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System design as a decisive step in engineering naval capability

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SYNOPSIS

Both costs and capability of naval ships are mainly determined in the early phases of design. The increasing power of computers and sophistication of simulation packages offers the challenge to create more different system designs in an early stage of ship design with a higher level of engineering detail, as well as the challenge to develop advanced tools to simulate actual service conditions to gain better insight in system cost and capability. This paper will introduce a PhD-research project in Model-based Ship Energy System Conceptual Design (MOSES-CD) and will explore the possibilities of the proposed approach by presenting a propulsion study for a future surface combatant of the Royal Netherlands Navy.

INTRODUCTION

The ship design process is divided into the conceptual, preliminary and contract design phase and detailed engineering phase. At the end of each design phase the ship design (alternatives) have developed to a higher level of engineering detail; this applies also to the energy systems on board. The increasing power of computers offers the challenge to create multiple designs in early stages of design for concept exploration. One approach to exploit computer power for ship configuration concept exploration has been described by van Oers [1]. This research revealed that new design methods are needed to better incorporate the ship's energy systems in early design.

With the increasing power of computers the level of sophistication of simulation packages has been increasing as well, which led to the development of computer models that can predict the dynamic behaviour of on-board energy systems. These models are currently used in later ship design stages or to study critical transient conditions of existing ship systems at relatively short time scales. It is also possible to use these models for investigating stationary situations (equilibrium) or carrying out voyage simulations, i.e. large time scales. In a recently started PhD-research both developments will be combined, thereby making it possible to create multiple concepts of different on-board energy systems, size and match their components, define their operating modes and explore them by using advanced computer models that have been and will be developed for dynamic simulation of transients, but are also able to quickly simulate stationary conditions. In other words, the goal of the PhD-research MOdel-based Ship Energy System Conceptual Design (MOSES-CD) is to make the analysis of performance characteristics of on-board energy systems possible in early stages of ship design using a variety of first principle models. The energy systems under consideration within MOSES-CD will be presented later in this paper. The reason behind this research is the notion that for complex service vessels, like naval vessels, one should start the design process by defining the ship's systems and later "wrap hulls" around these systems, i.e. start exploring different ship configurations, combined with the notion that dynamic models of such systems can effectively be utilized in early ship design. The case study presented in this paper shows the potential of the suggested approach. The case study concerns a conceptual design study of the propulsion and electric power generation system for a possible future surface combatant of the Royal Netherlands Navy (Fig 1). The considered propulsion concepts will be presented in the next

Fig 1: Artist impression of a possible future surface combatant (ref. Takken [4]).

Author's Biographies

Frank van Es MSc finished the theoretical part of his study for Naval Technical Officer in 2009, after which he started his Masters in Mechanical Engineering at the Delft University of Technology. He graduated in 2011 on a thesis on "Designing and evaluating propulsion concepts of surface combatants". Currently he is finishing the practical part of the Naval Officer studies on board HNLMS Rotterdam.

Peter de Vos MSc holds the position of assistant professor in Marine Engineering at the Delft University of Technology (DUT) since 2010, after having fulfilled the position of researcher for two years at DUT. He graduated cum laude in 2008 on a dynamic simulation of a fuel reformer necessary for PEM fuel cell application. His main research topics are design and dynamic behaviour of complex marine systems.

section followed by a component characterisation section and a multi-criteria analysis of the considered propulsion concepts. Conclusions about the case study will then be drawn, after which future developments within MOSES-CD will be described. The paper then concludes and initiates a general discussion on on-board energy system design.

PROPULSION CONCEPTS FOR FUTURE RNLN SURFACE COMBATANT

The design requirements that have been set for the next generation of surface combatants, together with an operational profile that was defined within the case study (based on current RNLN frigates), led to eight possible propulsion system concepts (Fig 2).

