A Systems Engineering based Fleet Design Model for a Future-ready Fleet

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Synopsis

Before designing a ship, the requirements for the ship are required. For innovative or complex technical ships, this is not instantly clear. In many cases, the expected operations of the ship need to be investigated first. Currently, this is often done on a ship-by-ship basis. However, a ship seldom operates alone, especially for technically complex ships. The ship will often be part of a fleet executing e.g. complex operations such as windmill installation or complex missions in case of navy ships. It is therefore important to investigate the role of the ship in this fleet and establish the contributions to the expected missions or tasks. Of course, the fleet will change over time and each stepwise change of the fleet could be investigated independently but should be investigated in cohesion. To enable this, an approach and validation model was developed within the DES4Ops project over the past two years. This paper will discuss the development of an optimal fleet design model to support decision making and requirement elucidation. The impact of existing ships on the choice for a new ship (brownfield development) and of a complete fleet redesign (greenfield development) are supported. A simple example case for an arbitrary set of navy missions will be discussed to highlight the potential of this approach. In the end, we conclude that the model allows the user to check the performance of a fleet in different scenario's, but more importantly, it will lead to fleet considerations that lead to better performances overall and over time.

Keywords: Fleet design; MILP; Optimisation; Mission allocation; Systems Engineering; Ship Design.

1. Introduction

In most cases (navy) ships are designed as replacements for existing ships with updated specifications. In this process, the current role of that ship is considered, and an updated version of a ship is created. Recently the US Navy has tried to implement some flexibility in this aspect with the LCS project (Alkire et al., 2007). Multiple roles and missions were considered for the same fleet. Though none of the roles would be required continuously, hence the choice for a modular approach. Besides this, a Navy, in general, wants to make use of the latest advancements in technology. Currently, these could be drones, advanced weapons or yet unimaginable options. This requires flexibility beyond what a modular solution like the LCS can bring and thorough consideration of both the existing and future vessels in the fleet. It might well be, that a more recent vessel should be replaced by a new concept, as the role of that vessel is not foreseen in the future. Such considerations can only be validated if the entire fleet is considered, together with a consideration of future mission types for that fleet. To study this, our

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Tijmen Veldstra is a former researcher at Delft University of Technology in Delft, The Netherlands. Currently he is a Data Analyst at Portbase where he is optimizing the logistic chains in the Netherlands in order to make the Dutch ports as attractive as possible. Within the Des4Ops project, his primary task was the development of the Des4Ops model.
Bart van Oers has a PhD in Ship Design (2011) and a MSc. in Ship Hydrodynamics (2005) from Delft University of Technology. He works for the Maritime Systems Division of the Netherlands Defence Materiel Organisation since 2009. Bart co-chaired the NATO Research Task Group AVT-RTG-238, and was involved in the Maritime Countermeasures Project at the European Defence Agency. As a team leader, he currently is responsible for conducting concept studies for future warships for the Royal Netherlands Navy.
Richard Logtmeijer holds the current position of Senior Staff Member Life Cycle Modelling at the Defence Materiel Organisation (DMO) of the NL Ministry of Defence. He is responsible for analysing through modelling and simulation the life cycle effectiveness and cost of new warship concept designs. He is also chairman of the NATO specialist team on total ship systems engineering (ST-TSSE). His previous experience includes three years serving as a naval officer and over twenty years working for the Royal Netherland Navy.
Sander Knegt is a Naval Architect at Damen Schelde Naval Shipbuilding in Vlissingen, The Netherlands. Here he designs naval ships for both the Royal Netherlands Navy as well as for the export market. For his master thesis research at Delft University of Technology he made a model that simulates naval fleet behavior for the purpose of optimizing fleet design. The experience gained from this research contributed to the Des4Ops project.
Willem-Jan van Driel is Naval Architect at Huisman Equipment. His focus is on developing and designing innovative offshore floaters in the oil & gas and offshore wind industry. He participated in the Des4Ops project as advisor and user of the model.

research proposes an optimisation model to be used in the pre-concept design stage to identify interesting ship design options. This paper will first explore research on fleet design and systems engineering, followed by a system engineering based fleet design approach and model description. In section 6 a simple case will be presented using this model followed by a discussion of the merits and limits of the model and a conclusion.

