HYDRA: multipurpose ship designs in engineering and education

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ABSTRACT: The cornerstone of post-graduate naval architecture and marine engineering education at UCL is the Ship Design Exercise. This three-month full-time project sees students placed in small, multi-disciplinary teams and challenged with the concept design of a new vessel based on broad outline requirements provided by the academic staff. This exercise exemplifies the use of design as an integrative teaching method, allowing engineering students to place their academic understanding of technical subjects in a whole-ship concept. This paper describes an innovative design – HYDRA – featuring a single core vessel capable of adaption during build to take on several military or civilian roles. This paper not only describes the technical aspects of the design solution itself, but also discusses the educational implications of setting students the challenge of designing ships to meet multiple, sometimes contradictory requirements. In addition to aligning well with some modern trends in ship design and construction, this type of problem is seen to offer potential benefits in engineering education. These benefits are discussed, in addition to the potential complications they bring to various aspects of the design exercise.

1 INTRODUCTION

Design is widely recognised as being an activity central to engineering education (McLaren, 2008), and many, if not all, naval architecture degrees will feature some ship design activity. Technological and social developments have an impact on education, however, and in discussing the use of new computer-aided approaches in preliminary ship design, Pawling et al (2017) raised the question of "what might be the new key fundamentals of engineering teaching", noting that:

"From 2019, most first-year undergraduates will be fully "21st century students", however it could be argued that some universities are still teaching them using 20th century tools and 19th century methods."

There has been some quantified research, such as that by Collette (2015) investigating the impacts of modern tools (in that case, 3D models) in teaching ship design, but it is still an area for development.

It is proposed that design exercises that cannot be reduced to simple mechanistic analysis or iteration, and which oblige students to make decisions, become more important as the sophistication of modelling and analysis tools available in ship design (and to students) increases. This paper describes the ways in which decision making, as an activity in ship design, are included in the various ship design exercises carried out by undergraduate and postgraduate students at UCL.

2 SHIP DESIGN TEACHING AT UCL

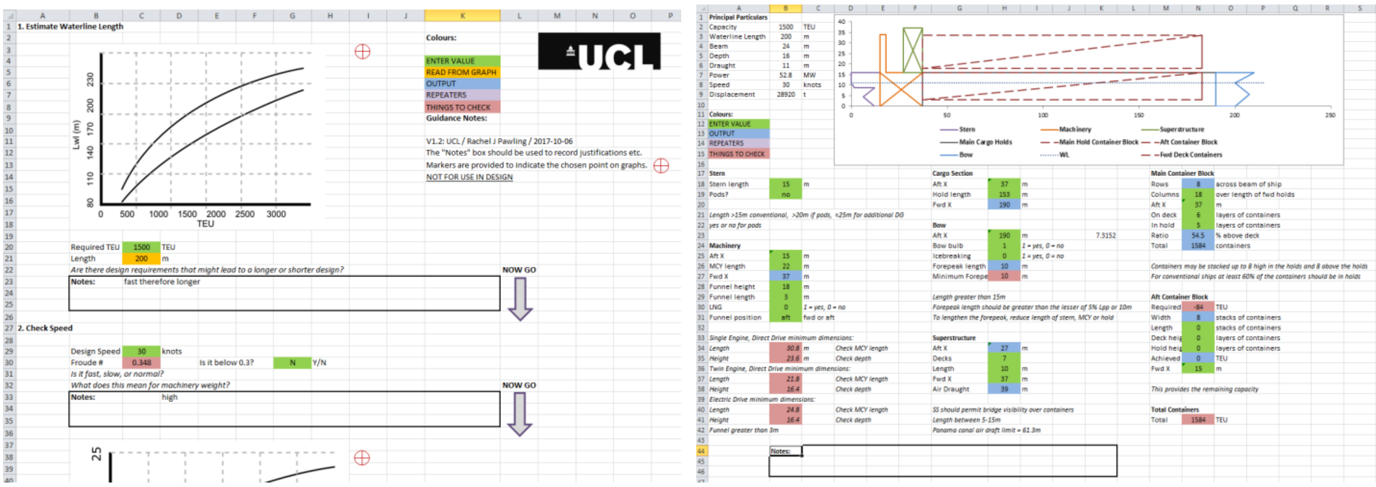
Historically, the Naval Architecture and Marine Engineering (NAME) group, part of the Department of Mechanical Engineering (UCL, 2018) taught ship design at two levels; one and two-year MSc and at the end of three and four-year undergraduate courses. The last undergraduate cohort graduated in 2015, leaving only the postgraduate course, but this is changing with the recent introduction of the "Integrated Engineering Programme" (IEP, 2018), a modular course using the major / minor structure familiar in other countries such as the US. A Maritime Design module, developed by the first author, is available to students in the third year of this course and more detail about this is given later in the paper.

The MSc Naval Architecture and MSc Marine Engineering courses at UCL last for 12 months (with a 12 month foundation year available for students without suitable previous qualifications), and have three main elements; six months of academic teaching and exams; group Ship Design eXercise (SDX); and individual project. Two introductory ship design exercises have recently been added to the MSc timetable, specifically during the academic portion of the course. These are intended to encourage students to consider how their technical tuition integrates with ship design, to illustrate the importance of exercising engineering judgement and introduce the general iterative procedure of initial design. The Introductory Ship Design Exercise, ISDX, takes place in the first month of the MSc, and the Ocean Patrol Vessel Design Exercise (OPV DX) occurs early in the second term.

2.1 *Introductory Ship Design Exercise (ISDX)*

The ISDX is a short exercise, usually taking three hours. The exercise begins with a lecture on the use (and limits of) historical data in ship design. The students rapidly estimate the overall dimensions of a container ship and generate a simple profile view using a highly simplified Excel tool, shown in Figure 1. The primary purpose of the ISDX is to introduce students to the need for engineers to make design decisions and justify them. The sizing relationships are all presented as ranges based on historical data, rather than single lines or algorithms, and the students have to choose where in the range their design is likely to lie, based on the broad implications of "special" requirements, such as icebreaking, gas fuel or high speed.

Additional teaching objectives for the ISDX include providing students with some understanding of the nature, utility and limitations of historical and "type-ship" data in engineering design, to address some of the issues regarding historical lessons raised by Tuttle (1997). The ISDX is deliberately kept more casual than a conventional lecture, to encourage the students to explore the various design options and introduce them to decision making in a "risk-free" environment (as the full SDX involves design reviews with senior staff). After sizing their container ships, the students each present their design to the rest of the group. They are required to state why they chose each parameter in the sizing.



