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Evaluating the Challenge of Selecting a Propulsion Plant for Surface Vessels at the Conceptual Design Phase

Selçuk Cin and Uğur Buğra Çelebi

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EVALUATING THE CHALLENGE OF SELECTING A PROPULSION PLANT FOR SURFACE VESSELS AT THE CONCEPTUAL DESIGN PHASE

Selçuk CİN[1] and Uğur Buğra ÇELEBİ[2]

ABSTRACT

Frigates are essential platforms for modern navies primarily to perform missions such as, anti-air warfare (AAW), anti-surface warfare (AsuW) and anti-submarine warfare (ASW) operations. Much less haeavely armed offshore patrol vessels (OPVs) are capable to conduct mainly maritime interception, crime prevention, terrorism-piracy fighting, protecting the environment and exclusive economic zone (EEZ), fishery resources patrol and humanitarian assistance. In order to fulfill above-mentioned tasks, both two types of vessels have highly variable mission profiles throughout the entire speed range. Thus, the propulsion plant should cover this wide operating range, maintaining the basic and vital stringent constraints of naval vessel requirements, as well as, efficient running. The design and selection of propulsion plant is clearly crucial in terms of overall platform integration and performance of the vessel. Necessities and limitations of various options, along with pros and cons, are challenges that the propulsion plant designer will face in early stages of the ship design process. Conceptual design is the first phase in the design process in which all considerations are initially discussed by relevant stakeholders. In this study, alternative propulsion plants and selection criteria for modern frigates and OPVs, will be presented. Subsequently, the interrelationships of these criteria and their influence on the alternative plants will be analyzed and evaluated.

Keywords: Conceptual Design, Propulsion Plant, Mission Profile, Frigate, Offshore Patrol Vessel

1. Introduction

The decisions that have the greatest impact in the ship design process are made at the very early design phases, when there is extremely limited data and great uncertainty. This also applies to the naval combatants. Naval combatants can be defined as surface vessels that have various capabilities for different warfare missions as well as peacetime duties. Frigates are designed to perform at least one or more of anti-air warfare (AAW), anti-surface warfare (ASuW) and anti-submarine warfare (ASW) missions. Frigates are the main battle force of most of the modern navies. Offshore patrol vessels (OPVs) have less complicated sensors and weapons compared to frigates and primarily are deployed to fulfill lower-intensity patrolling missions such as maritime security, protection of the environment, sea resources and exclusive economic zone (EEZ), humanitarian aid etc. These vessels are reasonable solutions in peacetime world.

Various approaches have been introduced for ship design processes [1-3]. The general form of naval ship design process and related activities are presented in Figure 1 [2]. Concept design explores different concepts/alternatives to achieve the desired goal. The basic goal for a propulsion plant of surface combatant is to drive the vessel at the desired speed to accomplish the assigned mission [1]. Initially two main components describe the mission capability of propulsion plant in terms of marine engineering: the mission profile and vessel speed-resistance (power) relation.

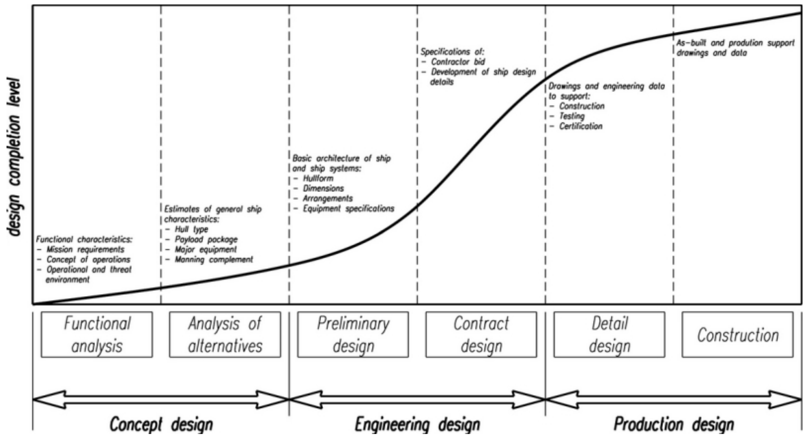

Figure 1. Naval ship design process [2].