2. Fleet optimisation in literature

Discussions on the design or composition of a fleet of ships are rare in the literature (Bye and Schaathun, 2015, Chen et al., 2011, Fagerholt, 1999, Perakis, 2013, Zeng and Yang, 2007). Those available seem to focus on ships with a single purpose or cargo, in a network of ports or even a single route. The main optimisation is found in the number of ships of a fixed design or at most a limited number of varying designs. The same goes when considering the optimisation of fleets of vehicles, plains or railcars for the transport of items e.g. (Jansen and Perez, 2016, Klosterhalfen et al., 2014, Vergara and Root, 2013).

In this discussion, the work of Jansen and Perez (Jansen and Perez, 2012, Jansen and Perez, 2013, Jansen and Perez, 2016) should be highlighted as it is the only work, to the knowledge of the authors, that simultaneously combines the optimal allocation of the designed fleet, with the design of the aircraft itself. It is still limited in the variation of the design (different capacity and a small number of features) but clearly shows the potential by combining this work.

Finally, there are several publications on the assessment of the operational performance of naval ships (Guagnano and Perra, 2008, Guagnano and Perra, 2009, Knegt, 2018, Perra and Guagnano, 2008, Alkire et al., 2007). These simulations are intended to allow the designer to assess the effectiveness of the design in the concept phase for various scenarios and designs. The work on the LCS (Alkire et al., 2007) optimizes locations and modules against a set of missions, but only for the LCS. Whereas Knegt (2018) seems to be the only one operating at the fleet level, rather than vessel level with a multi-mission, multi-objective scenario approach.

It should be clear from the discussion on fleet optimisation literature that there is a large gap to be found in this area. The idea of combining the optimisation of design with the allocation of the fleet in one approach, however, seems to deliver promising results. The next section will, therefore, investigate the design approaches especially those based on system engineering and the potential to optimise designs using system engineering in the concept design stage.

3. System Engineering in (Naval) Ship Design

System Engineering (SE) plays a key role in complex design efforts such as aeroplanes, space crafts and naval ships (Green, 2001, Kapurch, 2010, Navy, 2004, Williams, 2006, Logtmeijer, 2016, Support, 2007b, Support, 2007a). The single point optimization of a vessel design is being abandoned as shipowners are more aware of the fact that they determine many of the contract specifications on the current (economic) situation in the world. However, the ship will be working for 20 to 30 years and the only certain thing is that the world will change during its lifetime. Therefore, more and more ship owners are looking for ships that are slightly sub-optimal but will outperform the competition in a case of off-design (or better-said off-contract) condition. SE plays a crucial role in this process, where more time will be spent by the producer and client on determining the right requirements and the ways to measure the effectiveness of the design concerning these requirements. SE is fundamentally about creating and delivering successful systems by managing complexity, technical risk, and decision flow. It is not one technique or tool, but rather a design process containing not only techniques and tools but also guidelines and principles. The main idea is to divide each system into, as much as possible, independent systems, with their requirements and design. Through this hierarchy all requirements can be traced back to a source, but also developments are kept manageable. This process continues until a system is reached that can be bought (off-the-shelf) by the current producer. It is important to realise the view of the user or producer is crucial, e.g. for a car a GPS unit is an off-the-shelf item, however for the producer of the unit, it consists of many systems, both hardware and software.

