concept as a platform for yachts. To analyse this, a new concept 500GT trimaran yacht with a Hull Vane® attached to its outriggers is designed. Subsequently, it is compared to an equivalent monohull vessel on the basis of four criteria: lifetime costs, energy efficiency, luxury and seakeeping comfort. The analysis shows that the trimaran with Hull Vane® outperforms its monohull equivalent in all four criteria. The combination of a trimaran yacht and a Hull Vane® attached to its outriggers is thus found to be competitive with an equivalent monohull.

## NOMENCLATURE

| | |
|---|---|
| $A_{(\mathrm{PRE})}$ | (Prime Real Estate) Area (m$^2$) |
| $B_{(\mathrm{WL})}$ | Beam (on waterline) (m) |
| $C_\mathrm{F}$ | CO$_2$ emission factor (-) |
| $C_\mathrm{i}$ | Score for criterion i (-) |
| $\vec{D}$ | Drag vector |
| $\vec{F}$ | Force vector |
| $Fn$ | Froude number (-) |
| FV | Future Value (€) |
| $g$ | Inflation (%) |
| $GT$ | Gross Tonnage (GT) |
| $H_\mathrm{W}$ | Significant wave height (m) |
| $i$ | Interest rate (%) |
| $IC$ | Investment Costs (€) |
| $\vec{L}$ | Lift vector |
| $L$ | Length (m) |
| $P$ | Performance (-) |
| $P_{AE}$ | Power of auxiliary engine at sea (kW) |
| $P_{ME}$ | 75% of MCR of main engines (kW) |
| $RC$ | Running Costs (€/year) |
| $SFC$ | Specific Fuel Consumption (kg/kWh) |
| $T_\mathrm{W}$ | Wave period (s) |
| $V_\mathrm{ref}$ | Ship speed at 75% MCR (kn) |
| $w$ | Weight factor (-) |

Subscripts:

| | |
|---|---|
| d | Index for deck |
| D | Database |
| HV | Hull Vane |
| m | Index for method |
| max | Maximum |
| MH | Main Hull |
| min | Minimum |
| OR | Outrigger |
| u | Index for user profile |
| v | Index for vessel |

## 1. INTRODUCTION

The patented Hull Vane® consists of a foil below the waterline, near the aft-body of a vessel. It is aimed at regaining part of the energy lost in the transom wave, influencing the trim, and reducing the vertical motions of the vessel it is attached to. With a suitable hull shape, a well-designed Hull Vane® can reduce the resistance by 5-10%, and in some occasions more than 20%. The gains of the Hull Vane® are largest between *Fn* 0.2 and 0.7, making it an interesting option for fast displacement vessels.

Like the Hull Vane®, trimarans generally offer beneficial resistance characteristics at higher speeds, due to a lower pressure resistance, which is the dominant resistance component at higher ship speeds. Besides, a trimaran also provides a wide and stable platform, suitable for a wide range of applications. Combining the Hull Vane® and the trimaran concept, by attaching the Hull Vane® to the trimaran's outriggers, could thus prove to be beneficial.

To determine whether a trimaran equipped with the Hull Vane® between its outriggers forms a suitable platform for yachts, a concept for a 500GT trimaran yacht is developed and compared to an equivalent, high-performance monohull yacht.

## 2. BACKGROUND

The ongoing quest for fuel efficiency of ships is roughly divided into four areas of research: engine efficiency, alternative sustainable sources of power, propulsion efficiency, and the lowering of the resistance of the hull.

As naval architects, Van Oossanen Naval Architects mainly focuses on the latter. Within this category they have developed the patented Fast Displacement Hull Form, and the Hull Vane®. Since Peter van Oossanen's invention of the Hull Vane® in 1992, and the first patent application in 2002, a significant amount of research has been performed aimed at the optimization of the concept.

Because it is a relatively new device, the Hull Vane® and its working principles will be introduced first. Subsequently, trimarans will shortly be elaborated upon.

## 2.1 THE HULL VANE®

The early beginnings of the Hull Vane® can be traced back to 1992. The first full-scale application of the Hull Vane® was on a catamaran vessel not reaching its required speed due to excessive trim and wave generation. Placing a foil in the steepest part of the interacting wave system aft of the midship reduced the bow-up trim and the resistance significantly. This result led to an increased interest in the device and associated hydrodynamics, and formed a platform for further research.

The next application of the Hull Vane® was on *Le Defi Areva*, the French challenger for the 2003 America's Cup (Figure 1). During model tests a resistance reduction of 5% was found at model scale for a full-scale speed of 10 knots. Despite this result, the Hull Vane® was not applied during the races due to structural problems. In later editions of the America's Cup the Hull Vane® was disallowed by the regulations as an appendage that would give an unfair advantage.

