24th International HISWA Symposium on Yacht Design and Yacht Construction
14 and 15 November 2016, Amsterdam, The Netherlands, RAI Amsterdam
ISBN / EAN: 978-94-6186-749-0

FROM OPERATIONAL PROFILE TO HYBRID PROPULSION

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SUMMARY

Every Feadship is designed, engineered and built to a specific and unique design brief, of which the intended use of the yacht is a vital aspect. Intended use gives an insight into sailing times, frequently visited areas, frequency of performed operations and sailing distances. Understanding this usage is an essential part of optimising the yachts. Therefore, an analysis is carried out into the actual use of yachts to gain a thorough understanding of yachts' operational profiles.

A valuable application of the operational profile is in contemplating the propulsion configuration. Optimizing propulsion configurations based on the sailing profile offers a great variety of benefits. Firstly, the efficiency of the yacht can be further increased, yielding in lower fuel consumption and thus lower operating costs. Another benefit of better engine loading is less sooting of engines, which improves performance and lowers maintenance costs. Further benefits, and probably the most important objective for a yacht, is maximizing comfort and experience on board. A good example of a well contemplated propulsion configuration is the hybrid configuration on MY "Savannah", for which the differing objectives are achieved by sailing in various propulsion modes. Fuel savings up to 25% are attained sailing in economical mode with an efficient medium speed diesel. Maximum comfort is achieved sailing fully diesel electric, yielding minimum noise and vibrations. Top speed is attained by combining both modes.

The hybrid propulsion configuration can be even further optimized by attaining more knowledge of operating profiles. The benefits and drawbacks of various hybrid propulsion configurations can be subsequently compared to the design objectives.

1. INTRODUCTION

Feadship builds pure custom yachts; therefore any desire of the owner can be made into reality. During the early stages of designing a superyacht, an owner's dreams are transformed into requirements which are incorporated into the design of the yacht. The process of capturing and realizing these dreams continues to have its effect, throughout the design, engineering and production phases, as the final yacht is created to match the owner's wish perfectly. The intended use of a yacht is not only composed of features which can be directly incorporated into the design, such as required number of guests, swimming pool requirements, toys and tenders, etc. The intended use also incorporates more functional characteristics such as sailing areas, frequently visited harbours, intended sailing times and distances, and the frequency of performed operations such as mooring and anchoring. Logically the following applies; the better the intended use of a yacht is understood, the better the yacht can be designed, engineered and built to meet this intended use.

Besides gaining knowledge regarding the intended use of a yacht directly from the owner, general knowledge of usage of yachts will greatly benefit the process of capturing the owner's dreams and desires into their yacht. In order to enhance the knowledge of usage of yachts, the actual use of yachts has been analysed on a large scale. Based on historical data from various yachts' onboard Automatic Identification System (AIS), which is an automatic tracking system used for identifying and locating vessels by electronically exchanging data with other nearby ships, terrestrial AIS stations and satellites, the use of these yachts has been determined. This information has been captured in the operational profile of the yacht, which has been used to derive more generic operational profiles. It is this generic operational profile which has a valuable application when contemplating a yacht's propulsion configuration later on.

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2. USAGE OF A YACHT

2.1 Accustomed use of a yacht

When considering the use of a superyacht, the following is thought to be true. A majority of the time owner and guest are not on board. During these times, the crew maintains the yacht either in port, while the yacht uses shore power, or at anchor, where a small amount of power is required to be generated. Occasionally a yacht crosses oceans and seas, requiring power of the propulsion system, Whenever the owner and guests are on board, the yacht is most of the time anchored, requiring power for the hotel load. During these times, the owner and guests are often enjoying water sports or relaxing on board. Rarely are the owners or guests on board while the yacht is in transit and the majority of these times the yacht then sails at its cruising speed. From these statements the most common uses of the yacht can be derived, which are sailing, manoeuvring, in harbour or at anchor. However, these statements are all too general and abstract and they do not quantify the use of a yacht any more than the terms 'occasionally' or 'usually' do.

2.2 Operational profile

In order to truly understand the usage of yachts, actual use of yachts have been analysed on a large scale. Historical AIS-data (consisting of position, heading, course, speed and time) of 35 Feadships, for a total period of 132 years has been analysed, i.e. close to four years of data for each yacht. From this data an operational profile for each yacht has been determined. Each operational profile consists of a speed profile and a geographical profile. In the speed profile the sailing speeds of the yacht are expressed. This speed profile mainly shows how much time and on which speed the yacht has been sailing, which can be expressed in absolute speed, relative speed (relative to its maximum speed) or in Froude number (depending on the required application). For derivation of the geographical profile the speed of the yacht is less relevant. In the geographical profile the distinction is made between whether or not the yacht sails at all. For both scenario's the areas where the yacht is situated, i.e. sails or resides (at anchor or is moored), are considered. This is done on both a global and more local scale, each resulting in its own insights. Yachts could be characterized by the areas in which they sail and reside on a global scale. On a local scale, the time a yacht sails and/or resides in each area can be deduced and analysed. Furthermore, from the AIS-data the travelled distance of a yacht has been deduced as well. This data has been added to the geographic profile and has been analysed both on the earlier defined global and local scale.

2.3 Deduction of generic operational profiles

In order to derive a generic operational profile, representing the usage of a yacht, sufficient data is required to perform a sound analysis upon. When comparing and analysing the 35 deduced operational profiles, not only a lot of knowledge and understanding of the usage of yachts has been gained, moreover, it has allowed for the deduction of generic operational profiles.
Both a generic speed profile and a generic geographical profile has been determined.