With the advancements made and successes achieved by SE, researchers have also tried to reverse this idea and consider a fleet or group of cooperating units also as a system of systems. Especially in the military area, this has led to several publications and most notably the Littoral Combat Ship of the US Navy (Adams and Meyers, 2011, Cook, 2001, DiMario, 2006, Forbes et al., 2009, Sommerer et al., 2012). However, in all cases, the attribution of qualities to a certain system (ship) was already fixed. Like the effectiveness models discussed in section 2, these approaches help determine the number of certain ships required but do not help identify the best combination for a ship. This lack of design freedom in combination with fleet performance is tackled in the Design for Operations (Des4Ops) project. It will propose an SE and not a systems-of-systems based approach to platform and capability assignment, which allows the user to optimise the fleet for a given set of missions set in a fixed period. Next, this

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general approach will be further specified, followed by the mathematical general implementation (5), some examples of approaches and results (7) and a discussion of its potential and suggestions for further research.

4. System Engineering-Based Fleet Design

Before designing a ship, the expected use of the ship is investigated. However, a ship seldom operates alone, especially for complex multi-mission technical ships, it will often be part of a fleet. It is therefore important to investigate the role of the ship in this fleet and the desired contributions to the expected missions. Of course, the fleet will change over time and each stepwise change of the fleet should be investigated independently and in cohesion. An approach and validation model was developed within DES4Ops over the past two years. This section will explain the fleet design model set-up. Furthermore, the assumptions and limitations of the model are described. The approach allows the user to check the performance of a fleet in different scenarios, but more importantly, it will lead to fleet descriptions with superior performances.

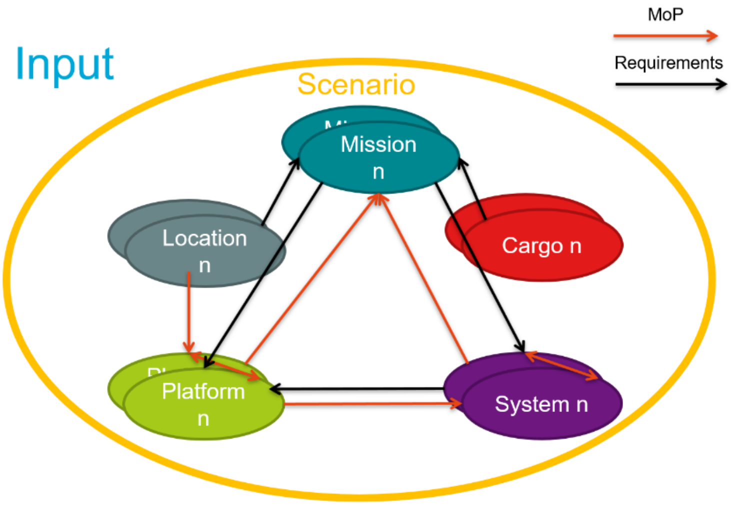

Figure 1: Basic model description

4.1. Main idea

The main idea is that there are five key elements to consider; a set of locations, the location-specific missions, the mission-specific systems, the mission cargo, and platforms to integrate the systems on and carry the cargos. Figure 1 shows these elements as well as two types of relations between them. The black arrows represent the directions of the requirements. The cargo (e.g. size or weight) and location (e.g. local conditions) requirements are transferred through the missions to the platforms and systems. Also, the systems have requirements for the platform (e.g. space or carrying capacity).

On the other hand, the red arrows identify the influences of elements on the performance. Locations may restrict the operations of the vessels (e.g. draft restrictions). Platforms may be carried by other platforms (e.g. drones or landing ships), influencing the original performance in transit. Systems may have dependencies between each other (e.g. torpedoes require a radar), but their performance also depends on the platform they are installed on (e.g. crane operations depend on the stability of the platform).

Finally, the complete set of missions, cargo's, locations, platforms, and systems is defined as the scenario. To successfully execute a scenario, all missions need to be completed within the maximum scenario duration. The model then searches which combination of platform and systems can do this against the lowest total costs, under the assumption that there is no option for lay-up. This will maximize the use of a selected system-platform combination in the model. In the next sub-section, each element will be discussed in more detail.