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[1] Yıldız Technical University, Department of Naval Architecture and Marine Engineering, Faculty of Naval Architecture and Maritime, e-mail: selcuk.cin@std.yildiz.edu.tr
[2] Yıldız Technical University, Department of Naval Architecture and Marine Engineering, Faculty of Naval Architecture and Maritime, e-mail: ucelebi@yildiz.edu.tr

Mission profile demonstrates the time spent at each speed step [4]. Frigate should perform top speed for missions such as high transits and maneuvers for avoiding threats as well as low speed missions such as sonar search. Frigates have often top speed up to 30 knots [5, 6], but they only spend 1%-3% of their time at this high speed. Most of the time is typically spent at the speed around 18 knots [5]. OPVs spend most of their time at low-speed patrol missions and have top speed around 22 knots. Mission profile is typical two-dimensional histogram of which the horizontal axis represents the speed in knots and the vertical axis represents the hours spent at each speed step. Mission profile is determined by user.

Resistance is roughly proportional to the square of vessel speed. For transforming of resistance to brake power, the vessel characteristics have to be determined. These characteristics are propeller performance and shaft-gearbox specifications [7, 8]. Speed-brake power relation is generally represented with a curve. By combining the mission profile and the speed-resistance (brake power) diagrams, the brake power demand from propulsion machine(s) can be determined for each speed step. The reader interested in pursuing the subject further should consult references [7, 8]. A typical speed-power curve and mission profile of surface combatant is presented in Figure 2.

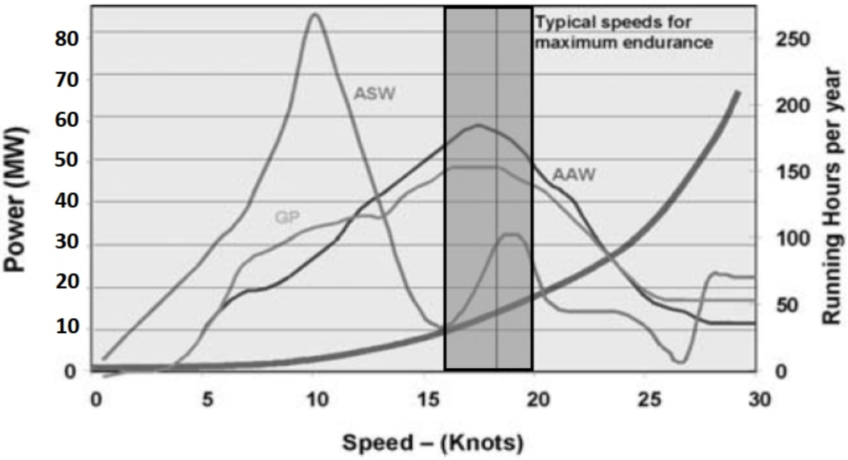


Figure 2. A typical speed-power curve and mission profile of surface combatant [9].

The propulsion plant impacts overall vessel design and should meet the rules of naval shipbuilding. All these stringent considerations and the unique mission profile makes the design process challenging for the power plant designer. In this study, these challenges and also interrelationship of the design criteria will be evaluated for frigate and OPV class surface combatants, using publicly available data.

2. Prime movers

Prime mover is a machine that provides propulsion power to the vessel. Naval vessels account for 18% of the world ship fleet in number, 23% of the total number of prime movers and 38% of the total installed power of prime movers [10]. There are numerous types of prime movers for different applications. Prime mover for surface combatants may be a diesel engine, an electric motor, a gas turbine and or a steam turbine plant.

Steam turbine utilizes steam heated in fossil fuel boiler or nuclear reactor plant. Steam turbine has low power density, low fuel economy and high initial costs, so steam turbine propulsion has lost ground in propulsion. However, steam turbine is currently in use on nuclear powered submarines and aircraft carriers [8]. Probably, the last representative of fossil-fired steam plant on frigates is FF 1052 class frigate.

Diesel engine, which is basically a reciprocating internal combustion engine, and the gas turbine, which is basically a rotating combustion turbine, burn fossil fuel as an energy source to generate power. Electric motor is another prime mover alternative and is designated as propulsion electric motor (PEM). The electric energy source of PEM may be conventional applications such as diesel or gas turbine powered generator sets, as well as novel applications such as photovoltaic (PV) generation system or fuel cell (FC).