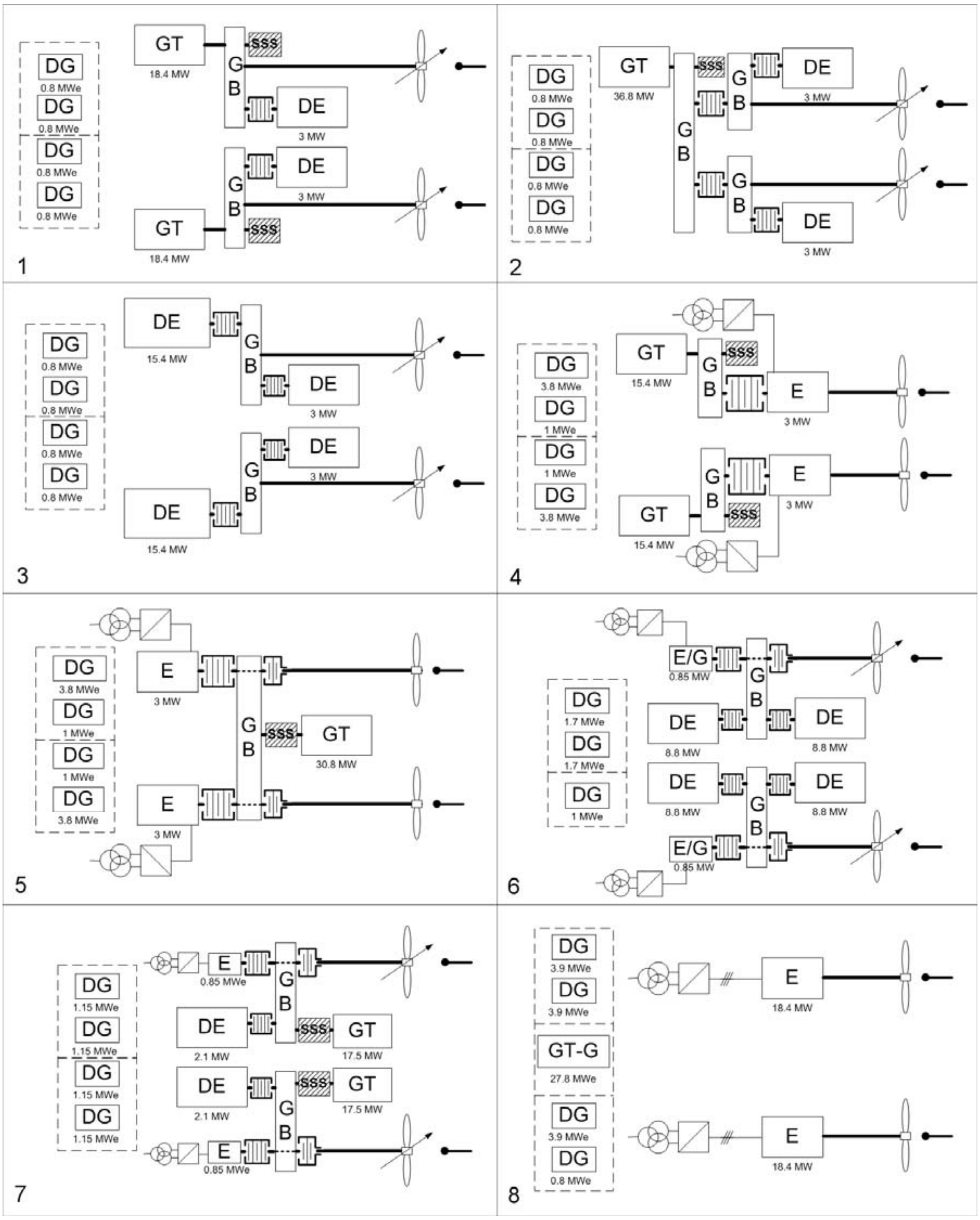

Fig 2: Propulsion and electric power generation system concepts.

The propulsion system concepts, defining both the components and the system lay-out, are:

- Concept 1: CODOG (2 GT, 2 DE, 4 DG) (Benchmark design)
- Concept 2: CODOG (1 GT, 2 DE, 4 DG)
- Concept 3: CODAD (4 DE, 4 DG)
- Concept 4: CODLAG (2 GT, 2 EM, 4 DG)
- Concept 5: CODLAG (1 GT, 2 EM, 4 DG)
- Concept 6: CODLADAD (4 DE, 2 EM, 3 DG)
- Concept 7: CODLADOG (2 GT, 2 DE, 2 EM, 4 DG)
- Concept 8: IFEP (2 EM, 4 DG, 1 GT-G)

With GT = gas turbine for propulsion, DE = diesel engine for propulsion, DG = diesel-generator set for electric power generation, EM = electrical machine for propulsion and GT-G = gas turbine-generator set for electric power generation. All systems are capable of sailing three main operational modes: high speed mode, cruise mode and silent speed operational mode. Ideally, one would like to analyse the performance of these concepts in all three operational modes in a time-domain, but this was not possible within this case study.

In order to compare the eight different concepts, a number of main assessment criteria are defined:

- Operational characteristics (capability to fulfil defined mission)
- Integration in ship (space and weight requirement)
- Availability (amount of uptime, vulnerability)
- Costs (initial purchase costs and operational costs)

Each propulsion concept gets a score on each of the assessment criteria by quantifying important characteristics of the main components of the propulsion concepts. The concept scores on the assessment criteria make a fair comparison between concepts possible and are the input for a multi-criteria analysis. Thus, before such an analysis is possible models need to be derived to describe component characteristics, which is the topic of the next section.

ESTIMATING PERFORMANCE, WEIGHT, SIZE AND COST OF SYSTEM COMPONENTS

Each propulsion concept is built up of a number of main components with specific characteristics. These characteristics need to be quantified to assess the proposed propulsion concepts on the main criteria. Component characteristics that influence the capabilities as well as the costs of the ship are:

- Power
- Weight
- Efficiency (fuel costs)
- Maintainability
- Purchase costs
- Dimensions
- Operating speeds
- Signatures
- Reliability

Some of these characteristics are relatively easy quantifiable, for others this is harder and the characterisation of the components for these aspects will be based on more subjective grounds. Also some of these characteristics, especially purchase costs, are confidential by nature and cannot be shared quantitatively in this paper.