**Figure 1:** The second application of the Hull Vane®, on the 2003 IACC yacht *Le Defi Areva*.

Throughout the following years various applications of the Hull Vane® have been analysed by means of model tests, Computational Fluid Dynamics (CFD), and full-scale trials. These include not only many sailing and motor yachts but also various merchant ships, naval vessels, cruise ships, and more. The found influences of the Hull Vane® on the total resistance have varied between a resistance decrease of -26.5% for a 65m motor yacht, and a resistance increase of +9.5%, for a slow steaming Ro-Ro vessel, showing that the fuel saving device is not suitable to all cases. Resistance reductions between 5% and 10% were found to be common [1].

In 2014, two Hull Vane®-equipped ships were launched. Shipyard De Hoop in the Netherlands built the 55 metre supply vessel *Karina*, which saw its required engine power during sea trials reduced by 15% after a Hull Vane® was retrofitted to the transom. The second vessel is the 42 metre displacement yacht *Alive*, built by the Dutch yacht builder Heesen Yachts (Figure 2). For this vessel, the Hull Vane® was incorporated during the design phase, which allowed for resistance reductions of up to 23%.

**Figure 2:** Application of the Hull Vane® on the 42 metre motor yacht *Alive*.

Below, four effects of the Hull Vane® will be discussed: a thrust force, a trim correction, the reduction of waves, and the reduction of motions in waves. After this, the influence of ship speed on the effectiveness of the Hull Vane® is discussed.

### 2.1 (a) Thrust Force

The first effect of the Hull Vane® is based on basic foil theory. In Figure 3, a schematic overview of the forces on the Hull Vane® is given.

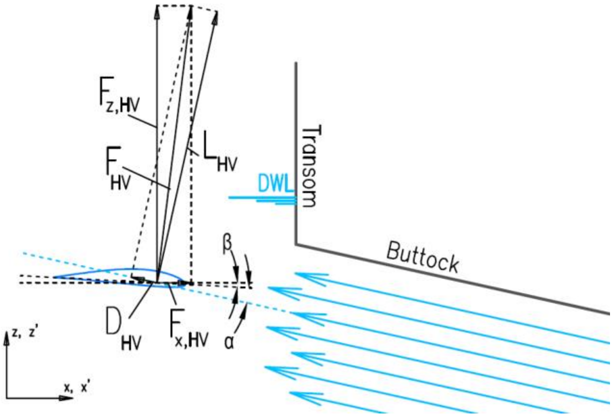

**Figure 3.** Schematic overview of the forces on the Hull Vane® in a section view of the aft ship. The vessel is displayed at zero trim.

The foil creates a lift force vector $\vec{L}_{\mathrm{HV}}$ which is by definition perpendicular to the local direction of the undisturbed flow of water, and a drag force vector $\vec{D}_{\mathrm{HV}}$ in the direction of the flow. The sum of these vectors $\vec{F}_{\mathrm{HV}}$ can be decomposed into a world-fixed x-component and z-component:

$$\vec{L}_{\mathrm{HV}} + \vec{D}_{\mathrm{HV}} = \vec{F}_{\mathrm{HV}} = \vec{F}_{\mathrm{x,HV}} + \vec{F}_{\mathrm{z,HV}} \quad (1)$$

If the x-component of the lift vector is larger than the x-component of the drag vector, the resulting force in x-direction provides a thrust force. From Figure 3 can be deducted that this thrust force is influenced by the hull shape (e.g. buttock angle) and the ship speed.

### 2.1 (b) Trim Correction

Besides the resulting force in x-direction, the force in z-direction also influences the resistance. This force affects the trim, and especially at higher speeds this trim reduction proves to have a large influence on the total resistance of the vessel. The trim also affects the angle of inflow of the water on the Hull Vane® in the world-fixed coordinate system. From Figure 3 can be deducted that this has an important influence on the $F_{\mathrm{x,HV}}/F_{\mathrm{z,HV}}$ ratio.

### 2.1 (c) Reduction of Waves

The third effect of the Hull Vane® is related to the reduction of the wave system of the ship. The flow along the Hull Vane® creates a low pressure region on the top surface of the Hull Vane®. If this low pressure region interferes favourably with the transom wave, the result is a significantly lower wave profile. This is visualised in Figure 4, in which the wave pattern of a 55m supply vessel with Hull Vane® (bottom half of the figure) is compared to the same vessel without Hull Vane® (top half of the figure), at 20 knots.

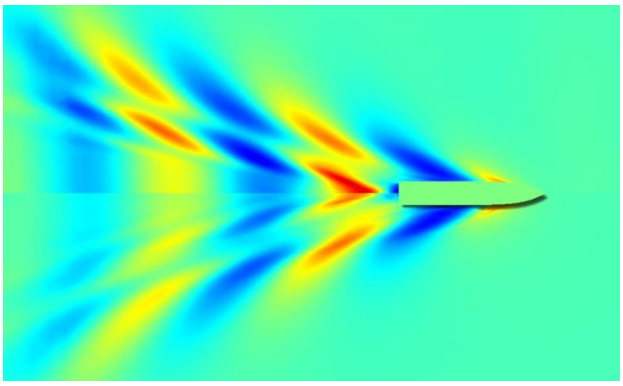

**Figure 4.** Wave pattern on the 55m supply vessel without Hull Vane® (top) and with Hull Vane® (bottom) at 20 knots, from CFD computations. Blue portrays a wave trough and red a wave crest.