4.2. Missions, Locations and Cargo

Missions are the core of the scenario model. A mission consists of three locations (port, transit, and site), one cargo and its maximum duration. Within a mission, the location and cargo requirements are combined. Each of the locations may have Measures of Performance (MoPs) available (such as cranes in ports for loading cargo) and requirements for the MoPs of the mission fleet. For example, if there is a mission to provide bunkers to a fleet, the tanker is required to have a minimum level of defence. Since there are often no heavy weapon systems on-board of a tanker, a support ship must join the mission to escort the tanker to fulfil this requirement. Ports are for loading

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cargo and function as the endpoint of the mission. For simplicity, each load is a full load, making the total load time conservative.

Depending on the amount of cargo each vessel will transit back and forth once or multiple times, this may be a single ship, but transit requirements may require the mission fleet to travel in convoy, using the lowest speed. Finally, on-site the cargo is "installed". Depending on the cargo, there is an installation time and/or a sailing time on site connected to this to represent the local actions. An example is a minesweeping mission with a total distance to be covered of 200 miles and a fictive 100 items to be installed. If a ship is appointed to "install" 10 items, it will cover 20 miles which both equal 10% of the total. Multiple ships will reduce the site time, but not the transit time, leading to diminishing returns.

4.3. Platforms and systems

The platforms are used to support systems and to transport cargo. These platforms have platform MoPs such as deck length/width and DWT but could be extended with e.g. radar signature if this is relevant for the missions. A key element of the model is that there should be direct links between the capabilities of the platform and systems and the requirements provided by the missions, locations, and cargo. For example, if sea states affect the motions of the platform. This is different per platform, but motions will also depend on the sea states found at the location. Therefore, for each platform motions can be defined per sea state.

Systems are installed on the platforms to execute the missions. This can be all kind of systems such as cranes, surface-to-air or subsea warfare systems. These systems have capabilities in the form of MoPs (e.g. crane lifting capacity), platform requirements (e.g. deck space, DWT) and requirements for other systems on the same vessel or within the same fleet. Systems have motion compensation, together with the maximum motions allowed for the handling of the cargo at the location, this will limit the sea states during which the platform-system combination is operational.

4.4. Model execution

The execution is based on a robust, brute force approach as shown in Figure 2. There is no smart preselection at this stage. This means that in module 1 all platform-system(s) combinations are generated, after which the infeasible ones are eliminated. A combination is infeasible if the platform MoPs do not match the system or combination of systems MoPs, if a system is missing a support system or if another combination of platforms and systems has the same MoPs with lower costs. Furthermore, each system can only be installed once, so two identical systems need to be defined as a new system. An optional action is to manually edit this selection, removing extra ships you are not interested in or ensuring currently existing ships are part of the model. You can also indicate the minimum numbers of a given ship in this sub-step, ensuring their use in the optimization.

In module 2 the mission durations for each ship are calculated. In module 3 the selection of ships is performed. This is the actual optimisation. A solution is only valid if all constraints are met. First, a minimum number of installations and transports are required for each mission. Second, the scenario and mission duration should not be exceeded. Finally, the MoPs required should be met.

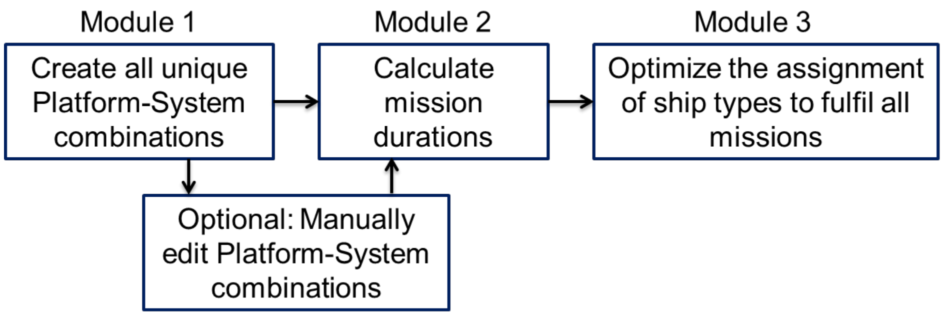

Figure 2: DES4Ops optimization process

5. MILP model description

The description of module 3 will be further explained in this section by presenting the mathematical description of this module. The allocation to the mission steps is done by the variable x_{klms}, while the total number of ships in the fleet is represented by y_k. Allocation is done on an hourly basis. As mission fleets might have to travel in a convoy, multiple variants with different sailing speeds exist for each vessel, these are represented by the s in the annotation. The complete overview of the equations and constraints is presented in Table 1. The objective function