(a) Sizing sheet showing historical data as ranges

(b) layout sheet

Figure 1: The UCL Excel-based ship sizing tool used for the ISDX

2.2 *Ocean Patrol Vessel Design Exercise (OPV DX)*

The main objective of the OPV DX is to introduce the students to the iterative and interactive nature of ship design, and to the specifics of the procedure and tools used in the main SDX. As with the ISDX it makes use of a greatly simplified dataset and constrained problem, but as the exercise spans two days the students are expected to go into more detail. The students are provided with a requirement that describes the required payload (combat systems), propulsion package and endurance (for fuel and stores), with each requirement having a "special study", a specific key capability which could be; a large flight deck; limited air defence capability; high speed etc.

During the OPV DX, the students use a simplified design databook to calculate the overall size of the vessel, then carry out a simplified parametric survey to determine the ratio of volume distribution in the hull and superstructure, to fit within various specified constraints. The design is then worked up with a block layout modelled in an Excel tool (shown in Figure 2) and analysis of stability and powering in Paramarine. The latter makes use of pre-defined template design files representing a typical OPV, so that the students need only enter the dimensions, weights and centres of their designs. The students then present their OPV designs to the group, with questions on the technical aspects of the design.

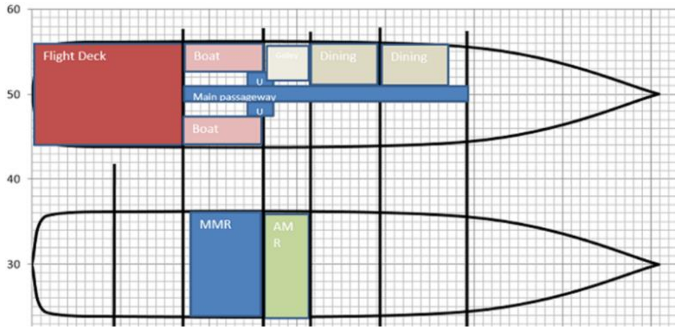


Figure 2: Simplified arrangements in OPV DX Excel tool

2.3 *Ship Design Exercise (SDX)*

The SDX runs for three months full-time between April and June and sees the students split into small groups of 2-4, with a mix of naval architects and marine engineers. The small size of the groups is important to ensure that all students have visibility over all parts of the ship design process, to avoid a student specializing in only a single aspect of the ship design. Each group has a different set of design requirements, mostly for warships and service vessels (due to the students background), and the requirements are characterized by being challenging and relatively open. Table 1 provides some examples of recent design requirements. Although the majority of MSc Naval Architecture students at UCL examine naval vessels, increasingly the course covers other complex service vessels. Unlike “type ship” based approaches – such as the now discontinued undergraduate design exercise for frigates and container ships – the academic staff do not know that the requirements they are setting can even be met.

Another feature of the SDX is the use of several design reviews and consultancy days with academic staff and external subject matter experts. The students must present the progress of their design and answer questions, with a particular emphasis being on the development of their ability to make design decisions and justify them, rather than the precise technical nature of the solution. The UCL MSc SDX groups consist of both naval architects and marine engineers, and each design review covers both domains, and the interactions between them. The whole-ship design decision making is expected to involve inputs from both domains, with more detailed technical analysis being specific to each MSc.

Table 1: Examples of UCL MSc SDX design requirements

Year	Title	Summary
2010	Low Carbon Export Frigate	Adaptable to different requirements, with low emissions cruise mode via fuel cells
2013	Offshore Wind & Marine Current Turbine Support Vessel	To carry staff and parts, with survey and tourism tertiary roles, 30 year life and access capabilities entirely determined by students
2013	Anti-Air Warfare Destroyer	With Anti-Ballistic Missile capability, optional electric weapons and a Lighter-Than-Air sensor system
2016	Mega containership for 2035	Icebreaking container ship carrying 40,000 TEUs at half the EEDI of MSC OSCAR

Figure 3 shows an overview of the MSc SDX and its’ key stages. The students are provided with a User Requirements Document (URD) developed by the teaching staff, in consultation with industry. The URD sets very high level requirements which can be met in a variety of ways. Few numerical parameters or equipment items are specified, and there are usually several “special studies” or constraints, which may include technologies not yet in operational use. The MSc SDX is notable for a wide variation in design requirements – challenges include unconventional hullforms, technologies or operating restrictions.

The SDX requires the students to integrate the subject specific technical knowledge gained during in the MSc into a coherent design. The design procedure used is a variation on the conventional design spiral. Although this model has been subject to some criticism (Pawling, Andrews & Percival, 2017) it is a relatively simple introduction to design as it represents a linear model of design development, assessing each technical aspect in turn. The particular advantage of using this model of the design process in education is that each type of analysis can be clearly delineated. Emphasis is placed on decision making and justification, and the understanding of influences and interactions in the design. Conceptually the design spiral as implemented in the UCL SDX is closer to the 3D helical model, proposed by Andrews (shown in Figure 4), with its highlighting of the progression of the overall design concept through time (the vertical dimension) and radial constraints and interactions. Importantly this later representation includes the exogenous nature of the constraints, which is not always clear in a simple spiral or linear model.