The reduction of waves not only reduces the resistance, it also leads to less noise from the transom wave on the aft deck, and a lower wake. The first is mainly beneficial for yachts, the latter is important for inland shipping, where wake restrictions limit ship speeds in ports or other enclosed areas.

### 2.1 (d) Reduction of Motions in Waves

The final effect of the Hull Vane® is the dampening of the heave and pitch motions of the vessel. When the vessel is pitching bow-down the stern of the vessel is lifted and $F_{\mathrm{z,HV}}$ is reduced by the reduced angle of attack of the flow onto the Hull Vane®. This counteracts the pitching motion. Similarly, at the moment the stern is depressed into the water, $F_{\mathrm{z,HV}}$ is increased, again counteracting the pitching motions. Similar reasoning exists for the heave motions. The reduction of these motions reduces the added resistance due to waves, which makes the Hull Vane® more effective in waves then in calm water. For the 169 metre container vessel *Rijnborg*, model tests at MARIN showed that the Hull Vane® reduced the required propulsion power at 21 knots by 10.2% in calm water and by 11.2% in waves.

Other benefits of the reduced motions are the increased comfort, safety, and range of operability. For the 55 metre supply vessel *Karina*, CFD analyses showed that the root mean square of the vertical accelerations on the foredeck was reduced by 10%, while that at the aft deck was reduced by 20% in typical wave conditions ($H_W$ = 1.0 m, $T_W$ = 5.7 s).

### 2.1 (e) Influence of Ship Speed on Hull Vane® Effectiveness

Testing various vessels at different speeds showed that the gains of the Hull Vane® generally improve with increasing speed. The dependency of the resistance reduction on Froude number is shown in Figure 5 for four different vessels. The found resistance reductions are results from CFD computations and tank tests. The Hull Vane® seems to be most favourable at moderate to high Froude numbers in the non-planing region, approximately between 0.2 and 0.7.

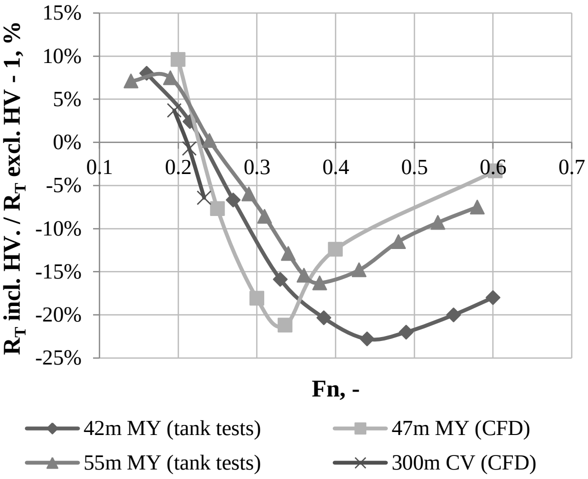

**Figure 5.** Measured resistance reduction for four different vessels, fitted with a Hull Vane® compared to the same vessels without Hull Vane®, as functions of Fn.

These results can be explained by the dominance of frictional resistance below *Fn* 0.2. The addition of a Hull Vane® to a vessel adds to the wetted surface area, and therefore increases the frictional resistance. Above *Fn* 0.2, the pressure resistance becomes a more dominant resistance component. As the Hull Vane® is aimed at decreasing the pressure resistance, most gains are found between *Fn* 0.2 and 0.7. At higher Froude numbers, the force generated by the Hull Vane® creates an unbeneficial bow-down trim.

The Hull Vane® can be specifically designed for the cruising speed or maximum speed of a vessel, or for its operating profile. In most cases the operating profile is such that a loss in the low Froude number region is acceptable since these speeds are only sailed while manoeuvring. In absolute terms, a resistance increase at the low Froude numbers is negligible compared to the potential fuel savings at higher speeds.

### 2.1 (f) Effectiveness

The fact that the gains from the Hull Vane® are dependent on ship speed and hull shape makes it clear that not every ship type is suitable for fitting a Hull Vane®. For bulk carriers and crude oil carriers the Hull Vane® will not bring much gain. Not only is their speed too low, but the difference in draft between loaded and ballast condition makes it challenging to achieve gains in both conditions. For small vessels (below ±30 metre) the investment costs are often too high, relative to the fuel savings to recoup these costs.

The ideal candidates for Hull Vane® application are medium and large-sized vessels operating at moderate or high non-planing speeds. Yachts are a good example of these. Others include ferries, supply vessels, cruise ships, patrol and naval vessels, Ro-Ro vessels, and container vessels.