For the quantifiable characteristics, regression analysis is used to find relations that describe the characteristic over a large range. Sources for data that are used to find the derived regression functions are manufacturer's information (online as well as offline), available data from existing RNLN vessels, literature like [2] and [3] and GES [5].

As an example, Fig 3 shows the derived relations between specific dimensions of a simple cycle gas turbine and its rated power. The specific length (l), width (w) and height (h), in meters per megawatt, of a simple cycle gas turbine are (equations (1), (2) and (3)):

$$l = 3.25 \cdot P_B^{-0.72} \quad (1)$$

$$w = 2.33 \cdot P_B^{-0.90} \quad (2)$$

$$h = 1.50 \cdot P_B^{-0.82} \quad (3)$$

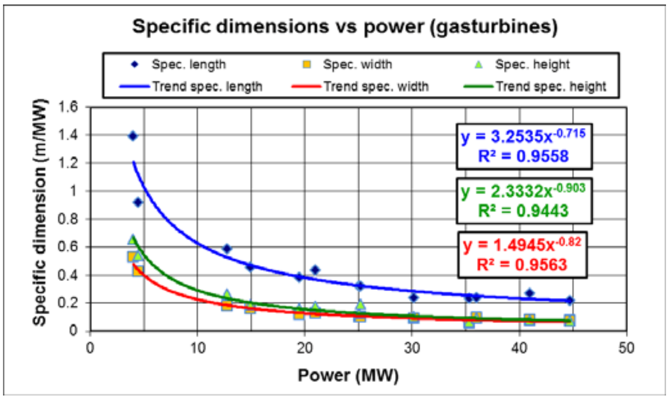

Fig 3: Specific dimensions of gas turbines as function of power.

Where P_B is nominal power in megawatt.

Another example is the weight of diesel engines, which is strongly related to the nominal speed of the engine (Fig 4). The specific weight (m) of a diesel engine, in ton per megawatt, is described in equation (4):

$$m / P_B = 1281 \cdot N^{-0.76} \quad (4)$$

Where N is nominal speed in rotations per minute.

Similar relations, describing the above mentioned important component characteristics as function of power, speed or torque, have been derived for:

- Diesel engines
- Gas turbines
- Electrical motors/generators
- Gearboxes
- Electrical auxiliaries (switchboards, converters)
- Propellers
- Water jets

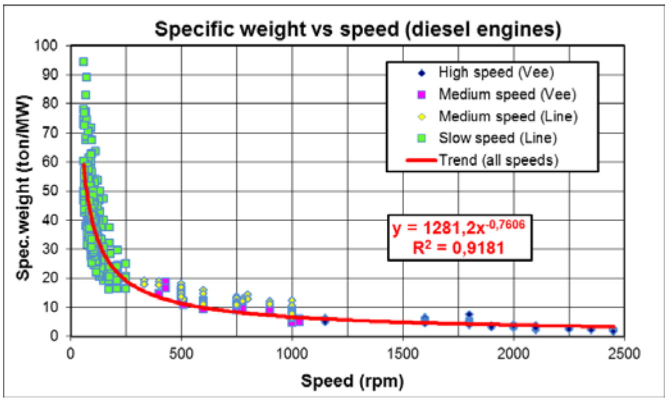

Fig 4: Specific weight of diesel engines as function of rotational speed.

A complete overview of component characterisation that has been realised is given in Fig 5. It is possible that more fundamental models for describing dimensions of components can be derived, which would lead to an increase of the accuracy of the models. However, this was not realised yet within this case study.