2.3 (a) Generic Speed Profile

Even though each yacht has a very specific and unique design brief, as stated earlier, which incorporates a specific cruising and maximum speed, the actual usage of the analysed yachts suggest a very similar use in terms of sailing time and sailing speeds (as absolute speed). Furthermore, the distribution of sailing speeds is very similar for each of the 35 yachts.

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Therefore it has proven possible to deduce a generic speed profile. Generally, each yacht sails approximately 10 percent of the time, thus it spends 90 percent of the time being anchored or moored. In addition, each yacht tends to sail most of the time at a speed of 12 to 14 knots, i.e. its cruising speed. Figure 1 shows a representation of the generic speed distribution (darker coloured bars), in which three speed regions (manoeuvre, cruise and max speed) are shown (lighter shaded areas).

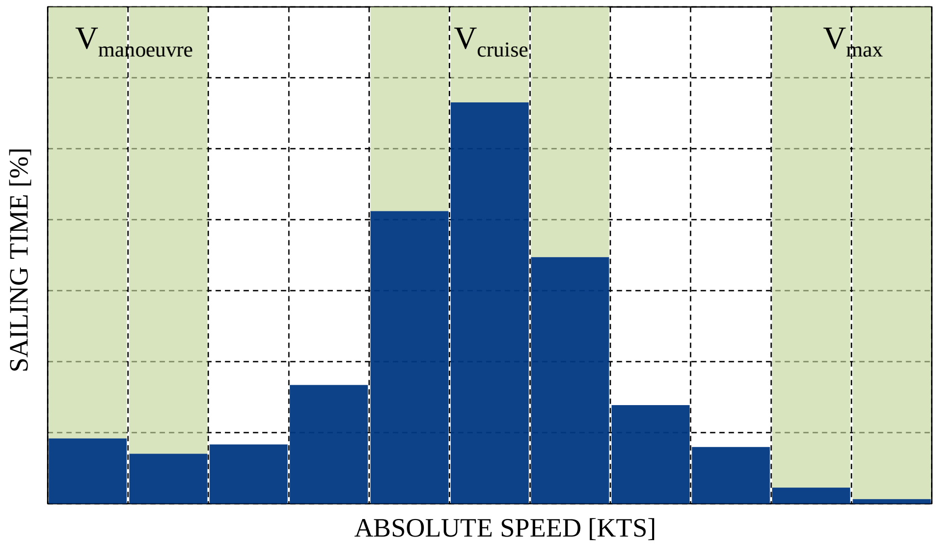

Figure 1: Generic (absolute) speed profile

The generic speed profile shows that a superyacht has a wide operating envelope regarding sailing speed. Indeed a majority of the time a yacht sails is at its cruise speed, but approximately 40 percent of sailing time the yacht sails at much lower or higher speeds. The lower speeds represent the yacht whilst manoeuvring or slow sailing, while the higher speeds represent the yacht sailing at its maximum or top speed.

2.3 (b) Generic Geographical Profile

On a global level, several distinct geographical areas where yachts reside emerge from the analysis. These areas are the Mediterranean Sea and the Caribbean Seas across the Atlantic Ocean. Crossing between these areas occurs mainly along two distinct routes. Other areas around the world where yachts sail to or reside are less frequently visited. Generally, the further away a yacht ventures from the Mediterranean or Caribbean, the less frequent these areas are visited. Figure 2 depicts the frequently visited areas around the world by all yachts in the fleet. These areas are indicated by the shaded areas on the map and the darker the colour, the more often are the areas visited or resided in. Also, dotted lines depict regularly sailed routes.

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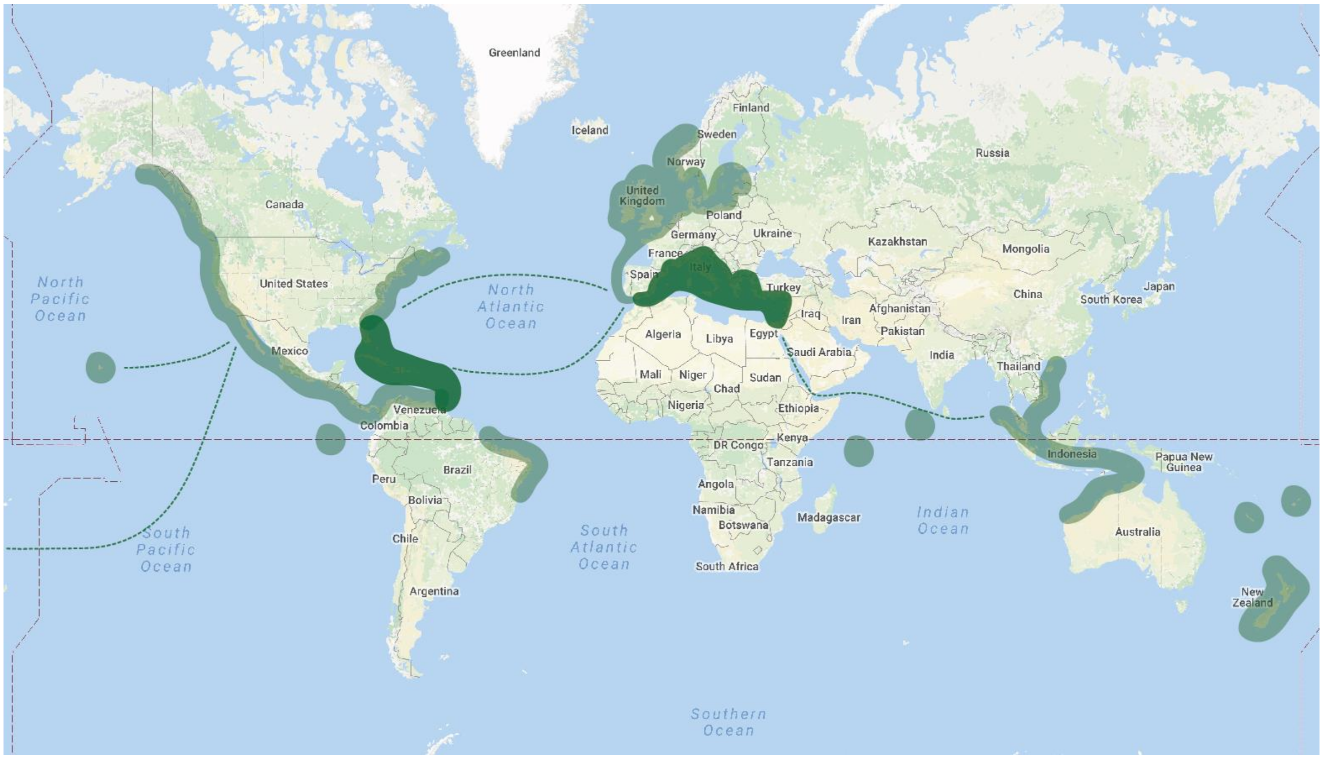