## 2.2 TRIMARANS

A lot has been written and said about multihulls and the comparison with monohulls (e.g. [2], [3], [4]). Like the Hull Vane®, multihulls generally offer beneficial resistance characteristics at higher Froude numbers. Even though the wetted surface area is generally increased causing an increased frictional resistance, the slenderness of the hulls reduces the pressure resistance, which is the dominant resistance component at higher speeds.

Additional benefits of multihulls are the increased deck area, which is useful in a wide range of applications, and superior comfort on board. Possible disadvantages are higher building costs due to more structural arrangements needed and added complexity, and a higher resistance at lower speeds, where the frictional resistance is the dominant part of the total resistance.

Markets that have already embraced trimaran design are those of fast ferries (e.g. the *Benchijigua Express*), or naval applications (e.g. the *USS Independence*). Rare examples of trimaran motor yachts are the 61m *White Rabbit Echo*, the 43m *Adastra*, the *Super Sports* series by Palmer Johnson, and an 84m trimaran to be launched by Echo Yachts in 2017.

# 3. METHOD

To determine whether a trimaran with a Hull Vane® attached between its outriggers can prove to be a suitable platform for yachts, a trimaran yacht concept is designed and compared to a reference monohull vessel on the basis of four criteria: Costs, energy efficiency, luxury and seakeeping comfort.

In this section, first the two yachts are introduced. Subsequently, the criteria are introduced more extensively. Lastly, the multiple objective comparison function is elaborated upon, which allows for a comparison between the two vessels in a quantitative manner.

## 3.1 THE YACHTS

### 3.1 (a) The Reference Monohull

The 50m, sub-500GT, high-quality reference monohull motoryacht has been designed by Van Oossanen Naval Architects in compliance with the Large Yacht Code (LY3). It is recently launched, and has a conventional layout. Its hull shape is of a Fast Displacement Hull Form (FDHF) type, which is found to be the most efficient round bilge hull shape tested at the Wolfson Unit until now [5].

The Hull Vane®-equipped trimaran is based on the same design brief as that of the reference monohull and complies with the same set of requirements. Among these requirements are:

- Top speed of at least 30 knots
- Range of 3250 nm at 15 knots
- Accommodation for 10 guests and 11 crew members
- MCA Large Yacht Code 3 compliant
- Conventional propulsion system
- Conventional building material (aluminium)

Because the concept of a Hull Vane®-equipped trimaran is unique, it was chosen to opt for more conventional options for other considerations, such as the propulsion system and building material.

### 3.1 (b) Design Considerations for the Trimaran

Designing a trimaran yacht differs from monohull design in various parts of the process. In this section, the hydrodynamic optimization, general arrangement, air gap, structural design and weight calculation will shortly be touched upon.

The shape and relative position of the hulls, as well as the Hull Vane® geometry are a result of an extensive series of CFD analyses. For this, the FINE/Marine CFD package was used, developed specifically for hydrodynamic application in ship design by École Centrale de Nantes and NUMECA International. It was shown to be better able to capture the interference effect between the hulls than other methods [6].

A large number of variations was tested. Among these computations were models with asymmetric or rotated outriggers, and different variations of Hull Vane® shape and angle. This process resulted in a trimaran and Hull Vane® configuration as displayed in Figure 6.

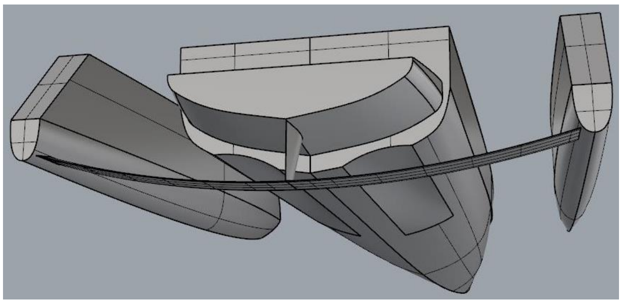

**Figure 6.** Perspective view of the trimaran configuration, including the Hull Vane®.

The trimaran was optimised for 30 knots, which resulted in a resistance reduction of 24.7% relative to the reference vessel at this speed. At the cruising speed of 15 knots, the trimaran with Hull Vane® has a 1.5% lower resistance than the monohull. At lower speeds, the resistance is higher than that of the monohull, due to the increased wetted surface area. As noted before, the reference vessel is already the most fuel efficient tested at the Wolfson Unit.