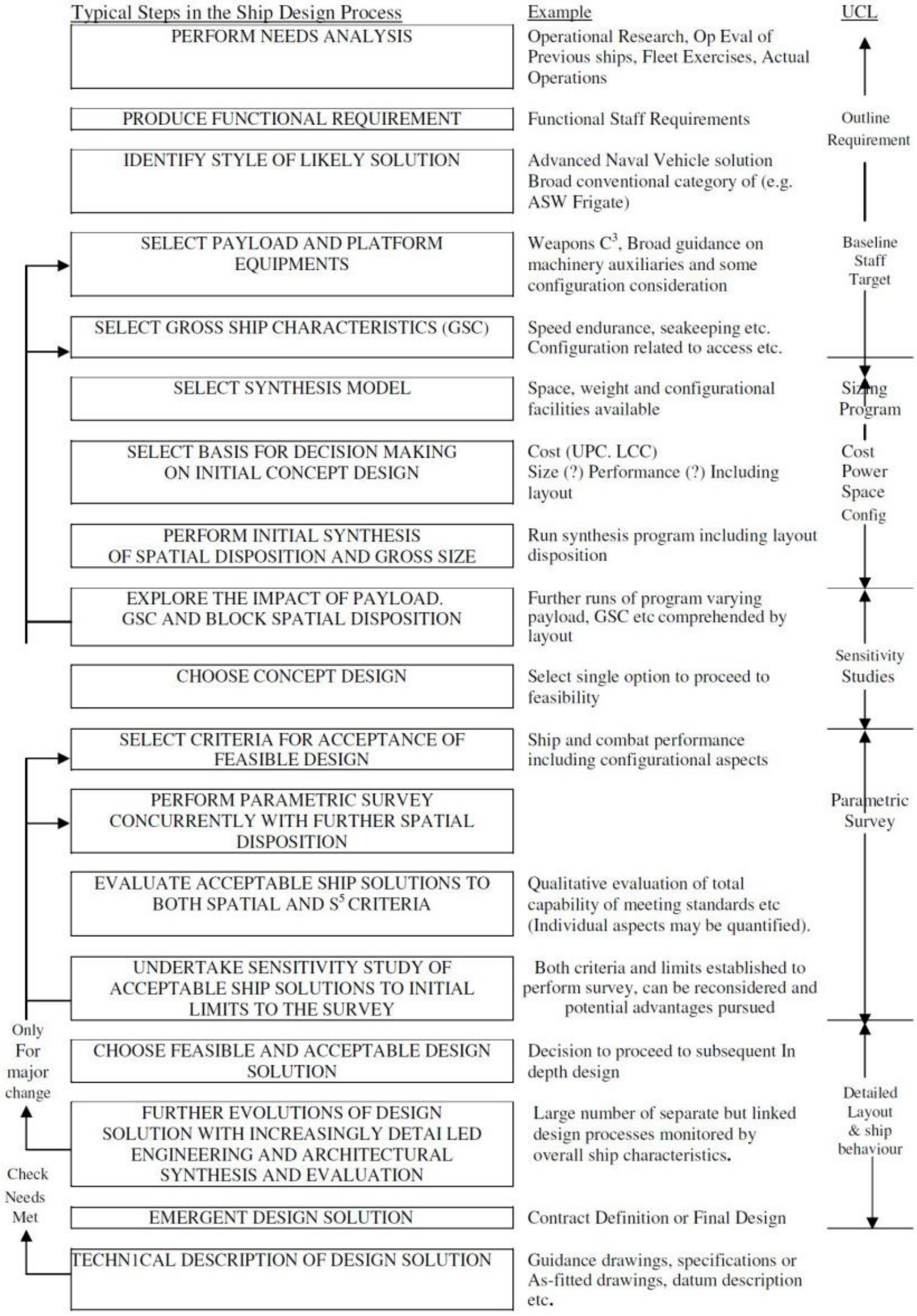


Figure 3: An overview of the MSc SDX process compared with a generic ship design process (Andrews 1986)

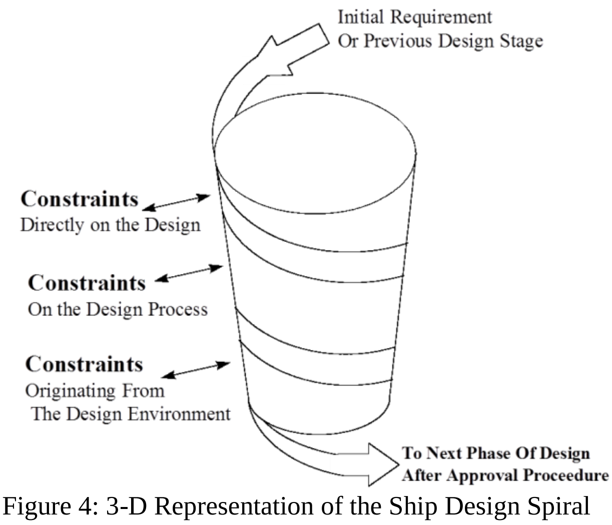


Figure 4: 3-D Representation of the Ship Design Spiral (Andrews 1981)

In addition to numerical sizing and analysis of the design, students are required to consider the configuration of the design as early as possible. As discussed by Pawling & Andrews, (2011), sketching of design options is promoted to aid in exploration and help the students understand the wider interactions in the developing ship design. The format of and tools used for these sketches is not specified; some groups produce hand-drawn sketches, others work directly in CAD tools, whilst other students with a professional or hobbyist background may use computer graphics tools. The importance of developing special modelling in assisting students in developing an understanding of their design has been discussed by Collette (2015), and the sketches in the MSc SDX serve a similar role. Technical aspects are of course examined, as the final reports upon which the students are assessed must contain details of not only the decisions and rationale but also the Naval Architectural and Marine Engineering modelling and assessment for the design.

3 PROJECT HYDRA: AN EXAMPLE UCL MSC SHIP DESIGN

3.1 *Introduction*

"HYDRA" is a 2017 student design developed by the second and third authors to meet a requirement for a "Mediterranean Multirole Coastguard Ship". The development of the design will be summarized in this section, with a particular emphasis on the decision making methods, to illustrate the approach used in the UCL MSc SDX described above. The key feature in this project was that a common design was required able to be completed as either; a coastguard vessel; a research vessel; or a submarine rescue vessel; the three roles giving rise to the name Hydra, the many-headed serpent in Greek mythology. Table 2 summarises the User Requirements Document provided by the academic staff to the design group.

In addition to setting the requirement for multiple, potentially conflicting, roles to be supported by a single, adaptable design, it is notable that the students are encouraged to challenge constraints placed upon them – in this case the displacement cap – with the provision that such challenges must be justified. For this design, no cost cap was specified. It is more typical for MSc URDs to have cost cap, but in this case it was omitted as finding accurate cost data for such vessels can be difficult (UCL's costing database being primarily for naval vessels), and there were seen to be sufficient technical challenges in the URD to occupy the students.