PV generation system converts solar energy into electric energy. The power generation from PV system relies on the date, local time, time zone, longitude, latitude and navigation route [11]. Since the panels of PV system must be installed on the deck, the installation and the operation of sensors and weapons, which are essential and vital equipment for naval vessels, will be hindered. The structural stealth feature, also will be disrupted bysystem components. These restrictions are unacceptable for surface combatants.

FC is a device that converts chemical energy into electricity [12]. FC promise to be more efficient and cleaner than conventional diesel engine and gas turbine. However, some technological restrictions prevents the development of FC in surface vessels: FC has high cost, additionally storage system of hydrogen has poor availability, low density and is heavy [13].

Kites, sails and rotor systems also provide propulsive power, but their performance is dependent completely on weather conditions [14]. These systems have almost the same disadvantages as PV systems. Consequently, such systems do not seem to be suitable for use on surface combatants due to the above-mentioned reasons.

In this study, diesel engine, gas turbine, electric motor and their combinations for frigates and OPVs, will be discussed and analyzed with reference to the considerations stated in this section.

3. Combined propulsion plants

Except for a few classes of vessels, frigates and OPVs have twin shaft arrangement. This is mostly due to the aftbody hull form of these surface combatants, as there is no room for larger propellers that produce the same thrust. Additionally this arrangement provides superior maneuvering. In this study, it is considered that both two vessels are of monohull type and have two shafts with screw propellers. In this section, alternative power plants for frigates and OPVs will be proposed.

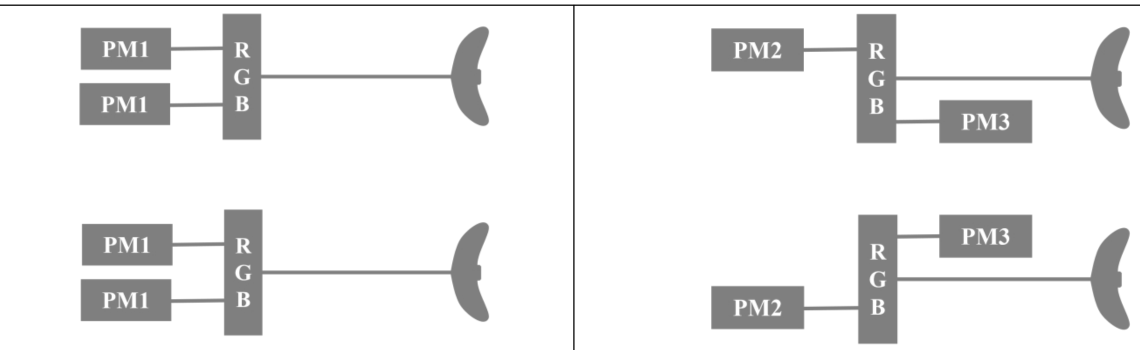
The diesel engines are of 4-stroke type and are mostly medium or high speed, depending on rated power and manufacturers. To optimize the propeller running characteristics, the diesel engine must be fitted with a reduction gearbox (RGB). This also applies to gas turbines, since gas turbines have higher rotational speed about 3600 rpm [15]. PEMs are directly flange coupled (mostly when there is no other prime mover connected to the same shaft) to propeller shafts or shaft-mounted. PEMs can be fitted with RGBs according to the propeller optimization needs mentioned above, but this depends on the electric motor technology that they are manufactured with. For more detailed discussions of these machines refer to [7, 8, 16].

The power plant on frigates is necessarily separated due to the high power requirement of the plant to move relatively large displacement up to high speed (30 knots) and also taking into account stringent limitations for overall vessel integration (e.g, combat systems, crew habitability facilities, auxiliary equipment, fuel storage). In this context, the power is “separated” and “combined” as presented in Figure 3. This also applies to OPVs.