Concerning the general arrangement of the vessel, there is less room available on the accommodation deck within the hull, as the trimaran's main hull is much more slender ($B_{MH}$ = 5.9 metre) than the monohull ($B_{WL}$ = 8.4 metre). On the other hand, the main deck on the trimaran is wider ($B_{max}$ = 12.5 metre) than that of the monohull vessel ($B_{max}$ = 9.0 metre), creating more area for guests on this more preferred position (more sunlight, more feeling of openness). This benefit can for instance be exploited by placing the guest accommodations on the main deck, instead of the lower deck as is done in the reference vessel. Due to the small size of the outriggers ($L_{OR}$ = 20 metre, $B_{OR}$ = 1 metre), this volume cannot be used as functional area for guests. The enclosed volume in the outriggers and cross-structure that cannot be used causes the total functional enclosed space to be less for the trimaran than for the monohull, as the enclosed space is limited by the sub-500 GT requirement for this design. This results a less inside area available for guests, but this is compensated by more outside area on the large aft decks.

The distance (air gap) between the design water level and the cross-structure (wet deck) needs to be sufficient to limit wet deck slamming. A seakeeping analysis is performed in the wave spectrum corresponding to that most observed in the Mediterranean [7]. The analysis shows that at the design speed, an air gap of 1.7 metre is sufficient to reduce the amount of slams below the conservative threshold value of 15 slams per hour.

The determination of the structural arrangement of the trimaran also brings additional considerations in comparison to that of monohulls. Extra attention must be paid to the global longitudinal strength: the slenderness of the main hull adds challenges in obtaining a sufficient section modulus. The cross-structures between the main hull and the outriggers need to be able to withstand the forces from the outrigger in waves. Because the air gap is set at 1.7 metre, and the main deck is positioned at 2.15 metre from the design water level, the cross-structure is limited to a height of 450 millimetres. A direct structural analysis is done for the midship section and the cross-structure, and shows that enough strength and stiffness can be obtained within these height limits.

The propulsion arrangement of the trimaran is conventional: two 1.75-metre diameter propellers are driven by MTU 12V4000M93L engines. This enables the vessel to obtain a speed of 30.5 knots. The reference vessel uses 16V engines to be able to reach this speed.

In the weight calculation there are differences between the trimaran and the monohull yacht as well. In total, the trimaran is calculated to be 4.8% (14.0 ton) heavier. The main differences between the two vessels lie in the construction weight, which is 15.6% (14.5 ton) more for the trimaran, and the engine room, which is 14.4% (11.3 ton) lighter due to the smaller engines that could be installed in the trimaran. A larger margin for the trimaran yacht (+12.5 ton) is included as well, as the weight of the monohull is based on a more detailed, existing design.

Omega Architects was asked to provide sketches for the exterior design of the trimaran vessel. One of these sketches is displayed in Figure 7.

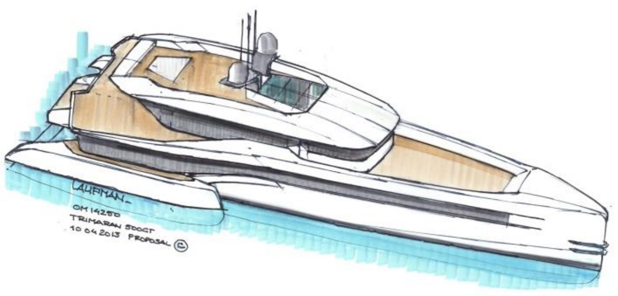

**Figure 7.** Perspective view of the trimaran yacht concept. By Frank Laupman of Omega Architects.

### 3.2 THE CRITERIAS

The trimaran yacht concept is compared to the reference monohull vessel in respect to four criteria: costs, energy efficiency, luxury and comfort. A score will be awarded for each criterion to both vessels to allow for a comparison. The criteria are elaborated upon in this section.

#### 3.2 (a) Costs

The first criterion over which the vessels are compared is the costs. For a yacht with an assumed lifetime of several decennia, it is important to consider both the investment costs *IC* and the running costs *RC* when comparing the two vessels, as they both play a major role in the total costs over the lifetime of a yacht.

Included in the investment costs are the costs for the acquisition of the yacht itself, and the berth. Examples of items that are included in the running costs are crew salaries, food and drinks, engine room maintenance, insurance, and fuel. These costs are based on a survey by Superyacht Intelligence [8].

The Future Value *FV* of the total costs also takes inflation *g* and loss of income from interest *i* (opportunity costs) into account, and is calculated as follows:

$$FV_{\mathrm{v}} = IC_{\mathrm{v}}(1+i)^{\mathrm{n}} + RC_{\mathrm{t=0,v}}\frac{(1+i)^{\mathrm{n}}-(1+g)^{\mathrm{n}}}{i-g} \qquad (2)$$

A lifetime of 20 years, an inflation rate of 1.5%, and an interest rate of 5% are assumed. Because the costs negatively influence performance, the costs' inverse is used to determine the score for this criterion.

#### 3.2 (b) Energy Efficiency

The last couple of decades the focus on sustainability, carbon footprints and greenhouse gas emissions has increased in all industries. This goes for the yacht building industry as well. Not only the emission itself is important for future owners, the image they get from a yacht is perhaps of even more importance: if others perceive the yacht as 'green' and energy efficient, the owner profits from a more positive appearance too. Therefore, the energy efficiency is used as a criterion in this comparison.