Table 2: Summary of the HYDRA User Requirements Document

Role	A common hull which can be completed as a coastguard vessel, research vessel or submarine res-cue vessel. Once completed, there is no requirement to change role during the ship's life.
Primary Tasks	Conduct one of the following sets of tasks, chosen at build: a. Coastguard i. Very broad area maritime surveillance (visual coverage of 4,000 square nm per hour). ii. Undertake Boarding operations at as long a range as practicable (up to 100nm.). b. Oceanographic & Scientific Research i. Deploy large USV / semi-submersibles for hydrographic survey. ii. Support ocean science research work with laboratory spaces and a working deck. c. Submarine Rescue i. Embark and deploy the NATO Submarine Rescue System ii. Provide medical care to the rescued submarine crew, at hyperbaric conditions if required.
Secondary Tasks	a. Provide firefighting capability to other vessels and installations. b. Provide humanitarian rescue & evacuation on a large scale, including provision of medical aid. c. Tow disabled ships, up to the largest container ships and bulk carriers.
Area	a. The Mediterranean Sea
Ship Life and ISD	a. Ship Life – 40 years b. ISD – 2025
Constraints and Special Studies	a. Cost – No cost cap b. Speed – Extended low speed loitering, capable of high speed dash for emergency response. c. Displacement – Deep displacement at start of life (in any Role configuration) may not exceed 5,000 tonnes. If required roles cannot be met on this displacement cap, a strong justification should be provided. d. Future Fuels and Emissions – Should design assuming that carbon-containing fuels will increase by an unknown amount between 200% and 500% by 2085, assuming linear increase per year. Strict future emissions regulations should be considered likely during the life of the ship; design to minimise the risk of having to scrap ships early. e. Vulnerability Reduction – Assume collision is likely during ship's life and design to continue operations. f. Must have sufficient gas protection to provide rescue/firefighting services to gas carrier vessels. g. Unoccupied Vehicles (UXVs) – Consider unoccupied vehicles for contributing to surveillance task. Should be able to operate four 11m RIB/semi-submersible USVs in the survey task. h. Technology Insertion / Mid-Life Update – Scientific facilities should be designed for ease of modification through life. Submarine rescue vessel should be designed to easily accept NSRS successor vehicle. i. Hullform – Multihulls should be considered, and the choice of hullform justified.

3.2 *Decision Making Processes*

Several major phases of decision making and options comparison occur within the MSc SDX and these were further complicated in the HYDRA design, due to the multifunction requirements. These can be summarized as; operational analysis (OA); payload selection; hullform type; modularity; and parametric survey.

3.2.1 *Operational Analysis*

Operational Analysis is required to determine how the proposed vessel will accomplish the very broad requirements given in the URD. The wide variety of ship types examined in the MSc SDX mean that the exact nature of the operational analysis varies, for example a cargo ship may focus on possible routes and economic modelling, whereas an air defence destroyer may compare missile options and magazine capacity. The objective in the HYDRA project was to design a common hull capable of supporting one of three roles, so the operational analysis focused on determining what each of those roles required of the ship.

For each of the three main roles for HYDRA, a survey of existing vessels used for each role was conducted, to determine typical ranges of dimensions, performance and main equipment or ship features. For each of the sub-tasks listed in Table 2 a technical solution with equipment options was proposed. This process was largely conducted by literature review (including the general arrangements of previous vessels), with different methods used to define different technical solutions. For example, primary task a (i) – broad area maritime surveillance – led to the proposal for a system of Uninhabited Aerial Vehicles (Figure 5), whilst initial estimates of lab space for the research role could be made from reference papers (Figure 6).

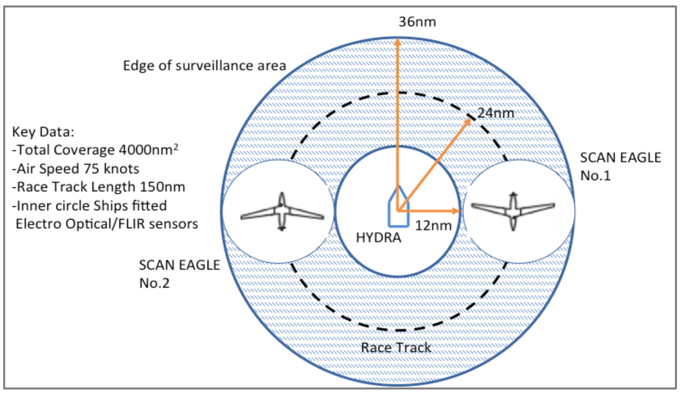


Figure 5: Concept of employment of Scan Eagle UAVs for maritime surveillance (Hunt 2017)

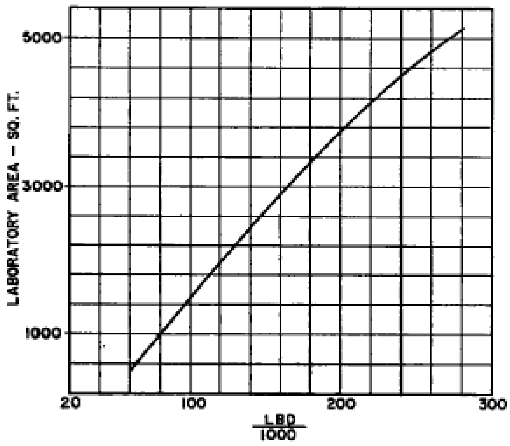


Figure 6: Reference data used for initial estimates of lab area (Rosenblatt, 1960)

The output of this process was the specification of target equipment fits and design features for each of the three roles. Most notably these targets also contained a justification; e.g. from previous ships, references, or specific capability requirements.

3.2.2 *Payload Selection*

Payload selection followed from the operational analysis, performing a cost-capability trade-off using the Equity software (Catalyze 2018). A specific challenge introduced by the multifunctional HYDRA design was that, ideally, each of the three role-specific equipment packages should have the same weight and space requirements, so that no one role was dominating the design. Individual items of equipment were sized based on a UCL database, published datasheets and calculation, and, for each primary role, combined into three functional packages (e.g. UXV equipment, sensors, lab area), each with three levels of capability (e.g. minimum, medium and maximum. Figures 7, 8 and 9 illustrate the equity analysis for each of the three main roles, showing the selected points.

The objective of this analysis was to determine the option providing the highest capability (y-axis) without excessive increases in cost (x-axis) on the right-hand plots. However, due to the HYDRA multi-role requirement, this was complicated by the need to align volume requirements of the ship (left-hand plots). This analysis showed that although the coastguard option was preferable from a cost/capability perspective, it had high volume demands that would drive the design. This allowed the students to challenge the requirements set by the customer (the academic staff), who agreed to a reduction in the minimum number of 11m boats from 4 to 2.