In Option 1, two identical diesel engines (PM1) drive single shaft [17]. For low speed missions only one engine per shaft is in operation and for high speed missions, two engines per shaft can be put in operation for efficient loading and longer time between overhauls (TBOs). In Option 2, two identical diesel engines (PM2) drive their own shafts for low speed missions. For high speed missions, two identical gas turbines (PM3) drive their own shafts. The plant is identified by the acronym CODOG if gas turbines operate alone and by the acronym CODAG if gas turbines operate in combination with diesel engines [18]. In Option 3, two identical diesel engines (PM4) drive their own shafts for low speed missions. For high speed missions, gas turbine (PM5) is cross connected to both shafts via so called cross-connect gearbox (CCGB). In CODOG-CC arrangement, gas turbine is connected alone, whilst in CODAG-CC arrangement gas turbine runs in combination with diesel engines [19]. Option 4 has the same philosophy with Option 3, but it differs in the way that PEMs (PM6) are installed instead of the diesel engines (PM4). PEMs can be mounted on shafts or directly flange-mounted to RGBs. In Figure 3 d, only the shaft-mounted arrangement is presented. Directly flange-mounted arrangement has the same appearance as Figure 3 c. Option 4 has recently become the most preferred option. The French Navy employs its own version of FREMM class frigates with CODLOG arrangement, the Italian Navy employs its own version of FREMM with CODLAG arrangement [20] and the German Navy employs F125 class frigates with CODLAG arrangement [21]. The acronym FREMM stands for FRégates Européenes Multi-Missions in French [22] and FRegate Europee MultiMissione in Italian [23]. This class of frigate is developed under a joint program by Italian and French Navies [20]. In Option 5, two identical PEMs (PM8) drive their own shafts in whole operating range of the vessel. This type of arrangement is mostly defined as integrated full electric propulsion (IFEP) and prime movers of IFEP are the generator sets that supply PEMs. Typical case vessel is Type 45 destroyer from UK Royal Navy [24]. In different studies this type of arrangement is designated as integrated power system (IPS) [25], integrated electric propulsion (IEP) [26].

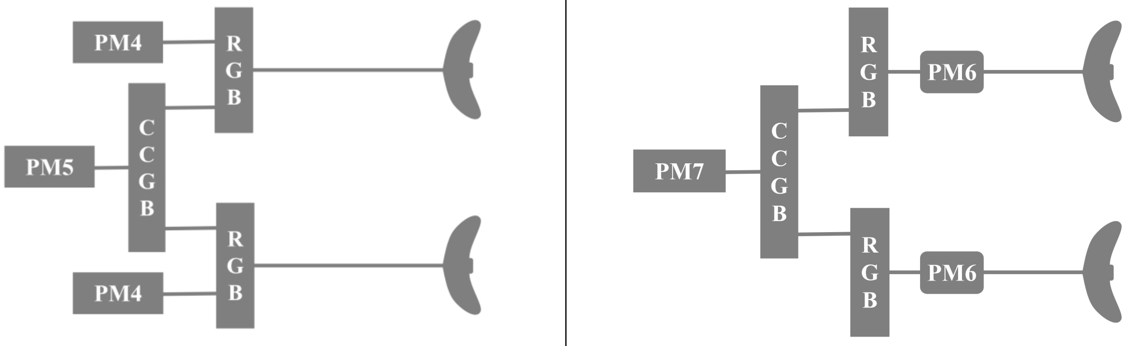
The power plant alternatives for OPVs are presented in Figure 4. In Option 1, only one engine (PM1) per shaft is in operation in whole operating range. The CODAD (twin engine) combination (Option 2) is similar to Option 1 in Figure 3. There are two identical engines (PM2) per shaft. In CODOD (father and son) combination (Option 3), for lower speeds one less powerful engine-the son (PM3) per shaft is in operation and for higher speeds, the son is shut off and a more powerful engine-the father (PM4) per shaft is put in. Option 4 is similar to Option 3, but the difference is that for lower speed a PEM (PM5) is utilized instead of “the son”. Option 5 is similar to Option 5 in Figure 3.

For options that employ PEMs and have common grid with the electric supply of other consumers (hotel load and sensor/weapon systems) onboard, the load demand of these consumers should also be considered while determining the power ratings of generator sets. Generally the plant that utilizes diesel engine(s) and or gas turbine(s) is designated as “mechanical” drive [8]. A plant utilizing a mechanical machine (diesel engine or gas turbine) and a PEM, both connected to RGB or CCGB, is designated as a “hybrid” plant [27].