		Available power	Dimensions			Weight	Speed	Nominal efficiency	Signatures			Shockproof	Maintainability	Reliability	Purchase costs
			Length	Width	Height				Noise	IR	EM				
		(MW)	*(m)*	*(m)*	*(m)*	*(ton)*	*(rpm)*	*(-)*	*(-)*	*(-)*	*(-)*	*(-)*	*(-)*	*(-)*	*(-)*
Prime movers															
Diesel engine	Slow speed (line)	1-84	$2.95 \cdot P_B^{0.49}$	$1.77 \cdot P_B^{0.28}$	$5.64 \cdot P_B^{0.26}$	$1281.2 \cdot N^{-0.76} \cdot P_B$	< 300	$0.69 \cdot N^{-0.07}$	−−	−	+	++	−−	++	−−−
	Medium speed (line)	0.5-35	$2.95 \cdot P_B^{0.49}$	$1.77 \cdot P_B^{0.28}$	$1.70 \cdot P_B^{0.46}$	$1281.2 \cdot N^{-0.76} \cdot P_B$	$300 - 1000$	$0.69 \cdot N^{-0.07}$	−−	−	+	++	−−−	+	−−
	Medium speed (vee)	0.5-35	$1.94 \cdot P_B^{0.66}$	$1.26 \cdot P_B^{0.42}$	$1.70 \cdot P_B^{0.46}$	$1281.2 \cdot N^{-0.76} \cdot P_B$	$300 - 1000$	$0.69 \cdot N^{-0.07}$	−−	−	+	++	−−−	+	−−
	High speed (vee)	0-9	$1.94 \cdot P_B^{0.66}$	$1.26 \cdot P_B^{0.42}$	$1.70 \cdot P_B^{0.46}$	$1281.2 \cdot N^{-0.76} \cdot P_B$	> 1000	$0.69 \cdot N^{-0.07}$	−	−	+	+	−−−	0	−
Gasturbine	Simple cycle	3.5-45	$3.25 \cdot P_B^{0.28}$	$1.5 \cdot P_B^{0.18}$	$2.33 \cdot P_B^{0.10}$	$5.97 \cdot P_B^{0.41}$	3600-7000	$0.27 \cdot P_B^{0.11}$	++	−−	+++	++	−	0	−−−
	ICR cycle	25	$3.25 \cdot P_B^{0.28}$	$1.5 \cdot P_B^{0.18}$	$3.50 \cdot P_B^{0.10}$	$11.9 \cdot P_B^{0.41}$	3600	$0.27 \cdot P_B^{0.11} + 0.05$	++	−	+++	++	−−−	−−	−−−−−
Electrical machines															
Synchronous	DC	≤ 5	$0.54704 \cdot T^{\frac{1}{3}}$	$0.45586 \cdot T^{\frac{1}{3}}$	$0.71607 \cdot T^{\frac{1}{3}}$	$1.5 \cdot$ Volume	100-5000	$\frac{1}{1.026+\frac{0.003162}{\sqrt{P}}}$	+++	+++	0	+	−−−	0	−
	AC	≤ 50	$0.61264 \cdot T^{\frac{1}{3}}$	$0.38290 \cdot T^{\frac{1}{3}}$	$0.75182 \cdot T^{\frac{1}{3}}$	$1.2 \cdot$ Volume	100-5000	$\frac{1}{1.026+\frac{0.003162}{\sqrt{P}}}$	+	+++	−−	+	−	0	−
	AC (HTS)	≤ 36.5	$0.27311 \cdot T^{\frac{1}{3}}$	$0.27311 \cdot T^{\frac{1}{3}}$	$0.32175 \cdot T^{\frac{1}{3}}$	$1.2 \cdot$ Volume	100-5000	$\frac{1}{1.026+\frac{0.003162}{\sqrt{P}}}$	+	+++	−	+	0	+	−−
	PM	≤ 5	$0.29420 \cdot T^{\frac{1}{3}}$	$0.29420 \cdot T^{\frac{1}{3}}$	$0.34659 \cdot T^{\frac{1}{3}}$	$2.65 \cdot$ Volume	100-5000	$\frac{1}{1.026+\frac{0.003162}{\sqrt{P}}}$	++	+++	−−	+	0	+	−−−
Asynchronous	AC	≤ 25	$0.61264 \cdot T^{\frac{1}{3}}$	$0.38290 \cdot T^{\frac{1}{3}}$	$0.75182 \cdot T^{\frac{1}{3}}$	$1.2 \cdot$ Volume	100-5000	$\frac{1}{1.026+\frac{0.003162}{\sqrt{P}}}$	0	+++	−−	−−	+	++	+
	AC (advanced)	≤ 20	$0.32183 \cdot T^{\frac{1}{3}}$	$0.26819 \cdot T^{\frac{1}{3}}$	$0.35809 \cdot T^{\frac{1}{3}}$	$2.65 \cdot$ Volume	100-5000	$\frac{1}{1.026+\frac{0.003162}{\sqrt{P}}}$	+	+++	−−	−−	+	++	−−
Conversion machines															
Gearbox	Single gear	n/a	$0.54\left(\frac{P}{N}\right)^{0.37}$	$0.84\left(\frac{P}{N}\right)^{0.27}$	$0.98\left(\frac{P}{N}\right)^{0.27}$	$0.3\left(\frac{P}{N}\right)$	n/a	0.98-0.99	−−−	+++	+	++	+++	+++	−
	Twin gear	n/a	$0.54\left(\frac{P}{N}\right)^{0.37}$	$\sum 0.84\left(\frac{P}{N}\right)^{0.27}$	$0.98\left(\frac{P}{N}\right)^{0.27}$	$0.6\left(\frac{P}{N}\right)$	n/a	0.95-0.97	−−−	+++	+	++	+++	++	−−
Converter	Cyclo	± 100	>PWM	>PWM	>PWM	>PWM	$< 0.35 \cdot f_{in}$	0.75	+++	+++	−	++	+++	−−	?
	Synchro	< 100	<PWM	<PWM	<PWM	<PWM	$< 0.5 \cdot f_{switch}$	0.85	+	+++	−	++	+++	++	?
	PWM (GTO/IGCT)	≤ 25	$0.7 + 0.06 \cdot S$	$\frac{7.5+0.7 \cdot S}{2.3 \cdot (0.7+0.06 \cdot S)}$	2.3	$1.5 + 0.75 \cdot S$	$< 0.5 \cdot f_{switch}$	$\frac{1}{1.01+\frac{0.01667}{\sqrt{S_{nom}}}}$	−	+++	−	++	+++	+	?
	PWM (IGBT)	≤ 10	$0.7 + 0.09 \cdot S$	$\frac{7.5+2 \cdot S}{2.3 \cdot (0.7+0.09 \cdot S)}$	2.3	$1.5 + 0.75 \cdot S$	$< 0.5 \cdot f_{switch}$	$\frac{1}{1.01+\frac{0.01667}{\sqrt{S_{nom}}}}$	−	+++	−	++	+++	+	?
Switchboards															
	High voltage	> 1kV	1.7	$0.65 \cdot n_f$	2.6	$1 \cdot n_f$	n/a	0.995	+	+++	−−	−−−	+++	++	−−
	Low voltage	< 1kV	1	$0.65\left(n_{f,in} + \frac{1}{4} n_{f,out}\right)$	2.2	$0.5 n_{f,in} + 0.45 \cdot \frac{1}{4} n_{f,out}$	n/a	0.995	+	+++	−−	−−−	+++	++	−
Propulsors															
Propeller	FPP	≤ 66	n/a	D= $\sqrt{\frac{P_p}{1} \cdot \frac{4}{\pi}}$	n/a	$0.337 \cdot D^{2.3}$	100-500	$\frac{2}{1+\sqrt{1+C_T}} - 0.175$	−	+++	-	+++	+++	+++	−
	CPP	≤ 44	n/a	D= $\sqrt{\frac{P_p}{1} \cdot \frac{4}{\pi}}$	n/a	$0.039 \cdot D^{3.9}$	100-500	$\frac{2}{1+\sqrt{1+C_T}} - 0.175$	−−−	+++	−	++	+	+	−−−