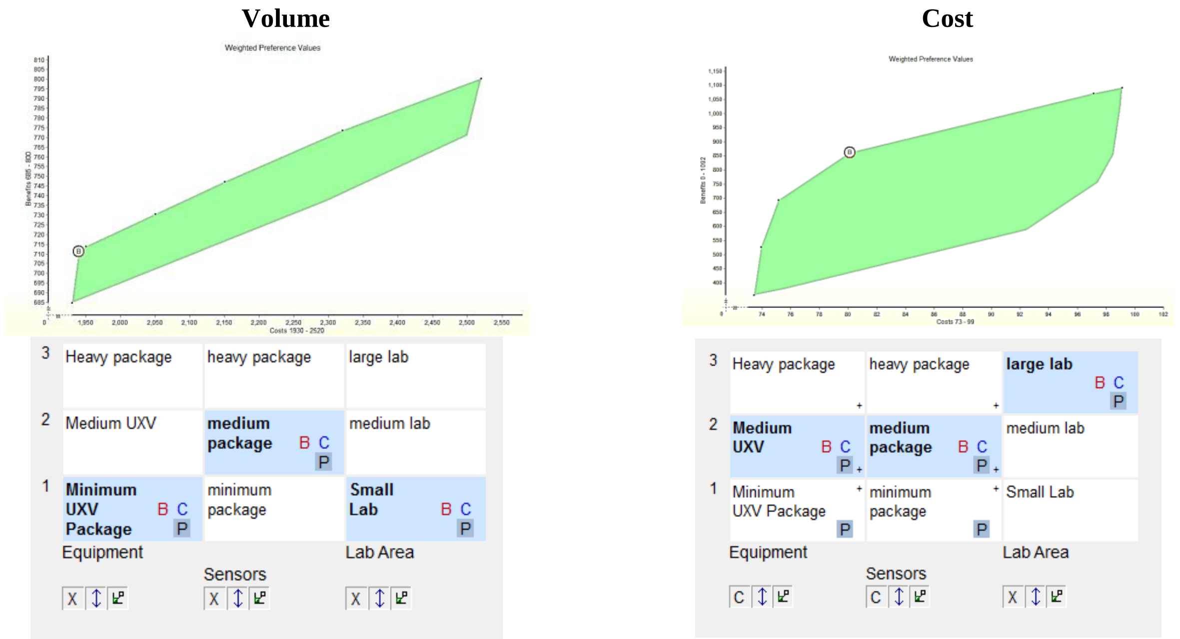


Figure 7: Cost Capability Trade-off output for HYDRA Research (Bilde, 2017)

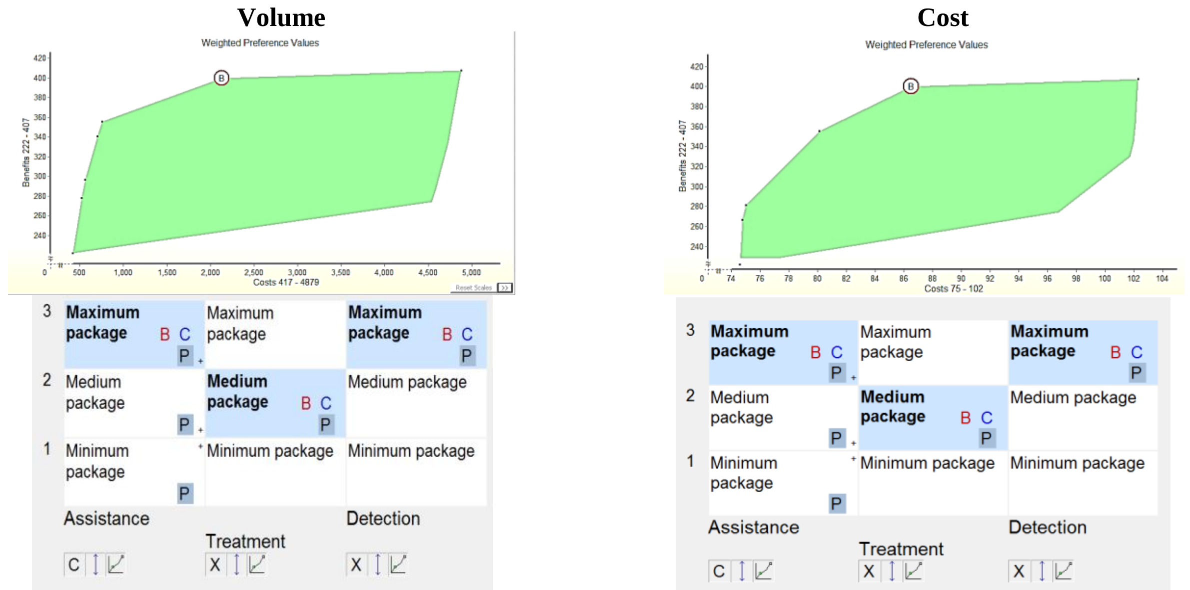


Figure 8: Cost Capability Trade-off for HYDRA SUBSAR (Bilde, 2017)