Figure 2: Global view of frequently visited areas and sailed routes

On a more local level, all yachts tend to visit the same popular locations in Europe and along the east coast of North America. Furthermore, around the same time each year, yachts are almost simultaneously crossing the North Atlantic Ocean and they all tend to follow the same routes (i.e. the indicated routes on figure 2). Yachts that sail both in Europe and the east coast of North America spend about equal time on either side of the North Atlantic Ocean. Yachts that venture worldwide spend around 40 percent of their time at locations outside the Mediterranean or Caribbean Seas, thus still spend a majority of time in the Mediterranean or Caribbean Seas. Overall it turns out that, even though each yacht has its own intended use, the general use of superyachts from a geographical viewpoint can be considered to be quite similar.

3. FROM SPEED TO PROPULSION

The operational profile demonstrates that yachts have a wide variety of sailing speeds, and thus a wide power demand, and that they rarely sail at top speed. While on the other hand the design point for the conventional propulsion train is mostly configured for top speed. Most yachts are equipped with two main engines, each driving a fixed pitch propeller via a gearbox. Consequently, the installed power of these main engines is determined on the required top speed during sea trials. Combining the relation between speed and engine loading, the operating profile gives an insight in the engine loading distribution, see figure 3.

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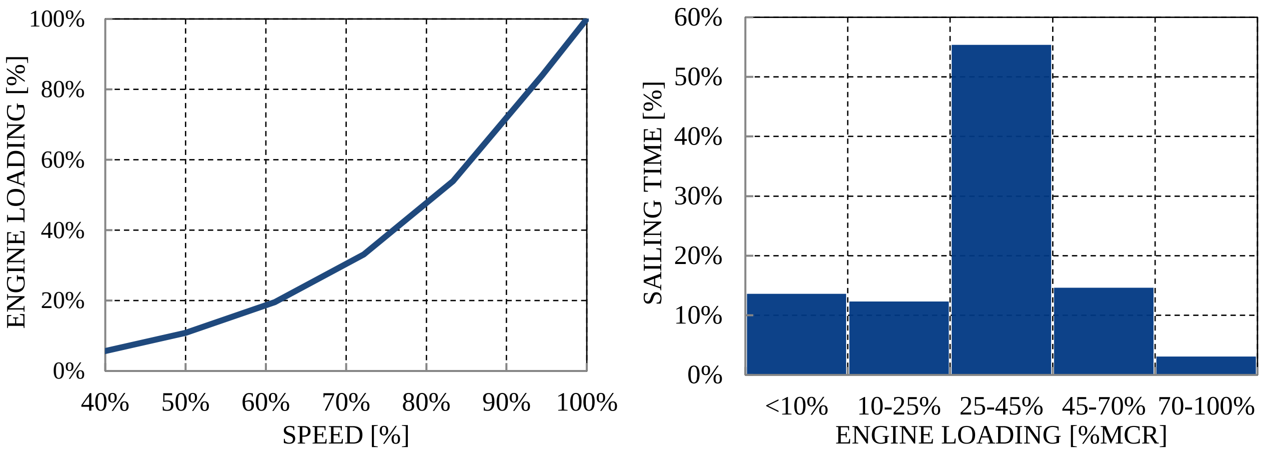

Figure 3: Engine loading versus speed and engine loading distribution

The engine loading lower than 10% can typically be associated with manoeuvring. The 25-45% MCR range represents the cruising speed at which it is very comfortable to sail with minimum noise and vibration, or to do large crossings. The main engines are seldom loaded between 70-100%. As can be derived, the engine loading is 45% MCR or less for about 80% of the time. The low loading on the engines results in lower fuel efficiency and may cause sooting and additional wear of the engine. Furthermore, figure 4 shows a typical specific fuel consumption curve of a high speed engine, the fuel efficiency significantly decreases when the engine load is below 40% MCR. An optimised power distribution will result in a better engine loading and consequently offers options for fuel efficiency.