The energy efficiency is compared with the use of the Energy Efficiency Design Index (*EEDI*) [9]. The result is a measure of how much $CO_2$ is emitted by all engines (including auxiliary engines) per nautical mile per unit of capacity. A simplified formula for *EEDI* for vessel v is as follows:

$$EEDI_{\mathrm{v}} = \frac{\sum P_{\mathrm{ME,v}} * C_{\mathrm{F,ME,v}} * SFC_{\mathrm{ME,v}} + \sum P_{\mathrm{AE,v}} * C_{\mathrm{F,AE,v}} * SFC_{\mathrm{AE,v}}}{GT_{\mathrm{v}} * V_{\mathrm{ref,v}}} \qquad (3)$$

The inverse of the *EEDI* is then used for the determination of the performance.

#### 3.2 (c) Luxury

The most important function of a yacht is to provide a high-end form of recreation for the guests on board. How well each vessel performs at this function is captured in the 'luxury' objective. It is based on the total area available on each deck for the guests.

For each vessel, the deck area available for guests on each deck is measured. However, not every form of deck area is of the same value to the guests. For instance, guest rooms are less valuable when located within the hull than when placed on the main deck. To account for this, the area for guests on each deck $A_{\mathrm{d}}$ is multiplied by a weight factor $w_{\mathrm{d}}$. The prime real estate area $A_{\mathrm{PRE}}$ of vessel v is defined as:

$$A_{\mathrm{PRE,v}} = \sum_{d=1}^{n_{\mathrm{decks}}} A_{\mathrm{d,v}} * w_{\mathrm{d}} \qquad (4)$$

For the determination of $A_{\mathrm{PRE}}$ it is required to assign weight factors to the different types of deck areas. This is a subjective process, and dependent on e.g. the future owner and the future berthing locations of the vessel. While some prefer to spend time on the outside decks, others prefer to spend time inside, and the better the climate suits outside recreation, the higher the outside areas can be valued. The numbers in Table 1 are a compromise in this.

**Table 1.** Weight factors for each of the areas, categorised per deck and whether it is located inside or outside.

| Deck | Inside | Outside |
|---|---|---|
| **Sun Deck** | - | 1.00 |
| **Wheelhouse Deck** | 1.00 | 0.85 |
| **Main Deck** | 0.85 | 0.60 |
| **Accommodation Deck** | 0.60 | - |

#### 3.2 (d) Comfort

The last criterion for which the two yachts are compared is the seakeeping comfort. Especially for yachts the seakeeping comfort is an important measure, as it limits the operability for a yacht owner. The seakeeping comfort on board of the vessels is assessed with CFD computations in waves. These CFD computations are carried out using the FINE/Marine package [10]. The vessels are modelled at 20 knots, in regular head waves of 1 metre high and 50 metre long.

To determine the performance of the vessels, the root mean square (RMS) of the vertical accelerations is calculated for two locations: at LCG and at 10% of the length waterline aft of the bow. In the comparison, both results are equally valued. Because higher accelerations imply less comfort, the inverse is used for the calculation of the performance.

## 3.3 THE MULTIPLE OBJECTIVE COMPARISON FUNCTION

The two designs will be evaluated using a multiple objective comparison function, based on multi-objective optimization. With this function, alternatives can be evaluated based on multiple criteria (objectives) in a mathematical manner. For each objective, normalised scores $C_{\mathrm{i,v}}$ are awarded to the choice options, and higher weights $w_{\mathrm{u,i}}$ can be assigned to the criteria that are perceived as more important than others. These scores are then multiplied by their weights and summed to form the Performance $P$ of vessel v:

$$P_{\mathrm{v,m,u}} = \sum_{i=1}^{4} w_{\mathrm{u,i}} * f_{\mathrm{m}}\left(C_{\mathrm{i,v}}\right) \tag{5}$$

Because the result is prone to subjectivity in the weight factors, four user profiles are created. To analyse the sensitivity of the result to the normalisation method used, three different methods are used. These normalisation methods and user profiles are discussed in this section.

### 3.3 (a) Normalising the Objectives

The objectives will be normalised in three different ways, such that the sensitivity of the result in relation to the normalisation method is taken into account.