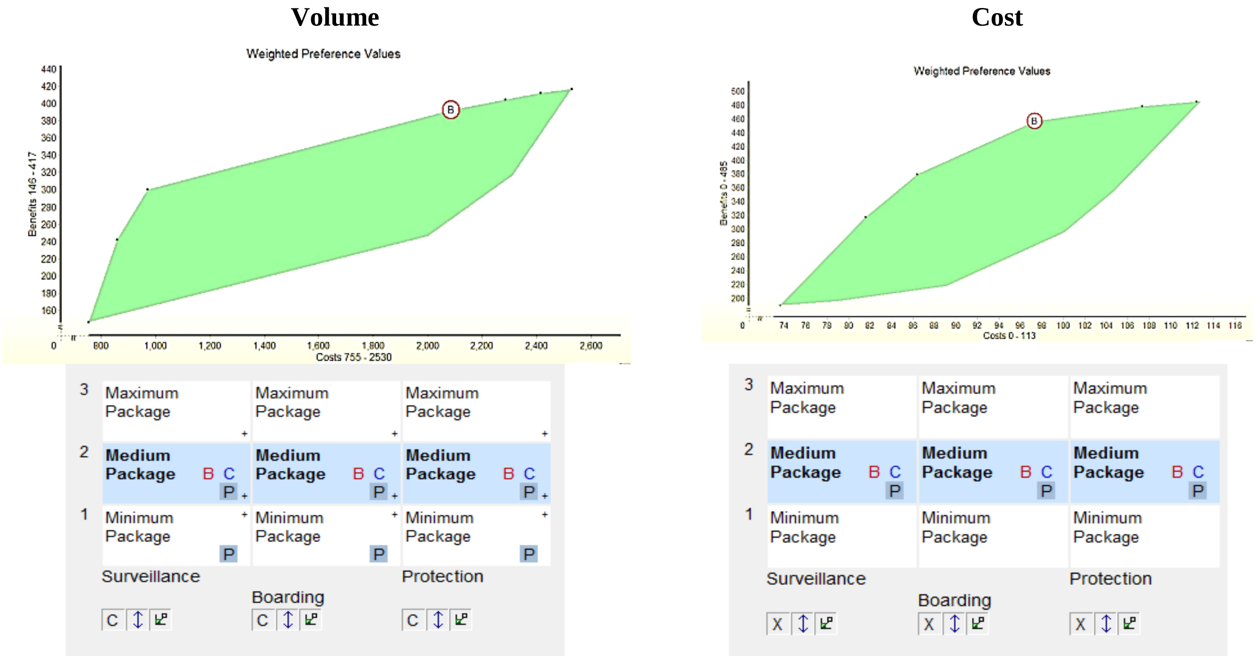


Figure 9: Cost Capability Trade-off for HYDRA Coastguard (Bilde, 2017)

3.2.3 *Hullform type and material*

Hullform type and material were selected using a Strengths-Weaknesses-Opportunities-Threats (SWOT) and Weight-Score Method (WSM). Four hullform types were considered: Catamaran (SWATH); Trimaran; conventional catamaran; and conventional monohull. Table 3 gives an example analysis for the catamaran-SWATH option and Table 4 summarises the WSM analysis for hullform type, with the monohull option being preferred. The WSM analysis for structural material compared steel, aluminum and carbon fibre composite, with steel being selected.

Table 3: Example SWOT analysis for the catamaran-SWATH hullform option

Strengths	**Weaknesses**
Large righting moment Significant roll damping due to wide beam (in SWATH mode) Beneficial for high speed vessel Shallow draught (in catamaran mode) Operational flexibility in conversion between being a highspeed catamaran or stable SWATH	Very difficult tank layout Difficult to implement podded propulsion High freeboard (in catamaran mode) Wave interference resistance between hulls Constrained layout options RIBs deployment must be at sides ► suggest narrow hull
Opportunities	**Threats**
Large deck area Possibly better work flow at main deck due to a more square shape Innovative solution Requires two shaftlines/azipods	Roll damping results in large relative motions in beam seas Structural issues in beam seas Sensitive to load changes in SWATH mode Requires high level of structural investigation Higher UPC due to complex design

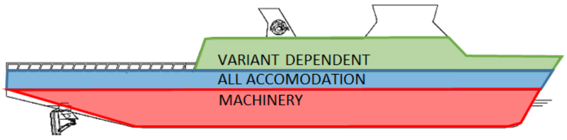
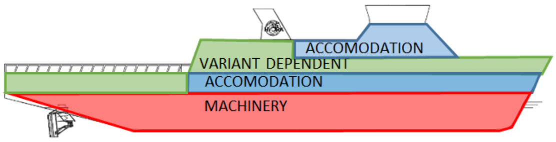
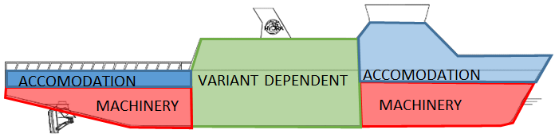
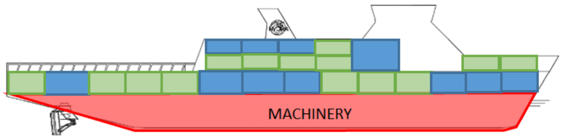
Table 4: WSM decision making matrix for hullform type

Criteria	**Weight**	**Hull form [1-5]**							
	[1-5]	**Cat-Swath**		**Trimaran**		**Conventional Catamaran**		**Conventional monohull**	
Longitudinal strength	3	2	6	3	9	3	9	4	12
Transverse Strength	4	2	8	3	12	1	4	4	16
Resistance at high speeds	4	2	8	3	12	3	12	4	16
Resistance at low speeds	4	2	8	3	12	3	12	4	16
Deck area	2	4	8	4	8	4	8	2	4
Roll damping	4	4	13	3	12	2	8	2	8
Pitch damping	4	5	20	2	8	2	8	4	16
Propulsion arrangement	4	1	4	2	8	3	12	5	20
Sensitivity to load changes	3	1	3	3	9	3	9	4	12
Design security	3	2	6	4	12	3	9	4	12
Project risk	3	4	12	3	9	3	9	5	15
Innovation	3	4	12	4	12	3	9	2	6
Total			106		114		102		**140**

Modularity was used to allow adaption of the basic vessel design to different options, the decision was taken to concentrate the variant-specific features into a single "Variant Dependent" area, thus encapsulating much of the variation between options. Table 5 summarises the four main approaches to design modularization considered.

The primary consideration for selecting between the options was the interaction of subsequent equipment and functional spaces with operations and capability. Option 2 was selected for further development, as it aligned with a "factory floor" mode of operations; the main deck is a factory floor producing a "product", where operations are managed in offices above and workers are accommodated elsewhere. The functional workflows for each design variant are outlined in Figures 10, 11 and 12 below.

Table 5: Modular configuration topologies considered

Option	Indicative Profile
Option 1: 1 deck and 01 deck 1 deck and 01 deck constitutes the variant. Below deck is all accommodation. This requires a low superstructure	
Option 2: Superstructure excl. bridge The variant dependent area is the main deck which becomes a factory floor, where offices and higher rank accommodation are placed above and all lower rank personnel is placed within the hull.	
Option 3: Parallel midbody Variant dependent section is part of the parallel midbody. Allows for length extension if needed	
Option 4: Modular blocks within ship Various blocks within the ship are reserved for the variants. Provides flexibility in allocation of spaces.	