Fig 5: Overview of component characterisation.

RESULTS: THE BEST SOLUTION – A MULTI-CRITERIA ANALYSIS

In order to find the best propulsion concept a multi-criteria analysis is performed. The definition of what is "best" is subjective, consequently the results presented in this section are subjective as well. Nevertheless, due to the taken approach, the authors feel the results that are presented here can be accepted as "best" by many. The earlier introduced main assessment criteria, or parent criteria, are sub-divided in to child criteria for which each propulsion concept is assigned a score:

- Manoeuvrability (acceleration capability and slow speed manoeuvring)
- Signature profile
- Redundancy
- Number of components
- Space consumption
- Weight
- Fuel capacity
- Reliability
- Maintainability
- Shock-proofness
- Initial purchase costs
- Annual fuel costs
- Annual maintenance costs

The scores of these child criteria are assigned quantitatively, based on the derived component characteristics models, or qualitatively, compared to the benchmark concept on a relative +++/--- scale.

Concept 1, CODOG, serves as the benchmark concept because this is the propulsion system on the current RNLN frigates. A summary of the concept scores on the assessment criteria is presented in Fig 6, these form the input for a Multi-Criteria Analysis (MCA).

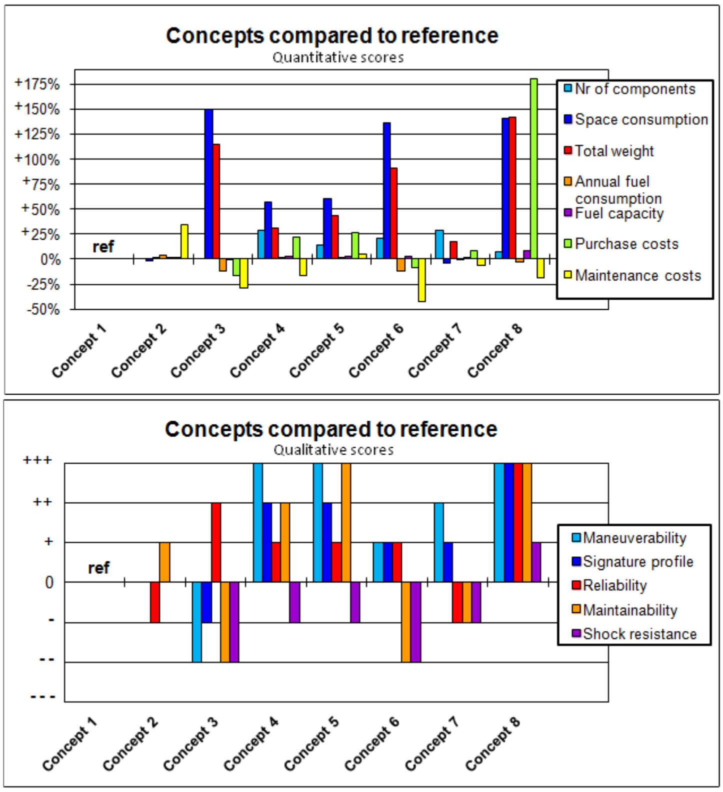

Fig 6: Scores of propulsion concepts on child criteria relative to benchmark concept (CODOG).

The scores on the parent criteria are calculated by weighing the child criteria with assigned weight factors. The parent criteria are themselves also weighted and a final aggregate score is calculated which leads to the best solution. The weight factors are assigned between 1 and 10, where 10 indicates the highest importance. The hierarchy of this MCA, including the used weight factors, is presented in Fig 7.