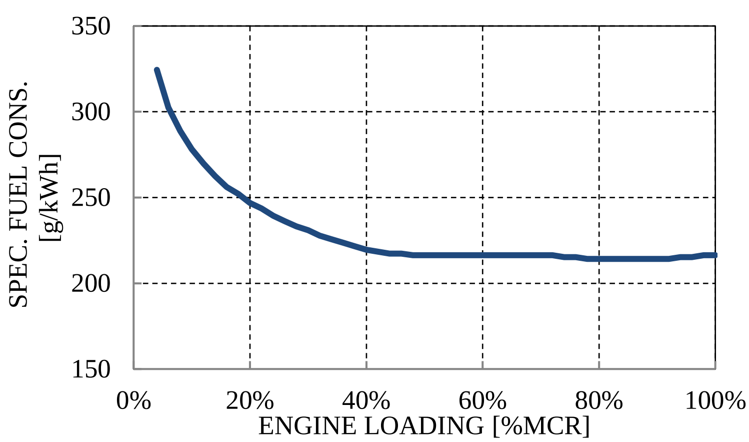

Figure 4: Specific fuel consumption versus engine loading

Based on the operating profile and the distribution of the engine loadings, the propulsion configuration could be optimised bearing in mind the following objectives: increasing comfort by further optimising noise and vibrations, improving the fuel efficiency and finally lowering maintenance costs by reducing running hours and increasing the engine loading, preventing sooting and additional wear on the engines.

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4. OPTIMIZED PROPULSION CONFIGURATIONS

4.1 Introduction

Taking into account the wide range of the propulsion power demand, the propulsion train can be further optimised by a different power distribution. The following propulsion configurations, all based on actual built Feadships, will be analysed:

- Fully diesel electric propulsion
- Hybrid propulsion with respectively a power take-in (PTI) / power take-off (PTO) connected to the gearbox
- 'Breathe' propulsion, an innovative hybrid contra rotating propulsion system, as applied on motor yacht 'Savannah'

The various propulsion concepts will be further detailed in the following paragraphs. The conventional propulsion with two main engines driving fixed propellers will be used as a reference case.

4.2 Reference case: conventional propulsion

The conventional diesel system driving two fixed pitch propellers via a gearbox is most often used on yachts. The generator supplies the electrical power for the hotel load. The system lay-out is represented in figure 5. The system contains fewer components compared to other systems, thus requires less investments. The efficiency at the design point is high due to minimum transmission losses, with typical shaft and gearbox losses, equal to about 4%. A drawback of the system is the limited flexibility in operational setting, reducing the efficiency in off-design conditions as detailed in the previous chapter.

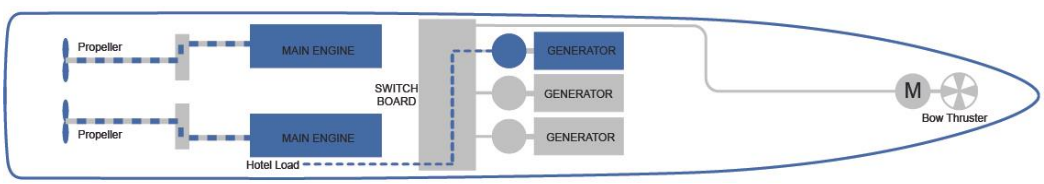

Figure 5: Reference case, conventional propulsion

4.3 Diesel electric propulsion

A diesel electric propulsion is characterized by multiple generator sets supplying electrical energy for the propulsion plant and the hotel load. The generators can be mounted double-elastically, minimizing noise and vibration transfer for optimum comfort. Fuel efficiency can be obtained by matching the size and the number of generators to the operating profile with the objective of optimum loading. This optimal loading will also minimize the sooting and additional wear on the engines and can save running hours. Usually two smaller generators are installed for supplying the electrical power for the hotel load in non-sailing condition. The system lay-out is displayed in figure 6. Disadvantages of a diesel electric propulsion are the larger required volume and the additional weight. The increase in components and complexity also increases the investments. Another drawback are the transmission losses from mechanical energy to electrical and vice versa. These losses can sum up to 10-15%, depending on various parameters, such as: efficiency of the electric motor/alternators, converters, harmonic filter, etc. Hence, a diesel electric yacht will consume more fuel at the higher speeds, compared to the reference case.

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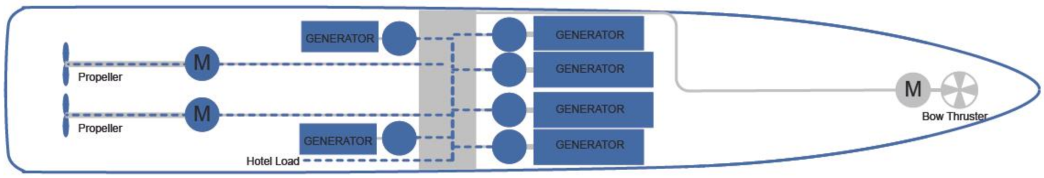

Figure 6: Diesel Electric propulsion

4.4 Hybrid propulsion

A hybrid propulsion combines the benefits of sailing diesel direct and diesel electric. At lower speeds the yacht is driven diesel electric, to avoid the low loadings on the main engines, see figure 7. The generators will supply the electrical energy for the hotel load and the propulsion. The electric machine at the gearbox acts as power take-in (PTI), and will drive the propeller. The efficiency losses in the diesel electric system will be the same as fully diesel electric configuration: 10-15%. The top speed on sailing diesel electric will be typically around lower cruising speed range. Higher speeds are possible, however will result in very large generators. Sailing diesel electric increases the comfort due to less noise and vibrations by not using the main engines. Furthermore it widens the speed range, most yachts running both engines at idle attain a speed of 6-7 knots. Sailing diesel electric offers very low speed sailing from about zero speed, e.g. for dinner cruises. Another benefit is that there are no exhaust gases on the open aft decks, since all generator exhausts will go to the mast. In the conventional system, the by-pass of the exhausts will be open when sailing on the main engines at low speeds, which causes exhaust gases to get to open aft decks.