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is to minimize the total costs of all used ships multiplied by the duration of the scenario. From a cost perspective, there is no fractional contribution of a vessel, it is assumed to function in the fleet during the entire scenario. This optimisation is subject to ten sets of constraints also presented in Table 1.

The first set of constraints (1) ensures that all cargo will be transported for each of the defined missions. The constraints (2-5) create the link between x_{klms} and y_k, the total mission time assigned cannot exceed the total scenario time for that ship type (2), the maximum number of ships of a certain type in each mission (3), cannot exceed the maximum number of ships either (4). Finally, constraint (5) ensures that y_k is always equal or larger than our identified minimum for that vessel type (in the sub-module).

Constraints 6-10 ensure that the mission requirements are fulfilled (9) using b_{klms} a binary variable that indicates is a ship type is present in a part of the mission (7a, 7b). Whereas constraint (6) enforces that a vessel in a mission at least does one transit back and forth, constraint (10) ensures that this is done at the same speed as the rest of the convoy. Finally, constraint 8 ensures that all ships in the mission perform an equal amount of work. The a-d for constraints 8 and 10 is a linearization of the constraint to allow the use of an MILP solver, instead of using an algorithm, without the certainty of optimality.

Table 1: Mathematical description of module 3.

$Minimize$	$\sum_{k \in K} y_k \, c_k \, d_{scenario}$		
$Subject\ to$:	$\sum_{ks \in S} x_{klms} \, u_{ks} \geq q_{lm}$	$\forall m \in M, \quad \forall l \in L$	1
	$\sum_{m \in M} \sum_{s \in S} \sum_{l \in L} x_{klms} \, t_{klms} \leq y_k 24 d_{scenario}$	$\forall k \in K$	2
	$\sum_{s \in S} \sum_{l \in L} x_{klms} \, t_{klms} \leq n_{km} 24 d_m$	$\forall k \in K, \quad \forall m \in M$	3
	$n_{km} \leq y_k$	$\forall k \in K, \quad \forall m \in M$	4
	$y_k \geq y_{k,obligatory}$	$\forall k \in K$	5
	$\sum_{s \in S} x_{klms} \geq n_{km}$	$\forall k \in K,$ $\forall l = Transport,$ $\forall m \in M$	6
	$-x_{klms} + b_{klms} bigm_x \geq 0$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	7a
	$-x_{klms} + b_{klms} bigm_x \leq bigm_x - 1$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	7b
	$x_{klms} = z_{klms}$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	8
	$z_{klms} \leq b_{klms} bigm_x$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	8a
	$z_{klms} \geq 0$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	8b
	$z_{klms} \leq c_{lm}$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	8c
	$z_{klms} \geq c_{lm} - (1 - b_{klms}) \, bigm_x$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	8d
	$\sum_{k \in R_{m,mop}} \sum_{s \in S} b_{klms} \geq 1$	$\forall l \in L, \ \forall m \in M,$ $mop \in MOPS$	9
	$b_{klms} \, V_{ks,actual} = w_{klms}$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	10
	$w_{klms} \leq b_{klms} bigm_{vs}$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	10a
	$w_{klms} \geq 0$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	10b
	$w_{klms} \leq c_{lm}$	$\forall k \in K, \quad \forall l \in L,$	10c

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	$\forall m \in M, \quad \forall s \in S$	
$w_{klms} \geq vs_{lm} - (1 - b_{klms})\ bigm_{vs}$	$\forall k \in K, \quad \forall l \in L,$ $\forall m \in M, \quad \forall s \in S$	10d