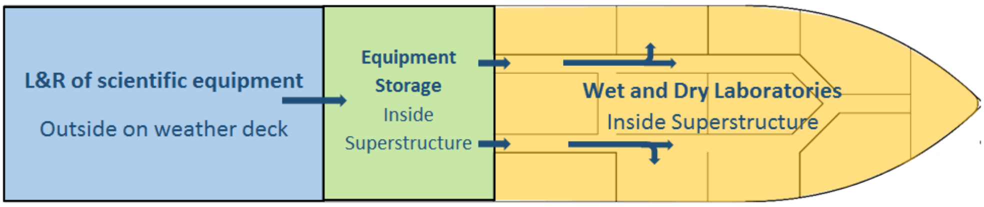


Figure 10: Research vessel workflow (Bilde, 2017)

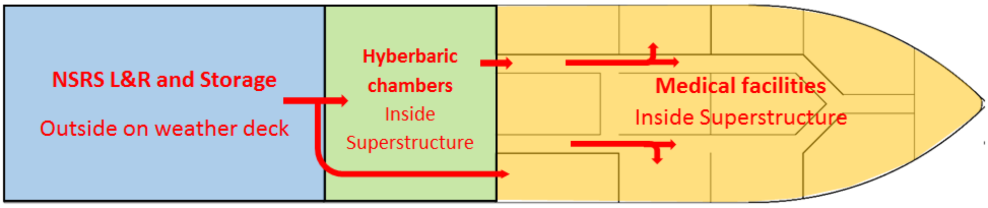


Figure 11: Submarine rescue vessel workflow (Bilde, 2017)

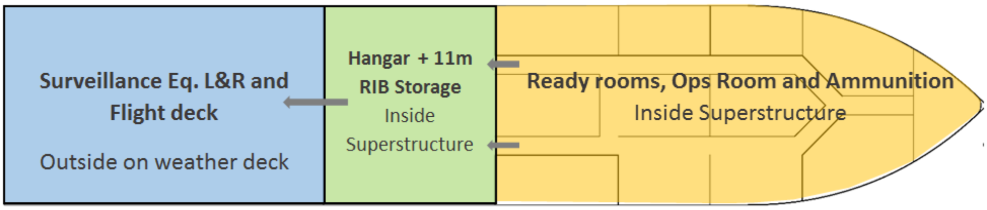


Figure 12: Coastguard vessel workflow (Bilde, 2017)

Research Vessel Workflow (Figure 10): The research vessels product is scientific data. Samples are gathered by deployed equipment ▶ The equipment is recovered at the open deck ▶ Equipment goes into storage ▶ Samples are taken out of equipment and transferred to laboratories ▶ Samples are processed and data is gathered.

Submarine Rescue Vessel Workflow (Figure 11): NSRS is deployed and recovered via A-frame at open deck ▶ NSRS interlocks with hyperbaric chambers ▶ Intoxicated submariners are transferred at correct pressure into hyperbaric chambers ▶ Hyperbaric chambers are slowly depressurized ▶ Submariners are transferred to medical facilities. Non-intoxicated submariners are transferred directly to medical facilities.

Coastguard Vessel Workflow (Figure 12): Boarding operations: Boarding team is prepared on ready rooms ▶ Boarding team board transport vehicle ▶ Transport vehicle is deployed.

Surveillance: Surveillance gear is launched and recovered at open deck ▶ Surveillance gear is transferred to storage area.

3.2.4 *Parametric Survey*

The parametric survey is a standard part of the UCL MSc SDX, taking place after the initial sizing process, in which the students construct a parametric model allowing the calculation of ship size, resistance etc. The parametric survey has two broad phases; major and minor. These surveys are based on the ship concept sizing methods described by van Griethuysen (1992). The major parametric survey allows the determination of the overall ship dimensions and ratio of superstructure to hull volume, whilst the minor parametric survey focusses on hullform parameters and their optimization for minimum resistance (or energy consumption). Figure 13 summarises the major parametric survey carried out on the HYDRA design. The variables were; number of internal decks (and thus deckhead height); proportion of internal volume in the superstructure (Vs) and length/depth ratio (L/D). Various constraints were applied to this process, such as a recommended range of Circular M (7-9), consideration of block coefficient suitability for the required speed and the minimum volume required in the superstructure based on the layout topology selected above.

With the overall dimensions fixed, the minor parametric survey was conducted on the midships coefficient (Cm) and Prismatic coefficient (Cp), as summarized in Figure 14. Just as the major parametric survey was constrained by previous considerations of arrangement etc. so the minor survey was itself constrained by the outputs of the major survey the reductions in prismatic coefficient suggested by Figure 14 were constrained by their impact on the preferred block coefficient.

Although the UCL design guidance does specify the variables to be investigated in the major and minor parametric survey, the wide range of ship and hullform types investigated by the students means that significant latitude is afforded to them. The design of a trimaran, for example, would be expected to include examination of aspects such as side hull spacing and proportion of overall displacement.

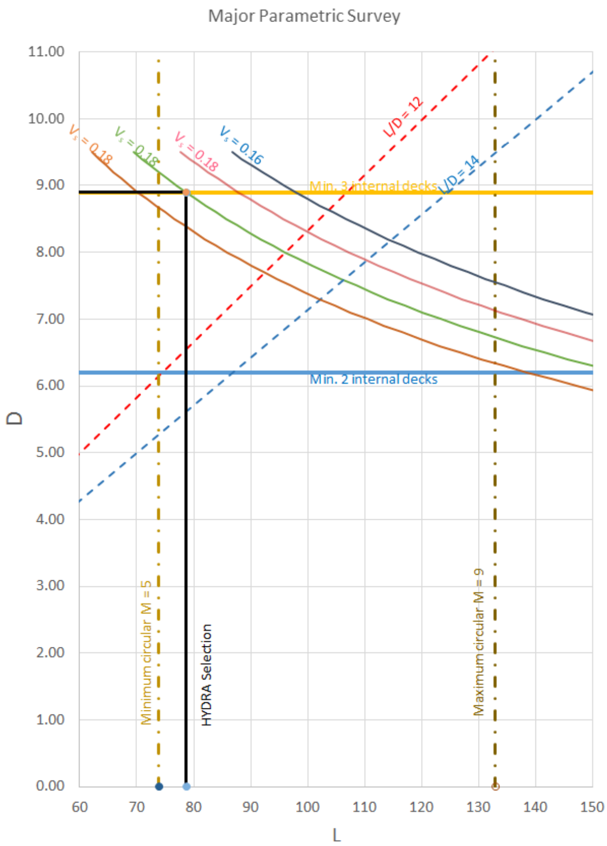


Figure 13: Graphical summary of the major parametric survey, showing constraints on the solution space (Bilde, 2017)