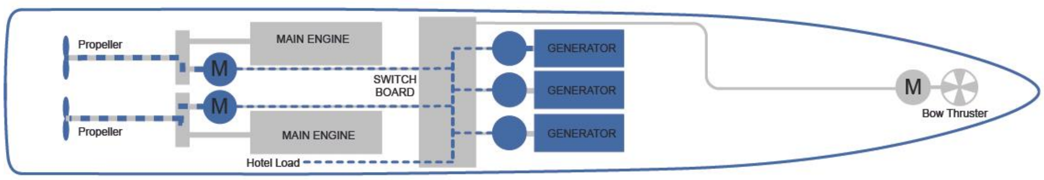

Figure 7: Hybrid propulsion PTI mode

The electric motor can also be used as power take-off (PTO), acting as an alternator. In this case the main engines will generate the power for the propulsion and hotel load, as displayed in figure 8. The shaft can have a variable speed, frequency drives will change the input frequency to match the frequency of the hotel load of the ship, e.g. 50 or 60 Hz. Using the PTO will increase the loading of the engine at lower speeds, increasing the fuel efficiency per delivered kW. Another benefit is that it will also reduce the running hours of the generators. This mode can typically be applied between cruising speed up to around 85% of top speed, depending on the operating envelope of the engine, combined with the hotel load and sea conditions.

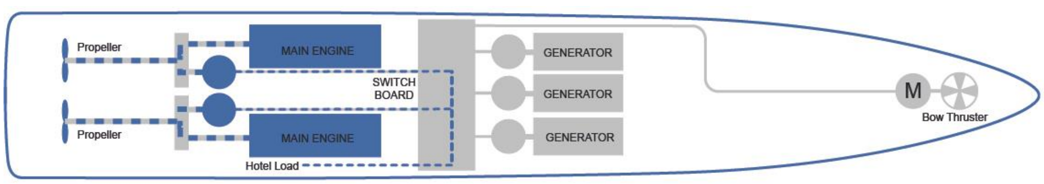

Figure 8: Hybrid propulsion PTO mode

In principle the diesel direct mode could be used for the complete speed range of the yacht, see figure 9. However the benefits of the hybrid propulsion in the off-design conditions are not used. The diesel direct mode will be used when the PTO mode is no longer possible, when a high speed is required, or in very adverse sea conditions.

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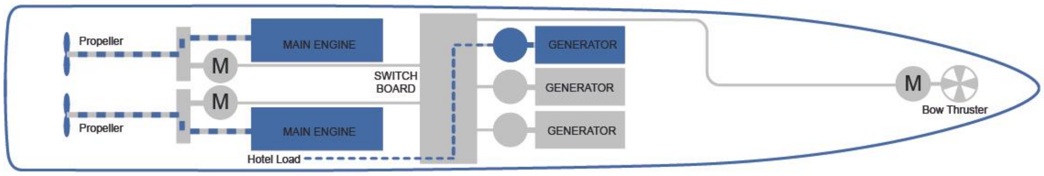

Figure 9: Hybrid propulsion high speed mode

The investments, required volume and increase in weight are significantly lower compared to the diesel electric propulsion: only a small part of the installed power is delivered by the diesel electric system, typically 10-25% of the main engine power.

4.5 Breathe propulsion

The Breathe propulsion, which is applied on 'M.Y. Savannah (figure 10), is a fully optimised hybrid propulsion system, which is characterized by simplicity and minimal components. It consists of a medium speed diesel engine driving a single propeller and an electrically driven azimuting stern thruster. This azimuting thruster can be used both for propulsion and manoeuvring.

Figure 10: Breathe propulsion on M.Y. Savannah

The Breathe propulsion system provides improved fuel economy, offers the possibility to sail completely diesel electrical on the generators and also batteries alone. It reduces engine hours and maintenance, uses less components, increases manoeuvrability, with lower noise and vibrations levels and higher redundancy. The fuel saving is based on a unique combination of individual technologies. Firstly the propeller has a larger diameter than would usually be installed. A larger diameter provides more efficiency and reduces noise and vibrations. The position of the single propeller at the centre of the yacht enables a larger propeller tunnel above the propeller and consequently allows for a larger propeller compared to a conventional system. The propeller efficiency will be further enhanced due to the wake, the centre body will reduce the inflow velocity into the propeller. Secondly the single propeller reduces the amount of hull appendages, the two exposed shaft lines and shaft V-brackets are not required, thereby reducing resistance. Thirdly the two propellers are contra rotating. While normally the first propeller will cause rotation of the water after the propeller. This rotation is actually a loss as it does not provide any thrust. In the Breathe propulsion system the aft propeller compensates the rotation of the first propeller avoiding rotational losses. Finally the Breathe propulsion system uses a medium speed diesel engine, which runs at about 900-1000 rpm and is more efficient than the high speed diesel engines, running at 1600 to 2400 rpm. These four components combined offer fuel savings of 20-25 percent.