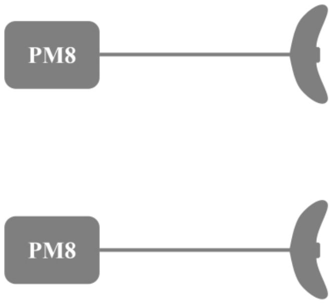
(a)
Option 1
COmbined Diesel And Diesel-CODAD

(b)
Option 2
COmbined Diesel Or Gas turbine-CODOG
COmbined Diesel And Gas turbine-CODAG



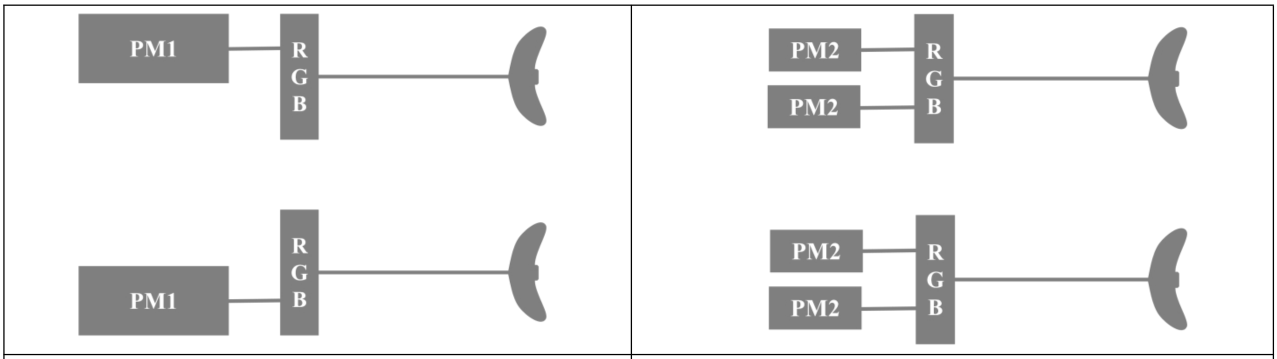
(c)
Option 3
COmbined Diesel Or Gas turbine Cross Connected-CODOG-CC
COmbined Diesel And Gas turbine-Cross Connected-CODAG-CC

(d)
Option 4
COmbined Diesel eLectric Or Gas turbine Cross Connected- CODLOG-CC
COmbined Diesel eLectric And Gas turbine-Cross Connected-CODLAG-CC



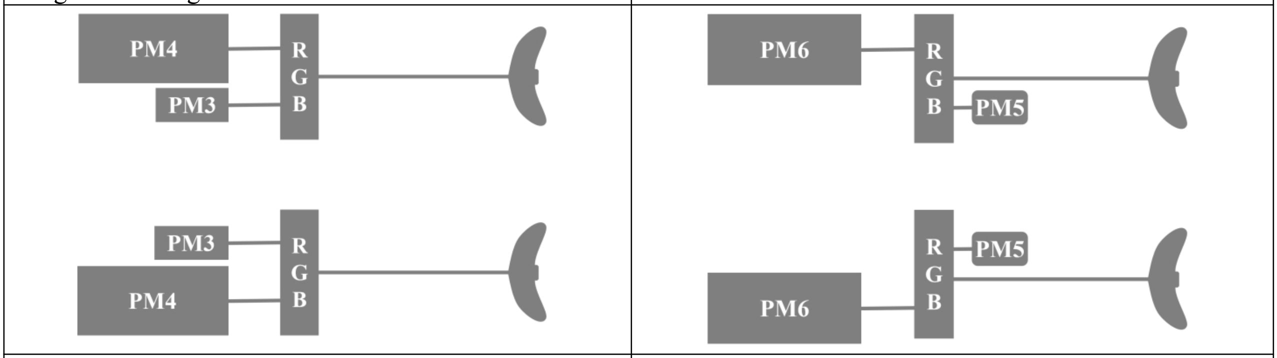
(e)
Option 5
Integrated Full Electric Propulsion (IFEP)

Figure 3. Power plant alternatives for frigates.