Variables

b_{klms} Binary indicator variable indicating if least 1 ship of ship type k with speed s is selected for mode l for mission m. Let b_{klms}=0 if ship type is selected and b_{klms}=0 otherwise.
c_{lm} Integer variable equal to the common number of installations/transports for mode l for mission m
n_{km} Integer variable representing the number of ships per ship type k for mission m
vs_{lm} Integer variable equal to the common ship speed for mode l for mission m
w_{klms} Integer variable equal to the multiplication variables b_{klms} and vs_{lm}
x_{klms} Integer variable representing the number of installations/transports for ship type k per mode l per mission m for speed s
y_k Integer variable of the number of selected ships for ship type k
z_{klms} Integer variable equal to the multiplication variables b_{klms} and c_{lm}

Constants

$bigM_x$ Big M value for x_{klms} variable
$bigM_{vs}$ Big M value for vs_{lm} variable
c_k Costs per day for ship type k
d_m Maximum duration of mission for mission m
$d_{scenario}$ Maximum duration of a scenario
$MoPS_m$ Set of MoPs, mop for each mission
q_{lm} Minimum number of installations/transports for mode l for mission m
$R_{m,mop}$ Set of ship types k with sufficient MoPs to fulfil MoP requirement, mop of mission m
t_{klms} Time to execute the mission for ship type k per mode l per mission m with speed s
u_{klms} Ship capacity for ship type k per mode l per mission m with speed s
$V_{ks,actual}$ Ship speed of ship type k with speed s

6. Preliminary results

To show the potential of the model six scenarios of one year are run. The first five scenarios will consist of one type of mission only (Escort, Mine Counter Measures (MCM), Submarine Search (ASW-search), Combat or Fuelling, see also Table 4), the last scenario is the addition of the previous five single mission scenario. Where each single mission type scenario will contain 50 missions, the final scenario will contain 250 mission (50 of each type) to be completed in the same year. For the platforms, four typical navy hulls and one tanker/supplier hull have been created, see Table 2. Except for costs, all other elements are Measures of Performance (MoPs), of which only speed is related to the mission capacities, whereas all others link up with the systems that could be installed.

Table 2: Platform properties

Platform	Deck Length (m)	Deck Width (m)	DWT (ton)	Fuel (ton)	Speed (kn)	Seastate motion (-)	Costs (kUSD)
PL 1	40	8	400	0	30	1,3,5	2000
PL 2	60	12	600	0	30	1,2,4	3000
PL 3	100	15	2500	0	30	1,2,3	10000
PL 4	130	17	5000	0	40	1,2,3	20000
PL 5	170	30	40000	30000	15	1,1,2	25000

The systems can be installed on the ship; however, they have certain MoPs as well as certain requirements (linked to their MoPs) of the other systems and platforms. In Table 3, an overview of the systems is presented. The first six MoPs (Subsea, Surface, Missile, Mine, Airborne, Motion comp) line up with the mission requirements. As firepower is difficult to assess, a virtual value from 1-10 is assigned to each system, this can, of course, be replaced by more sophisticated systems in a full implementation. The elements range and range required are an example of the intersystem constraints, the two systems require this specific radar present. The Sys. Length, width, and constraint are requirements on the platform. The system particulars were specified such that they will fit only on certain platforms, meaning sizes may be unrealistic, but at least the purpose of the model can be demonstrated. The last element is the cost, which is part of the optimisation effort.