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In principle, there are four operational modes which can be selected by the captain dependent on the required speed and circumstances. In all modes (except for the manoeuvring mode) the propellers will be contra-rotating and the azimuting thruster will be non-steerable to prevent noise and vibrations from oblique flow of the aft propeller. The power distribution typically ranges from 60-70% to the forward propeller and respectively 30-40% to the thruster.

4.5 (a) Manoeuvring mode

In manoeuvring mode only, the 360° azimuting thruster is used as a large stern thruster providing optimum manoeuvrability. The forward propeller will be feathered. This mode will be used while manoeuvring in port or for low speed sailing.

4.5 (b) Diesel Electric mode

In diesel electrical mode the main propeller is driven by the electrical motor on the gearbox. The electrical power for this motor, the thruster and the hotel load is provided by the generators or the optional batteries. This mode allows for speeds up to typical cruising speed, see figure 11. The diesel electric mode provides comfortable sailing with minimal noise and vibrations.

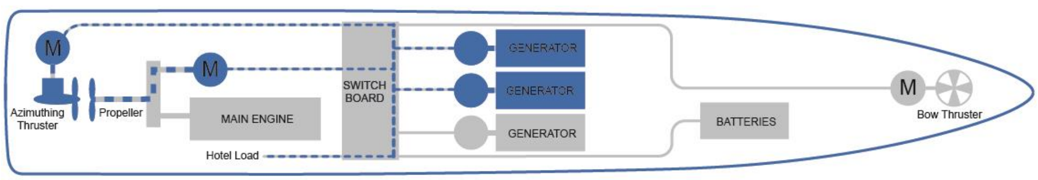

Figure 11: Breathe propulsion Diesel Electric mode

4.5 (c) Range mode

The range mode is the economical mode, offering optimum fuel efficiency with savings up to 20-25% . In this mode all power is generated by the medium speed diesel engine reducing fuel consumption and, as only one engine is running, engine hours and maintenance are reduced. The diesel engine drives the propeller via the gearbox as well as the alternator, acting as power take off, which provides electricity for the thruster and hotel load, see figure 12. Maximum speed in range mode is typical cruising speed.

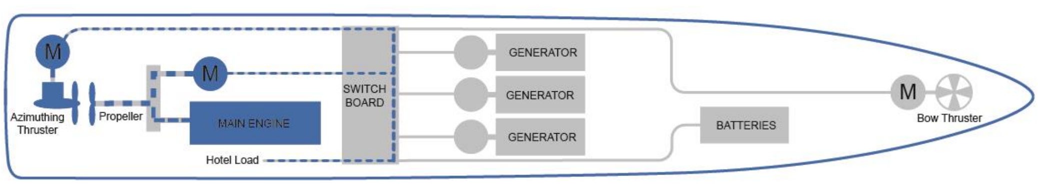

Figure 12: Breathe propulsion Range mode

4.5 (d) High speed mode

In high speed mode both the generators and main engine are used, combining all power for maximum speed. The main engine drives the propeller while the generators provide electricity for the thruster and hotel load, see figure 13.

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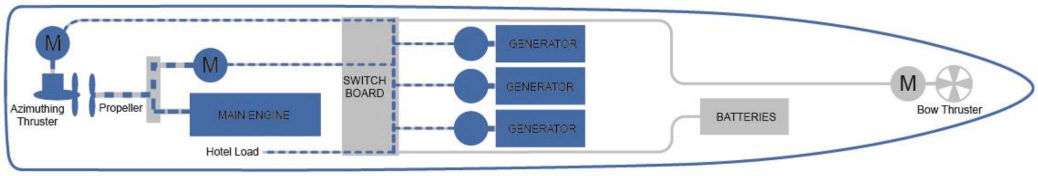

Figure 13: Breathe propulsion High speed mode

5. FROM OPERATION PROFILE TO OPTIMUM PROPULSION

5.1 Fuel consumption

In this section the fuel savings of the different configurations are analysed. The following method is used to calculate the fuel consumption, as displayed in figure 14:

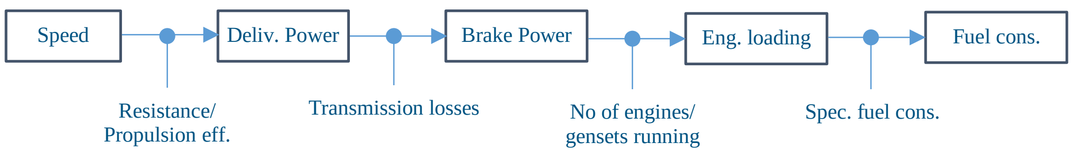

Figure 14 Calculation method for the fuel consumption

The delivered power at the propeller is calculated for each speed, based on the resistance curve and propulsive efficiency. Next, transmission losses are calculated depending on the configuration, resulting in the total required brake power (mechanical power at input flange engine/generator). The total power is optimally distributed over the available engines and/or generators, yielding the engine loadings and consequently the specific fuel consumptions. Finally, fuel consumption is calculated multiplying required power with specific fuel consumption.