A TNO[1] tool called TOPSYStem [6], is used to calculate and visualize the results of the MCA. Within this tool multiple methods exist to calculate aggregate scores. The mixed concordance method is chosen because this method uses a qualitative concordance method on the qualitative scores, and a quantitative concordance method on the quantitative scores. The calculated aggregate scores for the alternative concepts are relative to each other. This matches with the way the qualitative scores were assigned: scores relative to the benchmark. The concordance methods use a [-10...10] scale to express the aggregate score. A score 0 means that the weighted positive differences between that concept and all others, just outweigh the weighted negative differences. A score 10 means that the concept has the best score on every criterion compared to the other concepts, and -10 that the concept has the worst score on every criterion. The aggregate score is a measure for the overall, relative performance of that concept.

[1] Netherlands Organisation for Applied Scientific Research TNO

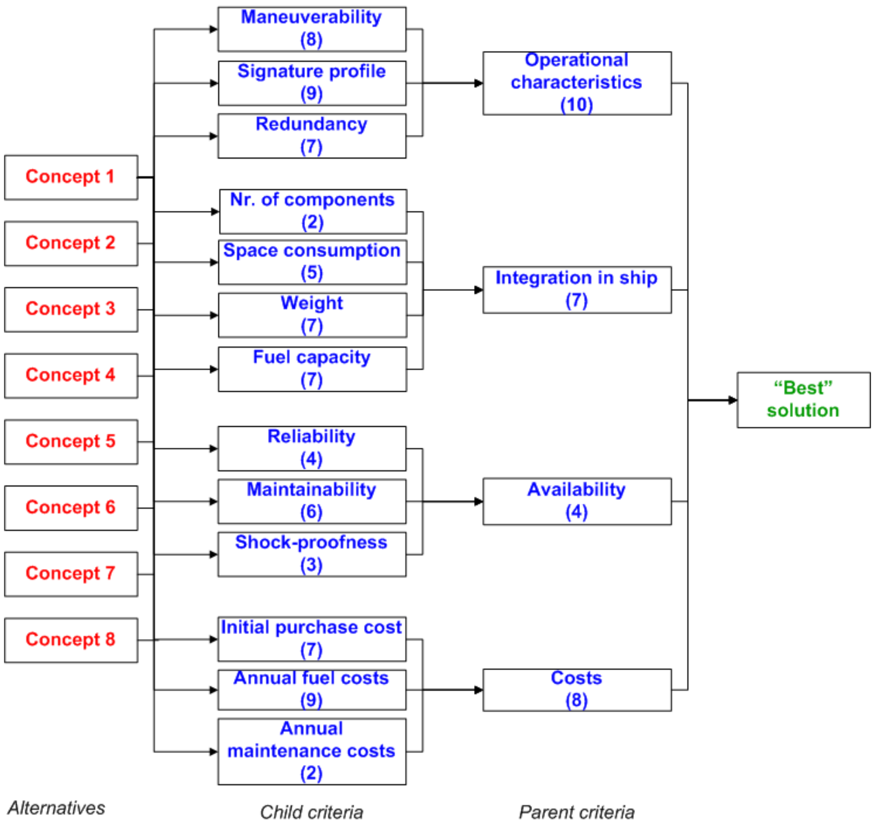

Fig 7: Multi-criteria analysis hierarchy.

The following results are calculated with the used weight factors and the mixed concordance method:

1. Concept 5 (1.89)
2. Concept 4 (1.80)
3. Concept 8 (0.90)
4. Concept 7 (0.02)
5. Concept 6 (-0.16)
6. Concept 1 (-0.75)
7. Concept 2 (-1.37)
8. Concept 3 (-2.33)

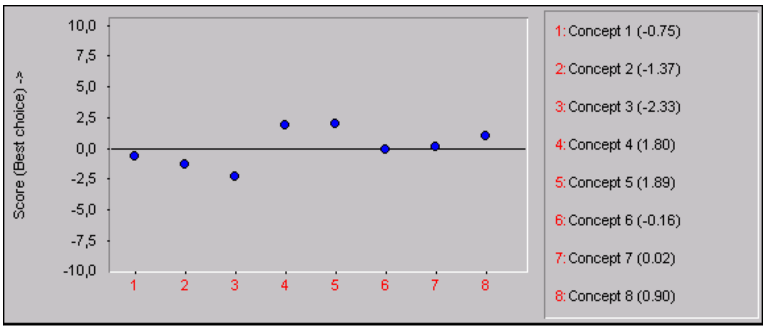

Fig 8, multi-criteria analysis results.

It is clear that concept 5, closely followed by concept 4, i.e. the CODLAG systems, end up as the best solutions.