Table 3: System properties

System	Subsea	Surface	Missile	Mine	Airborne	Motion Comp.	Range	Range Req.	Sys. Length	Sys. Width	Sys. Weight	Sys. Costs (kUSD)
Sonar 1	10	0	0	3	0	-3	0	0	25	8	300	20000
Sonar 2	10	0	0	10	0	-5	0	0	45	12	800	40000
Radar 1	0	0	0	0	0	-100	500	0	20	15	400	40000
Anti Air 1	0	0	10	0	10	-5	0	500	25	12	500	60000
Anti Surface 1	0	3	0	0	0	-3	0	0	15	8	300	30000
Anti Surface 2	0	10	0	0	0	-5	0	500	45	15	800	60000

The next table contains the mission examples. As explained at the start of this section six scenarios will be run, one with each type of mission and one with the sum of these missions. The missions in the scenario are all identical except for the selection of the transit and location, that part was randomized for the demonstration purpose. Table 4 presents all the mission properties. The first five properties relate directly to the first five system MoPs in Table 3. These values can be summed if more systems are present in the fleet of ships. For now, it is not possible to place two identical systems on the same ship, meaning that for the combat mission at least three ships are required. The speed requirements pose limits on the platform that can partake, the same counts for the fuel requirement. Finally, the last three columns represent the cargo carried, the limitations of the cargo and the maximum duration of the mission. In this case, the cargo is a fictive one hundred units to allow sharing the mission, but in e.g. a windmill installation case, the cargo could also claim deck space or DWT during transit and installation. The max motions restrict the operations of the ship, in this case only during operations. The effect of the motions of the platform in a sea state plus the compensation of the system cannot exceed this value. If it does the ship is not operational during that particular sea state. Finally, the max duration is how long that particular mission may take, a limitation on the operations and with long location work on distance locations, it may require more than one ship to be successful.

Table 4: Mission properties

Mission	Subsea	Surface	Missile	Mine	Airborne	Min Transit	Min Site Speed	Fuel	Amount	Max Motions	Max Duration
Escort	3	10	0	0	0	30	0	0	100	0	10
MCM	0	3	0	10	0	30	15	0	100	0	15
ASW-Search	10	3	0	0	0	30	15	0	100	0	15
Combat	10	30	10	0	10	30	15	0	100	0	10
Fuelling	0	0	0	0	0	15	15	30000	100	0	10

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The locations and their primary properties are captured in Table 5. Mission requirements are valid only for the site location. To prevent tankers and other ships from sailing independently around the globe a minimal fighting power is required for all transits through the locations, this is the role of the first requirement. In fact, any of the mission requirement could be present here as well. The distance is either the transit distance or the distance on the location. The location distance is relevant for e.g. the Mine Counter Measures (MCM) or the submarine search (ASW-search). Each location may have own MoPs as well, in this case, the port can load all the mission equipment all the time and in no time (motion comp and move time). The final three columns represent the occurrence of a certain sea state in that particular location. Notice that the sea states are the only difference between Site 1 and Site 2 to bring some variation in the model. As mentioned before, if the combination of platform motions and system motion compensation is not enough to lower the motions below the mission level the vessel will not be operational in that particular sea state. This means the duration is increased by dividing the mission time by the fraction of sea states the vessel is operational.

Table 5: Location properties

Location	**Surface**	**Distance**	**Motion Comp**	**Move time**	**Sea State 1**	**Sea State 2**	**Sea State 3**
Port	0	0	-100	0.001	1	0	0
Transit 1	3	500	0	0	0.6	0.3	0.1
Transit 2	3	1000	0	0	0.6	0.3	0.1
Transit 3	3	1500	0	0	0.6	0.3	0.1
Transit 4	3	3000	0	0	0.6	0.3	0.1
Site 1	0	0	0	0	0.5	0.3	0.2
Site 2	0	0	0	0	0.2	0.3	0.5
Site 3	0	500	0	0	0.5	0.3	0.2
Site 4	0	1000	0	0	0.5	0.3	0.2
Site 5	0	1500	0	0	0.5	0.3	0.2
Site 6	0	3000	0	0	0.5	0.3	0.2