The first method is to award the better scoring vessel a score of one, and the other a score of zero:

$$f_1\left(C_{\mathrm{i,v}}\right) = \begin{cases} 1, & C_{\mathrm{i,v}} = C_{\mathrm{i,max}} \\ 0, & C_{\mathrm{i,v}} = C_{\mathrm{i,min}} \end{cases} \tag{6}$$

The second method is to scale both objective values such that the better vessel has a score of one. The other yacht will have a score between zero and one for this objective:

$$f_2\left(C_{\mathrm{i,v}}\right) = \begin{cases} 1, & C_{\mathrm{i,v}} = C_{\mathrm{i,max}} \\ \frac{C_{\mathrm{i,v}}}{C_{\mathrm{i,max}}}, & C_{\mathrm{i,v}} = C_{\mathrm{i,min}} \end{cases} \tag{7}$$

The third method involves a small database with comparable monohull vessels, to be able to scale the scores. This is done to have a reference of the range of the objective values. The vessel with the maximum value in the database $C_{\mathrm{i,D,max}}$ is awarded a score of one, while the vessel with the minimum objective value in the database $C_{\mathrm{i,D,min}}$ is awarded a score of zero. The two vessels are then provided a score between zero and one according to how their objective values compare to the minimum and maximum score:

$$f_3\left(C_{\mathrm{i,v}}\right) = \frac{C_{\mathrm{i,v}} - C_{\mathrm{i,Dmin}}}{C_{\mathrm{i,Dmax}} - C_{\mathrm{i,Dmin}}} \tag{8}$$

The performance of the two vessels will be compared in all three methods to determine to what extent the results are uncertain and dependent on the method chosen.

### 3.3 (b) Assigning Weight Factors

Because of the subjective nature of the determination of the weight factors for the multiple objective comparison function, four different user profiles are created. Each of these user profiles u has its own preferences and assigns the weight factors $w_{\mathrm{u,i}}$ to the objectives i in Formula 5 in a different manner. Doing this sensitivity analysis makes it possible to analyse the uncertainty of the multiple objective comparison function and the dependency of the choice for either the reference vessel or the trimaran yacht on the preference of the future owner. An overview of the weight factors that are assigned to the objectives for each user profile is displayed in Table 2.

**Table 2.** Weight factors for each of the objectives used in the multiple objective comparison function, displayed for each user profile u.

| **User Profile** | **Costs** | **Energy Efficiency** | **Luxury** | **Comfort** |
|---|---|---|---|---|
| Economist | 0.50 | 0.20 | 0.15 | 0.15 |
| Environmentalist | 0.20 | 0.50 | 0.15 | 0.15 |
| Family man | 0.15 | 0.15 | 0.50 | 0.20 |
| Retiree | 0.15 | 0.15 | 0.20 | 0.50 |

The performance of the vessels will be compared for each of the user profiles. Creating these user profiles provides a sensitivity analysis of the performance function, and shows an insight in how dependent the calculated performance is on one of the criteria.

## 4. RESULTS AND DISCUSSION

### 4.1 RESULTS PER CRITERION

The costs of the vessels are assessed over a lifetime of 20 years. In this calculation, inflation and opportunity costs are also taken into account. Due to the larger required berth and the additional material and construction costs, the investment costs of the trimaran are 5.1% higher than those of the reference monohull yacht. On the other hand, the yearly running costs of the trimaran are 7.7% lower, mainly due to the lower maintenance costs for the smaller engine and the lower fuel costs. The Hull Vane® does not require any additional maintenance costs. After 6.5 years, the trimaran proves to be less expensive than the monohull reference yacht.

The energy efficiency is assessed with the Energy Efficiency Design Index (*EEDI*), which is a measure of how much $CO_2$ is emitted by the vessel. The results show that the *EEDI* is 38% lower for the trimaran than for the monohull, mainly due to the smaller engines, and their lower specific fuel consumption.

The luxury is compared based on the prime real estate area. Higher decks offer more sunlight, feeling of freedom and privacy, and are therefore perceived as more preferable than lower decks. Despite the slightly (0.5%)

lower functional deck area on the trimaran, its score for luxury is 5.4% higher because the guest areas are placed on higher, more preferred decks than those of the monohull yacht.

Lastly, the seakeeping comfort of the vessels is evaluated with the root mean square (RMS) of the vertical accelerations. The two models were tested at 20 knots in regular waves of 1 metre high and 50 metre long. The average RMS of the vertical accelerations over the length of the vessels is 5.2% lower for the Hull Vane$^{®}$-equipped trimaran. The dampening effect of the Hull Vane$^{®}$ on the motions is mainly noticeable for the pitch motion: the RMS of the pitch is 52% lower, leading to a significantly lower chance of seasickness, due to the reduction of accelerations. The average RMS of the vertical accelerations at LCG and at 10% of the length waterline from the bow is 11.8% lower for the trimaran with Hull Vane$^{®}$.

The resulting performance of both vessels for each criterion are then calculated for each method. The results are displayed in Table 3.

**Table 3.** Performance for each criterion per method m.

| m | Costs | | Energy Efficiency | | Luxury | | Comfort | |
|---|---|---|---|---|---|---|---|---|
| | Tri. | Mono. | Tri. | Mono. | Tri. | Mono. | Tri. | Mono. |
| **1** | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 |
| **2** | 1.00 | 0.98 | 1.00 | 0.72 | 1.00 | 0.95 | 1.00 | 0.88 |
| **3** | 0.61 | 0.58 | 0.32 | 0.01 | 0.24 | 0.18 | 0.45 | 0.07 |

In the table above it can be observed that for all criteria the Hull Vane$^{®}$-equipped trimaran outperforms the equivalent monohull vessel. Particularly for the energy efficiency and comfort the trimaran reaches higher scores.