The assigning of qualitative scores and weight factors is a subjective matter. A sensitivity analysis is performed in TOPSYStem to gain insight in the sensitivity of the final outcome of the MCA on variation of the scores and assigned weight factors. A stable best solution is more valuable than an unstable one. Based on expert opinion the accuracy in assigning the initial weight factors is assumed to be plus/minus 1. The accuracy in assigning the qualitative scores on the relative +++/--- scale is assumed to be plus/minus 2. Within these ranges a deviation from the initial value is considered realistic. For the uncertainty in the quantitative scores different accuracy ranges are used depending on the accuracy of the used models.

From the sensitivity analysis on variation of weight factors of parent criteria it was concluded that "Availability" is the most critical parent criterion. This criterion requires a change of -1.1 of the weight factor to result in another outcome (Concept 4) of the MCA. A deviation of -1.1 lays just outside the defined accuracy range, which means that the solution of the MCA is considered stable with respect to a change in parent criteria weight factors. In Fig 9 a trade-off sensitivity graph of "Availability" is presented. This graph shows the global weight on the horizontal axis instead of the local weight. On the vertical access the ranking of the concept is shown, a ranking of 1 represents the best concept. The white vertical line in the graph shows the assigned value for the weight factor. Variation of the weight factor will result in sliding of that white line. The figure clearly shows that relatively little sliding of the white line to the left is necessary for Concept 4 to become the best solution.

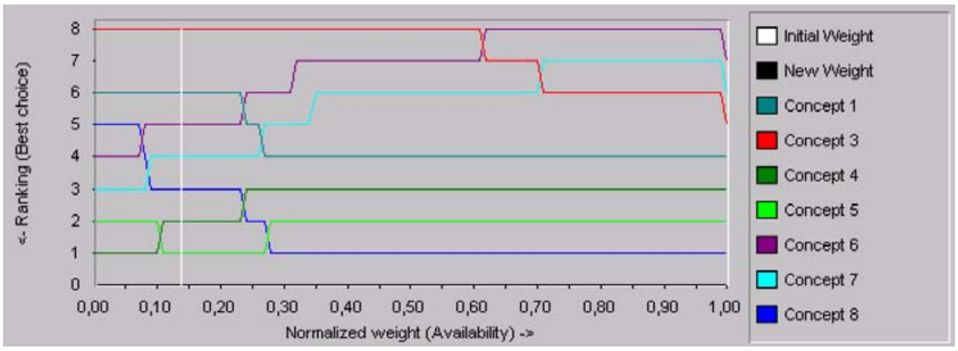

Fig 9: Trade-off sensitivity graph of "Availability" weight factor.

The sensitivity analysis of the weight factors of the child criteria resulted in the “Number of components” being the most critical child criterion, which requires a deviation of -1.4 from the initial weight factor to result in another outcome. This means that the solution of the MCA is also considered stable with respect to a change in child criteria.

The sensitivity of the solution with respect to the uncertainty in concept scores, quantitative and qualitative, within the accuracy ranges results in all cases in a change of outcome. Either an increase of the concept score of Concept 4 occurs, or a decrease of the concept score of Concept 5 occurs. This continuously results in another best solution, namely Concept 4 instead of Concept 5. Strictly speaking this makes the solution of the MCA unstable. However, when concept 4 and 5 are regarded as one concept, CODLAG, the MCA shows that such a propulsion system represents a very stable best solution.

CONCLUSIONS ABOUT CASE STUDY

The case study shows the steps that need to be taken before a general conclusion about the best system design can be reached. First the requirements for the ship and its systems need to be defined as clearly as possible. Then different system lay-outs need to be set-up, i.e. the different propulsion concepts, and component characteristics need to be defined. The component characteristics models derived in the case study are a step in the right direction, but do leave room for improvement.

Together the system lay-out and component characteristics lead to the overall performance characteristics of the different concepts. A weak point in the presented analysis is that matching of components was not done systematically for the three operating modes, which may result in deficient matching for one of the operating modes. Consequently the performance characteristics would be inferior, but this would be overlooked with the current approach. A simulation in time-domain of the system concepts would immediately show deficient matching.

The overall performance characteristics can be assessed using a multiple-criteria analysis for which a sensitivity analysis should always be performed. The multiple-criteria analysis then finally indicates a best system design within the framework of utilized models and assigned weight factors.

Note that any changes in the design requirements, which is still possible, would change the outcome of the study.

These steps together form an approach to system design which is expected to be more generally applicable than only for the design of the propulsion and electric power generation system on board a surface combatant, as done in the case study. Therefore further research is needed to check the generality of this approach.

FUTURE DEVELOPMENTS: PhD-STUDY MODEL-BASED SHIP ENERGY SYSTEM CONCEPTUAL DESIGN (MOSES-CD)

The case study concerns possible propulsion and electric power generation systems of a future RNLN surface combatant. On a more abstract level such systems can be regarded as on-board energy systems or, even more abstract, distribution systems. Distribution systems are characterised by having a network structure, i.e. a topology consisting of nodes and connections, and the fact that they distribute a commodity. Often this commodity is some form of energy flow, e.g. mechanical power, electrical power, hydraulic power, chilled water, etc., but in case of an information system it may also be data. In case of energy distribution systems the nodes are the power suppliers, like engines, generators, pumps, etc. that provide a generalized effort and flow, and power consumers that utilize the supplied effort and flow:

- P = Power [W] = [J/s]

- P = Effort · Flow [W] = [J/s]
- P = R · vs [N] · [m/s] = [J/s]
- P = M · ω [Nm] · [rad/s] = [J/s]
- P = U · I [V] · [A] = [J/s]
- P = p · Q [N/m2] · [m3/s] = [J/s]
- Q = (cp·ΔT) · dm/dt [J/kg] · [kg/s] = [J/s]

The connections between the nodes are the shafts, cables, pipes etc. Distribution systems may also contain components for conversion, like gearboxes and electric converters, or storage components, like batteries. The connected components to distribution systems may be distributed all over the ship, thereby having a certain effect on possible ship configurations. This is the reason that it was stated in the introduction that the design of ship's systems need to be defined before "hulls can be wrapped" around the systems.

Typical component characteristics are generally a function of the effort and flow variables. For example, what might be termed as capability charts (also known as operational characteristics) are usually plots of effort versus flow, see Fig 11 and Fig 10 for examples.

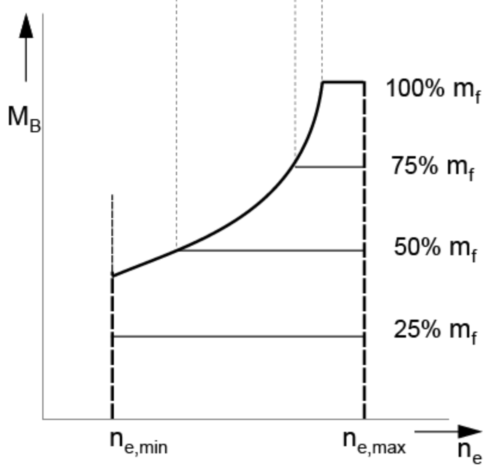

Fig 11: Turbocharged diesel engine operational characteristic (ref. Klein Woud and Stapersma [2]).

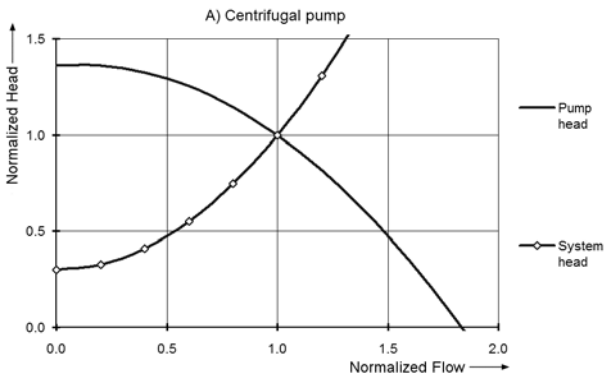

Fig 10: Centrifugal pump operational characteristic + load = pipe flow system (ref. Klein Woud and Stapersma [7]).

Within MOSES-CD models will be developed to describe important component characteristics, like the ones that were defined in the case study, as a function of effort and flow variables. The result of the research should be a more efficient, i.e. less time-consuming, and more accurate approach to energy system design than current approaches. For ship designers this would have the following advantages:

- Better estimation of dimensions and performance of distribution systems in early stages of ship design.
- Matching of components and off-design analysis of systems can be performed at earlier stage.
- Better cost estimation: since assessment of system designs in early stages is improved, less alterations of system components will occur at later stages of ship design, resulting in less deviation from initial cost estimation.
- Models can grow with ship design to full simulation models for voyage simulation in time-domain or scenario simulation (what-if).
- Testing of controls becomes possible which saves time during trials.

Distribution systems that are under consideration within MOSES-CD are:

- Propulsion system
- Electric power generation and distribution system
- HVAC system
- Pump – pipe flow systems:
  - Chilled water system,
  - Cooling water systems,
  - Fuel supply, distribution and cleaning system
  - Etcetera

- Mission-specific systems

CONCLUSION AND DISCUSSION

The case study resulted in CODLAG being the most promising concept for the propulsion and electric power generation system of a future RNLN surface combatant. This is true within the framework of derived component characteristic models, considered system concepts and assigned weight factors, but that framework leaves room for improvement. The approach taken is considered more generally applicable and gives direction to a PhD-research project, MOSES-CD, which is a follow-up to the PhD research as described in van Oers [1].
Challenging aspects of MOSES-CD concern:

- Create more accurate first-principle component characteristic models.
- Finding the appropriate scope and level-of-detail of system and component models which can describe characteristics of distribution systems on board.
- Automatically generate distribution system lay-outs.
- Finding typical "templates" for the lay-out of the considered distribution systems, similar to existing "templates" for propulsion systems (e.g. CODOG and CODLAG).
- Deriving some general rules for the relation between the design problem at hand and the above mentioned appropriate scope and level-of-detail of applied models.

The authors feel that the presented case study has proven and, once completed, MOSES-CD will prove even more that conceptual design of on-board distribution systems is in fact a decisive step in early stages of ship design, when naval capability of vessels is determined. Any improvement on design methodology for such systems will ultimately improve the quality of ship design and naval capability.

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