For each scenario in step 1, 105 feasible ships are created. As explained before feasible means that no requirements are broken and ships with the same performance, that cost more are eliminated. In step 2, the time each mission takes for each ship is calculated, also at different speeds. E.g. a ship with a speed of 40 knots, is also run for speeds of 30 and 15 knots, the other two speeds in this example. By making these calculations before the optimisation (step 3) a linear solver can be used, ensuring an optimal solution. The solutions obtained are presented in Table 6. The provided examples are not overstretching the fleet with short missions (2-20 days) and a year to complete them. Therefore, in all single mission type scenario's one vessel suffices unless the mission situation itself requires more ships. This is the case for the combat scenario, where three ships are needed to achieve the surface strength and the fuelling scenario, where a tanker needs to be unarmed, requiring a second ship to escort it during transit. In the final scenario, the more expensive PL 4 is chosen as more systems can be combined on this ship, allowing it to perform a multi-role, replacing the single objective PL 3's in the single mission scenarios. Of course, this does not mean that multi-objective ships are the best solutions, especially as in the current set-up at sea and in port/idle is equally expensive. A more detailed study of such effects and changes is not part of this paper but could be of interest to further demonstrate the options of the model.

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Table 6: Optimisation Results

Mission	Vessel ID	Number Required	Properties 1st ID	Properties 2nd ID	Properties 3rd ID	Properties 4th ID	Total Costs
Escort	ID 97	1	PL 3, Sonar 1, Radar 1, Anti Surface 2				47
MCM	ID 99	1	PL 3, Sonar 2, Radar 1, Anti Surface 1				44
ASW-Search	ID 96	1	PL 3, Sonar 1, Radar 1, Anti Surface 1				37
Combat	ID 92, ID 108	2, 1	PL 3, Radar 1, Anti Surface 2	PL 3, Sonar 1, Radar 1, Anti Air 1, Anti Surface 2			150
Fuelling	ID 4, ID 160	1	PL 1, Anti Surface 1	PL 5			21
All	ID 92, ID 108, ID 140, ID 160	1, 1, 1, 1	PL 3, Radar 1, Anti Surface 2	PL 3, Sonar 1, Radar 1, Anti Air 1, Anti Surface 2	PL 4, Sonar 2, Radar 1, Anti Surface 2	PL 5	177

7. Discussion and Conclusions

The current model was designed to prove that the approach considered could work, our choices lead to several simplifications to be aware of. The lack of mission timing is the first limitation of the model there is no fixed timing for the missions, the model only checks the individual mission time and total scenario time. For a long-term scenario with a duration of 5-10 years and mission duration of 3-12 months, this does mean that the missions are planned optimally from the perspective of the fleet. The result is that the resulting fleet may be smaller than desired. However, the same model can be used to design a stress test, using a short scenario duration in combination with a large selection of missions with a duration close to the scenario duration. This way there is no way to shift missions in time and the resulting fleet can deal with the stress test.

The missions have a single cargo and one site as a destination. However, this should be considered flexibly. Repair or maintenance of ships could be implemented as a special mission type, it could even be tailored to specific ships or ship types. The same holds for bunkering, the fuel amount required is not considered, but if certain missions are known to go beyond the range of the ships, these could be cut up in multiple shorter missions, or sufficient bunkering missions could be added to the mix to ensure enough tankers and escorts for these tankers are available in reality.

While in this paper the focus is on the naval fleet design, it should be mentioned that the same model has also been successfully applied to study the installation of windmills with a fleet of mixed vessels. Especially interesting in this case was the shift from transport and installation with one ship to the split assignments for this due to the increase in transit time or mission density.

It must be admitted that the current model requires some practice to use as well as some flexibility to achieve the desired implementation. Some choices are debatable but in general, we have discovered that a pragmatic approach in combination with solid MILP optimisation will give relevant results within a short time (minutes on a regular to heavy workstation) for small to medium implementations.

This can certainly be improved as genetic algorithms can speed up the process. A better pre-selection of ships can speed up the process especially if the mission number increases significantly. This is important to consider. Finally, as with any optimisation, there is no one best solution, but the developed approach and tool allow designers to play around discover new options for the fleet and embrace or discard new technology at an early stage.

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