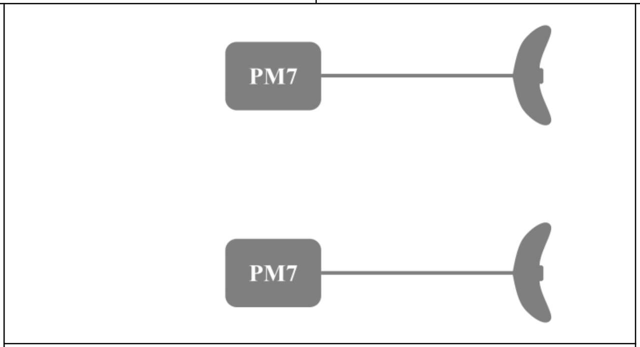
(a)
Option 1
Single diesel engine

(b)
Option 2
COmbined Diesel And Diesel-CODAD



(c)
Option 3
COmbined Diesel Or Diesel-CODOD

(d)
Option 4
COmbined Diesel ELectric Or Diesel-CODELOD



(e)
Option 5
Integrated Full Electric Propulsion (IFEP)

Figure 4. Power plant alternatives for OPVs.

Illustrations in Figures 3 and 4 are only indicative and demonstrate the principal arrangements, however the real configurations include additional equipment such as thrust blocks, clutches, oil distribution boxes etc. The connection location of the prime movers to the RGBs and or to the CCGBs can vary depending on the installation and integration needs of other system/equipment onboard.

4. Selection criteria analysis and evolution

The main criteria that effect the selection of plant of frigates and OPVs are presented in Table 1 [7,8].

Resistance characteristics, aftbody hull form and design of propeller are basic components for determination of brake power of prime movers. Aftbody hull form determines the propeller diameter which is an important parameter for propeller efficiency and RGB/CCGB ratio. **Mission profile** is determined by the user and was explained in detail in the previous sections.

Table 1. Main criteria for selection of propulsion plant.

Resistance	Carbon monoxide (CO_2) footprint
Aftbody hull form	Manning (manpower)
Design of propeller	Life-cycle cost (LCC)
Mission profile	Maintenance
Efficiency- specific fuel consumption	Availability
Volume	Reliability
Weight	Redundancy
Signature	Complexity
Commonality with the fleet	Vulnerability

Efficiency can be divided into two categories such as fuel (for diesel engine and gas turbine) and plant (all the components that build the whole power plant) efficiency. Fuel efficiency is inversely proportional to specific fuel consumption (sfc), which basically defines the fuel consumed for a unit of power output per unit time [28]. For a given fuel type and power demand, the engine with lower sfc will burn fuel more efficiently. As a rule of thumb, for low-load operations below about 50% of rated power, mostly, sfc increases considerably as load decreases. This applies to both diesel engine and gas turbine, but gas turbine has higher values for the same loads than diesel engine [29]. IPS arrangement can have higher efficiency than mechanical system due to inefficiency in low loading [30] (as described above). Sfc is directly proportional with fuel consumed, thus with fuel storage capacity of vessel.

Plant efficiency refers to the efficiency resulting from loss of mechanical and or electric power throughout the plant. Mechanical losses in shafts, RGB and CCGB, result in efficiency decrease. The plant that utilizes CCGB will have additional loss. Mechanical propulsion is particularly efficient at design speed, between 80 and 100% of top speed [31]. On the other hand, typical power losses in plants that utilize PEMs are presented in Figure 5 [32]. There is a power loss of about 10% in electric propulsion [33] and this loss can rise to 15% [31].

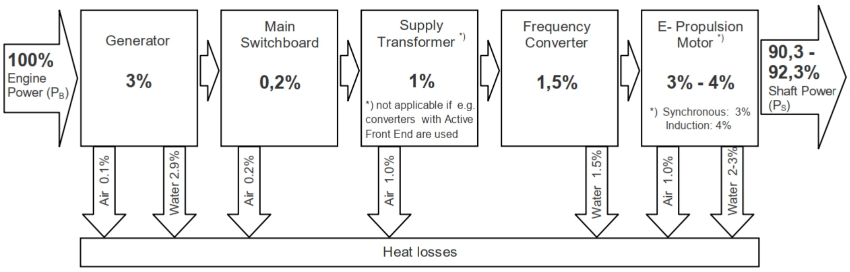


Figure 5. Power loss in electric propulsion [32].

Volume and weight can be held together. Gas turbine has higher weight/power ratio and weight/volume ratio than diesel engine. For instance, a specific 7000 kW engine weighs 21 tonnes (0,84 tonnes/m^3), whilst a specific 22000 kW gas turbine weighs 22 tonnes (0,35 tonnes/m^3) [7]. The volume and weight characteristics of PEM depend on the requirements (low speed, high torque) from the motor [34]. In [18] it was noted that an IFEP plant needs dramatically larger volume (so greater weight) for the proposed vessels compared to the alternative combined plants examined in the study.