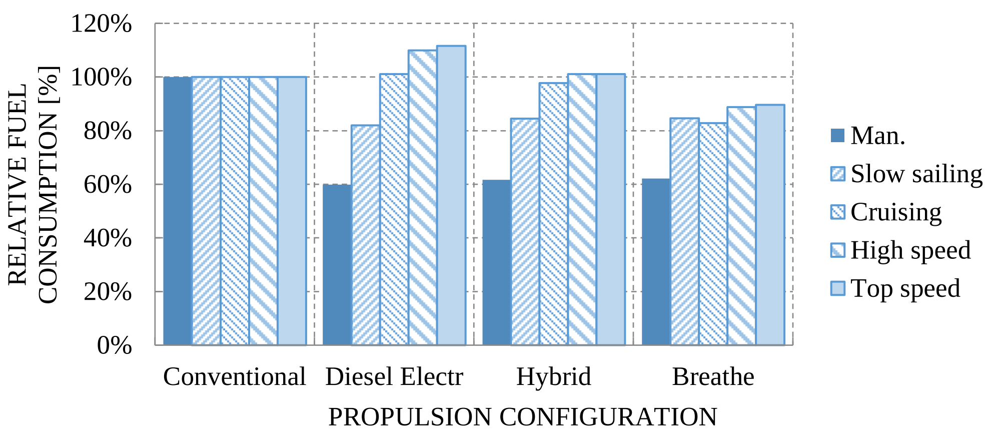

Figure 15: Fuel consumption over the speed range

Figure 14 shows how to determine the fuel consumption over the speed range of the yacht (excluding the fuel consumption required for the hotel load). Figure 15 shows the relative differences in fuel consumption where the conventional propulsion is used as a reference, and set to 100%. The fuel consumption of the Breathe propulsion is lower over the complete speed range of the yacht. The optimum fuel efficiency savings is about 20%, as can derived from figure 15.

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This is slightly lower than the optimum fuel saving of 25%, since only a part of the time the yacht sailed in economical range mode (with only the medium speed diesel running), and the remaining time the yacht sails diesel electric. The fuel reduction at top speed is equal to about 12%. The diesel electric propulsion shows a significant increase in fuel consumption in the higher speed range, due to the electrical losses. The electrical losses are higher than the gain in fuel efficiency due to optimum loading. At top speed the diesel electric system consumes about 10% more fuel due to these losses. At the lower speed range, however, both diesel electric and hybrid propulsion systems show significant reduction in fuel consumption. The diesel electric and hybrid propulsion typically have their break-even point at about cruising speed, where the fuel consumption is equal compared with conventional propulsion. The increase in fuel efficiency of diesel electrical propulsion no longer compensates for the electrical losses at higher speeds. In this analysis, the hybrid system was switched to PTO mode offering a small fuel efficiency gain of about 1%.

The differences in fuel consumption over the speed range are interesting, however, it does not provide any information on fuel savings for an annual basis. The operating profile, deduced earlier, gives insight in the duration and various speeds sailed during one year. This way they offer an insight into potential fuel savings using a hybrid system. The annually fuel consumption is displayed in figure 16.

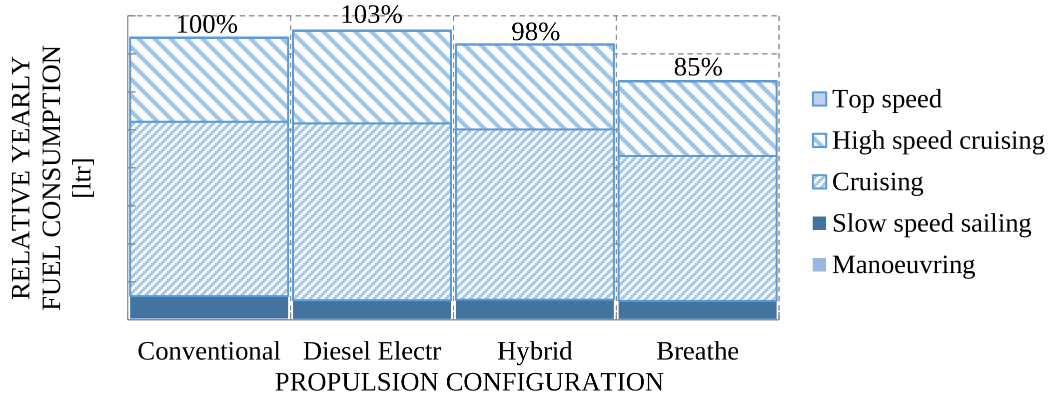

Figure 16: Yearly fuel consumption based on operating profile

All advanced propulsion configurations show significant fuel reductions during manoeuvring compared with the conventional propulsion, by around 40%. However since the power is very low, the contribution to the total fuel reduction is negligible. The Breathe propulsion offers fuel savings over the complete speed range, resulting in a significant fuel reduction of around 15% overall. The hybrid system offers a fuel saving of approximately 2%, since the break-even point is typically at cruising speed. The diesel electric motor configuration does not offer any fuel savings. In fact, the fuel consumption is about 3% higher due to the fact that at higher speeds electrical losses are higher than the increase in fuel efficiency (due to optimal loading of the generators).

5.2 Reducing maintenance costs

The maintenance costs are driven by the total running hours and the corresponding loading on the engines. Firstly the effect on the total running hours is investigated. The total running hours can be significantly reduced by optimising the propulsion train, as displayed in figure 17.