### 4.2 RESULTS PER USER PROFILE

After the performance has been determined for each criterion, the multiple objective comparison function is used to calculate the performance for each user profile. The results are displayed in Table 4.

**Table 4.** Weighted performance for each user profile per method m.

| m | Economist | | Environm. | | Family Man | | Retiree | |
|---|---|---|---|---|---|---|---|---|
| | Tri. | Mono. | Tri. | Mono. | Tri. | Mono. | Tri. | Mono. |
| **1** | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 |
| **2** | 1.00 | 0.91 | 1.00 | 0.83 | 1.00 | 0.90 | 1.00 | 0.88 |
| **3** | 0.47 | 0.33 | 0.38 | 0.16 | 0.35 | 0.19 | 0.41 | 0.16 |

From Table 4 can be concluded that every user profile that was created has a preference for the trimaran with Hull Vane$^{®}$, regardless of the normalisation method used. The Environmentalist and the Retiree have the strongest preference for the Hull Vane$^{®}$-equipped trimaran, because their appreciation for the vessels is mainly dependent on the energy efficiency and comfort of the vessels.

### 4.3 DISCUSSION

The trimaran with Hull Vane$^{®}$ outperforms the equivalent monohull in all four criteria. This results in all four user profile having a preference for the trimaran yacht. Particularly the Environmentalist and the Retiree have a preference for the trimaran because they focus on the energy efficiency and comfort of the vessels.

The three methods of normalisation and the four user profiles were introduced to account for subjectivity. The results show that the resulting preferences are not dependent on these methods and user profiles. However, investing in a yacht is still a very personal and therefore subjective process, and therefore some side notes to these results can be made.

Besides the chosen criteria, other criteria can be thought of as well. However, the four criteria that are chosen (costs, energy efficiency, luxury, and seakeeping comfort) are assumed to be covering the most important ones for future yachts owners. Every person has its own preferences. These personal preferences are very subjective, and only part of this subjectivity can be accounted for by taking the difference in weight factors.

These personal preferences are of influence on the weight factors used in the calculation of the scores on luxury as well. In this research, a compromise was made between possible future owners that prefer outside or inside deck area.

Another factor that might be of influence of the future owner's preference for either one of the vessels is the fact that the trimaran option is a relatively new concept for yacht application. One may perceive it as unconventional, unproven and untraditional; another may find it new, progressive and advanced.

## 5. CONCLUSION AND FUTURE RESEARCH

### 5.1 CONCLUSION

In a world where every percent of reduction of fuel consumption is important, the found resistance reduction of the trimaran platform with Hull Vane$^{®}$ of 24.7% at 30 knots in comparison to an equivalent, fuel-efficient monohull is quite remarkable. Especially if such high speeds are required, the concept of a trimaran with Hull Vane$^{®}$ that has been developed in this research could definitely be a good alternative. Because the Hull Vane$^{®}$-equipped trimaran outperforms the monohull on all four selected criteria, it seems to be a good investment (with a discounted payback period of approximately 6.5 years), energy efficient (with a lower $CO_2$ emission), luxurious (with having its guest areas in a more appealing location), and comfortable (with lower vertical accelerations).

This research has proven that Hull Vane®-equipped trimaran yachts can definitely have advantages over their monohull equivalents. Additionally, the results suggest that a trimaran platform with Hull Vane® might also be very useful for other applications as well. The beneficial resistance characteristics at higher speeds as well as the increased deck area on main deck makes the concept also very suitable for other applications, such as fast yacht support vessels, offshore supply vessels and naval or coastguard vessels.

### 5.2 OUTLOOK

For future research, some recommendations can be provided.

For the assessment of the seakeeping capabilities of the two vessels, only one type of head waves were used. Due to the large beam of the trimaran vessel, it will also be very interesting to look at beam waves. Besides this, the dependence of the stability on the outriggers submersion also make it interesting to analyse the vessel in quartering and following waves, where dynamic stability is at interest.

Currently, manoeuvrability has not been looked into. Due to the hull shape differences between the trimaran and monohull, and the application of the Hull Vane® some differences in manoeuvrability are likely to be found. Whether this is in favour of the monohull or trimaran needs to be investigated.

Although the research has given good results for yacht application, the operating profile that has been defined is typical for yacht users. It does not fully value the speed regions in which the trimaran offers its most benefits. Because the resistance reduction of the concept is highest at higher speeds, other applications can be thought of that have different, more beneficial operating profiles, such as the aforementioned fast yacht support vessels, offshore supply vessels and naval or coastguard vessels. The large deck areas would give benefits for these applications as well. Further research is needed whether the trimaran offers other benefits or disadvantages in comparison with the contemporary, often monohull vessels that are used for these applications.

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