Signature can be handled in three types: acoustic, infrared (IR) and magnetic. In [35] it was stated that gas turbine has lower airborne noise than diesel engine. For both engine types, resilient mounts and acoustic enclosures can be installed to provide better insulation. The hot gases emanating from the engine exhaust have a significant impact on overall vessel IR signature. This impact can suppressed by implementing air and or water as cooling agents [36]. For high air flow application, the electric demand of blowing fan should be considered for generator set rating determination. MEKO® A-200 class frigate has no funnel and exhaust gases are discharged horizontally on or below the waterline to reduce IR signatures [37]. Local disturbance of the ground magnetic field increases the perceptibility of detecting naval vessels, especially for triggering magnetic mines. Magnetic suppression equipment is mostly designed for entire vessel [38].

Commonality with the fleet is an issue related to storage of spares and familiarity of staff with plant. Commonality provides better logistic support and ease in operation and maintenance activities.

Carbon monoxide (CO_2) is the leading contributor to the Green House Gasses (GHG) emissions [39]. CO_2 emission is proportional to the content of carbon in fossil fuel [39] and is irrespective of the engine combustion conditions [40] and engine type [41]. The higher the sfc, the higher CO_2 emissions will be. This implies that gas turbine has higher CO_2 emission than diesel engine since gas turbine has higher sfc than diesel engine. An approach for estimating CO_2 emissions from a case OPV was proposed in [42]. The energy efficiency design index (EEDI) basically defines the theoretical design efficiency of a new ship and provides an estimation of CO_2 emissions and is related to the ships built after 2013 [43]. But this index is related with payload capacity as well as machinery onboard. Surface combatants do not have payload, so for naval vessels more suitable calculation methods were presented in [43, 44], designated as warship EEDI (WEEDI) and integral warship EEDI (IWEEDI), respectively.

Manning (manpower) of engineering department has a significant impact on propulsion and power plant. Automation level of propulsion and power plant, maintenance policies, watchkeeping roles-crew deployment and training, play an important role in sizing the manpower of naval vessels. This size also affects accommodation, hence the overall size of the vessel and the integration of the whole systems on board [45, 46].

Life-cycle cost (LCC) can be divided in three groups mainly acquisition, operation & support (O&S) and disposal. Acquisition cost is highly dependent on specific engines and equipment and probably the most driving issue is the number of sister vessels in class. Also, initial cost estimates for a purpose-built ship typically yield an error of ±40% [47]. Therefore, acquisition cost is out of scope of this study. O&S costs constitute of so many components such as manning costs, consumable costs, spare parts-maintenance costs.

Maintenance is highly dependent on maintenance policy, culture, resource, investment, wider support enterprise and requirements of specific engines and equipment manufacturers [48].

A description of the remaining criteria from Table 1, will be presented in the following paragraph according to the relevant literature, followed by a discussion of their interrelationships (notation of calculation not presented in this study). These criteria are related more to the overall propulsion and power plant rather than their components.

Availability can be defined as the probability that a system or equipment used under stated conditions is in an operable state at any given time [23]. **Reliability** can be defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions [49]. **Redundancy** is the ability to fulfill mission after a damage or failure [8]. In general usage, **complexity** term often tends to be used to characterize something with many parts in intricate arrangements [50]. **Vulnerability** is evaluated as the probability of losing mission capability following damage from threat weapons [51].

It was stated in [52] that in IPS plant at low vessel speed is more efficient, since prime movers and generator sets in mechanical drive are low loaded. Additionally, it was specified for this case in [52] that the number of rotating machines will be reduced and better fuel efficiency, reduced acquisition cost, reduced maintenance, and reduced manpower will be achieved. For the case in [5], it was remarked that having lower number of prime movers will not reduce the number of types of prime mover. This potentially will reduce the redundancy in the plant, and certainly increases the training and stores required to support the additional types of prime mover, moreover decreasing the number will decrease reliability. For electric propulsion, the electrical energy demand should also be included when designing the power plant.