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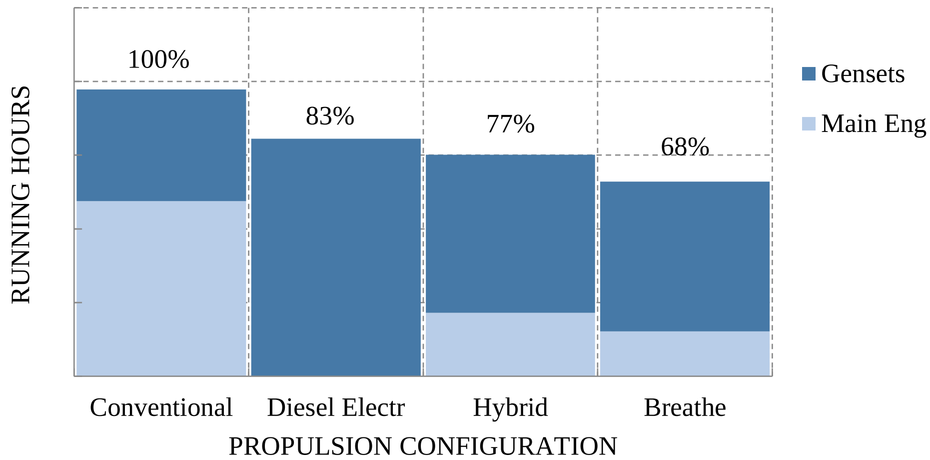

Figure 17: Running hours on engines/gensets

Due to diesel electric sailing, the running hours on the generators increase for the hybrid and Breathe propulsion system. More generators are running, compared to a conventional system with one generator running for the hotel load. Consequently, the running hours on the main engines are significantly reduced. Since the Breathe propulsion has only one main engine, it shows the greatest reduction in total running hours with saving of about 32%. The total running hours on the hybrid and the diesel electric system are about 20% less.

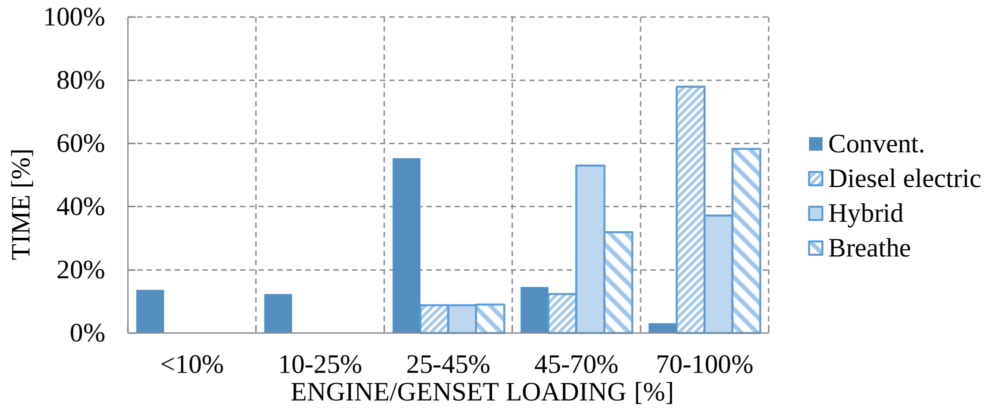

Figure 18: Distribution of engine loading

Figure 18 shows the loading distribution of the engine and generators. For the conventional propulsion train the engine loading was 45% MCR or less for almost for 80% of the time, as was demonstrated earlier. The engine loading for the optimised propulsion trains is significantly improved; the engine loading is 45% or more for 80% of the time. The loading between 25-45% MCR can typically be associated with manoeuvring. In theory, it would be possible to further optimise the loading, however a captain requires additional power to be readily available for manoeuvring and sailing in congested waters. The diesel electric propulsion shows the best engine loading with almost 80% of the time having an engine loading between 70-100% MCR. The better loading on the engines will reduce sooting of the engines.

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5.3 Comfort

The optimized propulsion configurations all offer a diesel electric sailing mode. Sailing diesel electric will give lower noise and vibration levels. Secondly, at low speed, there will be no exhaust gases on the outside decks due to an open by-pass of the main engines, since the yacht will run on generators with the exhausts running to the mast. The final advantage being that the diesel electric sailing widens the low speed range. The speed is normally 6-7 knots with main engines running idle. Sailing diesel electric is already possible at very low speeds, offering the opportunity, for example, very low speed dinner cruises along the coast.

6. CONCLUSIONS

Every Feadship is unique in its design, of which its intended use is a vital aspect. From analysing the actual use of a large fleet of yachts, it shows that the actual use of these yachts is quite universal. Generic operational profiles have been deduced, which clarify the actual use of yachts in terms of sailing speeds, sailed distances, visited areas, routes, and percentage of time for the main activities of a yacht. These profiles prove to be of great value when contemplating a suitable propulsion configuration for a yacht.

Research into the operational profiles shows that yachts have a very versatile operating speed range. This wide range of operating speeds results in a very wide propulsion power demand. Furthermore, based on the operational profiles, the propulsion train can be further optimized to reduce fuel consumption, reduce maintenance costs and increase the comfort on board. The Breathe propulsion, which is a fully optimized hybrid system, offers significant reduction in fuel consumption. Furthermore, it shows the lowest amount of total running hours, reducing maintenance costs. Finally it provides excellent manoeuvring behaviour with the steerable thruster. The hybrid propulsion system offers great potential in reducing maintenance costs due to less running hours and better loading of the engines. This is also the system with the lowest investment costs. The diesel electric propulsion will offer optimum comfort by full diesel electric sailing. Drawbacks of this system are the investments costs and a slight increase in fuel consumption.

Selecting the optimal propulsion configuration for a yacht is greatly dependant on the delicate balance between specific design objectives, such as fuel savings, reducing operating costs and increasing comfort. And matching the propulsion configuration with the operating profile of the yacht, i.e. distribution of sailing speeds and sailing hours per year. Required investment costs are also a major factor in this. Even though actual usage of yachts can be quite generic, the following applies; just as each Feadship is unique in its design, so is the selection of the optimal propulsion configuration.