Diesel-mechanical and diesel-electric (hybrid) propulsion were compered in [53] and it was noted that there are economic benefits of diesel-mechanical configuration if part load conditions occur quite rarely.

It was stated in [54] that IFEP plant "deemed" not feasible for FREMM class frigates and the reasons are explained. In the analysis presented in the study [55] for the IFEP plant of Σigma 9113 class corvettes (which coincides with the OPV's specifications of this study) with 22 knots top speed, the initial investment cost was calculated to be 62% higher than the equivalent diesel mechanical propulsion system. It was also stated that this cost cannot be balanced with the fuel cost, since the IFEP plant consumes more fuel. It was also emphasized that the IFEP plant is more complex, heavier and occupies more volume, but can decrease vulnerability and can increase reliability.

It was generalized in [56] that electric propulsion will enhanced redundancy, improve fuel efficiency, but is very complex, needs sophisticated control systems, requires additional training and awareness of crew, are not suitable for vessels that sails at constant speed. It was noted in [24] that IFEP has grater volume and weight compared to other types of more mechanical based propulsion, and has higher acquisition cost.

The option that has more prime movers has higher redundancy, reliability and availability [31]. In the event of one or more prime mover failures, the remaining prime mover(s) will keep vessel on duty. However, in this case, the plant will become more complex and vulnerable in design. For combined plants, more complicated RGBs will have to be installed, additionally for the plants with CCGB, the state of complexity will be much higher [54]. This can make vessel more vulnerable. Higher number of prime movers can provide more efficient running for them and for generator sets (for electric propulsion plants), since they will be put in operation sequentially, according to propulsion power demand and consequently will operate at their efficient envelop. For instance, the plant with CCGB can operate the single prime mover and drive both shafts up to a certain speed range. This case can extend overall maintenance downtime of the vessel, thus decreasing costs and increasing availability. The more complex system may require more crew onboard and or ashore. Option 1 in Figure 4 is less complex but does not have the advantages mentioned above. Conventional installation locates prime movers down to align with shaftline, whilst IFEP provides more flexibility for installation almost in any compartment, thus decrease vulnerability and ensure more space for other systems and.

Some of the world's navies are consuming well over 50% of their budget on personnel costs [45]. It was stated in [57] that only the salaries of the crew for a German F122 class frigate (220 crewmembers) are in the order of at least US$ 50.000.000 per year. New generation German F125 class frigates will accommodate up to 120 crewmembers [21]. In surface combatants, consumption at unit level accounts for about 25% of the total O&S cost. Petroleum fluids account for more than 50% of these, hence 12.5% of the total O&S cost. The other 50% of the consumption at unit level are caused by spares, shore maintenance, training expendables and support services [57]. Another potential factor in cost increase is vulnerability reduction assessment. If the vulnerability is taken into account later in the design, the cost can tend to increase [58].

Maintenance policy has a significant impact on downtime, crew size and spare storage onboard, and also on LCC. Conversion of maintenance policy to reliability centred maintenance (RCM) for Type 23 class frigates from UK Royal Navy, changed 50% of maintenance tasks to "No Scheduled Maintenance", thus reducing down time and increasing availability [59]. It was stated that F125 class frigates are designed that can be deployed up to two years without turning to homeport [21].

5. Conclusion

The market for new surface warships is expected to reach US$ 165 billion by 2030 [60] accordingly the design of propulsion plant to be installed on these vessels will be gaining increasing importance. Selection of propulsion plant is one of the major decisions made in the surface vessel design process. Decisions made early in design phases have a significant impact throughout the entire design process as well as throughout the life cycle of the vessel. Each component that constitutes the propulsion plant has its own advantages and disadvantages as well. While designing the plant, the whole system should be handled together. The designer should also consider the impact and interaction of the propulsion system on overall vessel integration, as surface combatants have stringent constraints. The relationship between all stakeholders, user, designer and manufacturers should be well established and maintained throughout the design process to be able to achieve the desired goal, the decisions should be optimally made before still cut. This study presents a brief analysis of the design criteria of propulsion plant for modern surface combatants, evaluates interrelationships between the criteria in design process, examines the challenge of selection of complicated factors and alternatives. Multi criteria decision support methods can be implemented to overcome this challenge and select the optimal solution. This will ensure evaluation of tangible and intangible factors and exploration of best possible selection.

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