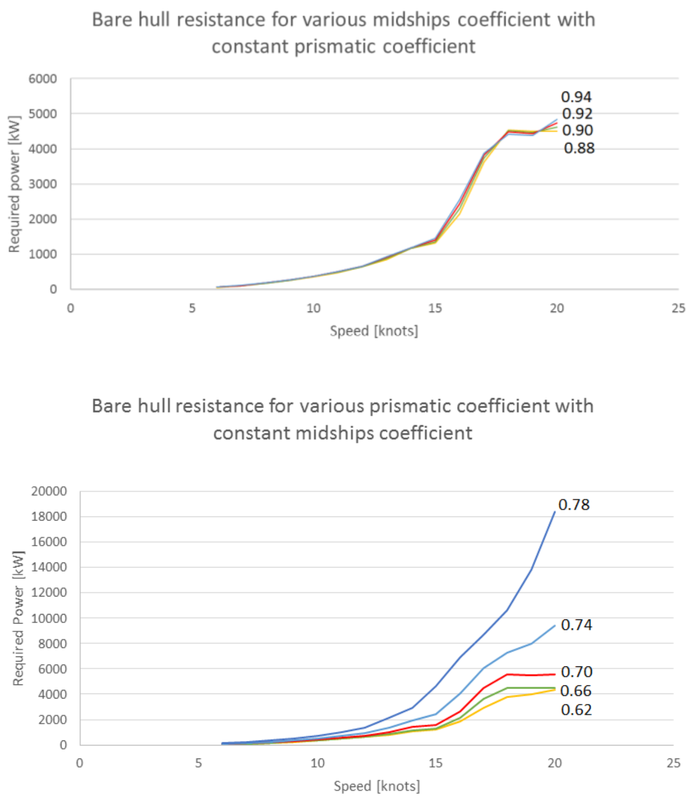


Figure 14: Summary of the resistance-focussed minor parametric survey (Bilde, 2017)

3.3 *HYDRA Design Solution*

Figure 15 illustrates the HYDRA coastguard option, showcasing the large flight / working deck, 360-degree bridge and twin azipull propulsors, selected for use in dynamic positioning (DP) and including ducted propellers for greater bollard pull during towing operations. The primary external differences between the three options were the upper-deck equipment (weapons or cranes) and the replacement of the aft boat bays with increased accommodation in the research and submarine rescue variants. Table 6 summarises the principal particulars for the core design, and Table 7 outlines the primary features unique to each variant.

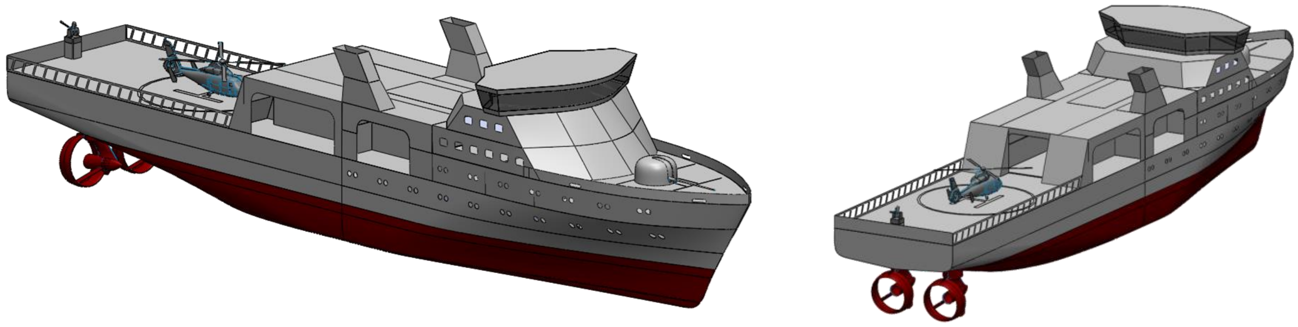


Figure 15: External views of the HYDRA coastguard option (Bilde, 2017)

Table 6: Principal particulars of the core design, common to all variants

Main Dimensions	
Length over all	89.5m
Length on waterline	83.5m
Beam	15.7m
Depth	8.9m
Draught (SLL)	4.42m
Design Displacement	3577tons
Cb	0.61
Cw	0.8
Cp	0.66
Cm	0.92
Speed	14knots
Cruise speed	20knots
Top speed	
Platform Features	
Class 1 Lloyds Fire Fighting	
Towing Bollard Pull	110tons
Towing Winch Force	300tons
Humanitarian Aid	200survivors
Platform TEU capacity (NEO)	18TEU

Machinery and Propulsion	
Integrated Fully Electric Propulsion	
Diesel Generator	2x4.2MW
Fuel Cells	2x4.4MW
Steerable Azipull Thrusters	2x3.2MW
Fwd. Tunnel Thruster	1x0.8MW
Fwd. Retractable Thrusters	2x0.8MW
Capacity	
Total DFO capacity	531m3
Convertible to Future Fuel tank	370m3
Total Freshwater	74m3
Deck Area	400m2
Costs	
Core vessel	£66.93M
Coastguard module	£28.56M
Rescue module	£20.02M
Research module	£20.68M
Accommodation	
Single Standard	24
Single Deluxe	22
Double Standard	6
Officer Suite	2
Captain Suite	1

Table 7: Features and equipment unique to each of the three variants

Research	**Coast Guard**	**Rescue**
Accommodation for 30 scientist	4 x Scan Eagles, 1 x Helicopter	Organic Decompression facitlites
180m^2 Drylab	Large hangar	NSRS compatible
120m^2 Wetlab	2 x 11m RIBs	8 resuscitaiton wards
80m^2 equipment bay	2 x 7m RIBs	20 IC wards
Internal L&R system	1 x State-of-the-art Ops Room	Bloodbank
A-frame	Accommodation for maintenance and boarding teams	

Figure 16 expands on the topological arrangements shown in Figures 10 to 12, showing the location of the main and auxiliary machinery spaces. HYDRA uses an Integrated Full Electric Propulsion (IFEP) arrangement, with two 4.16MW diesel generators, two 1.4MW fuel cells and two 2.125MWhr battery systems. Given the in-service date of 2025 and the requirement for emissions reduction, the fuel cells were selected for cruising speeds up to 14 knots (also providing a reduction in acoustic noise), with the diesels providing boost power to make the maximum speed of 20 knots. The battery system serves several purposes; a load-levelling and boost system during towing operations (allowing the diesels to operate at constant load); a completely silent mode of operation; and an emergency power source.

It should be noted that the MSc SDX requires the development of the design to some technical detail. Table 8 summarises the naval architectural modelling and analysis activities carried out in the MSc design development. As with the parametric survey, it is expected that all designs in the MSc SDX will cover each of these aspects, but that there may be a focus on specific aspects if the design warrants it (e.g. hullform for a high speed vessel). Figure 17 provides an example of the level of detail in the general arrangement drawing (of the research option in this case).

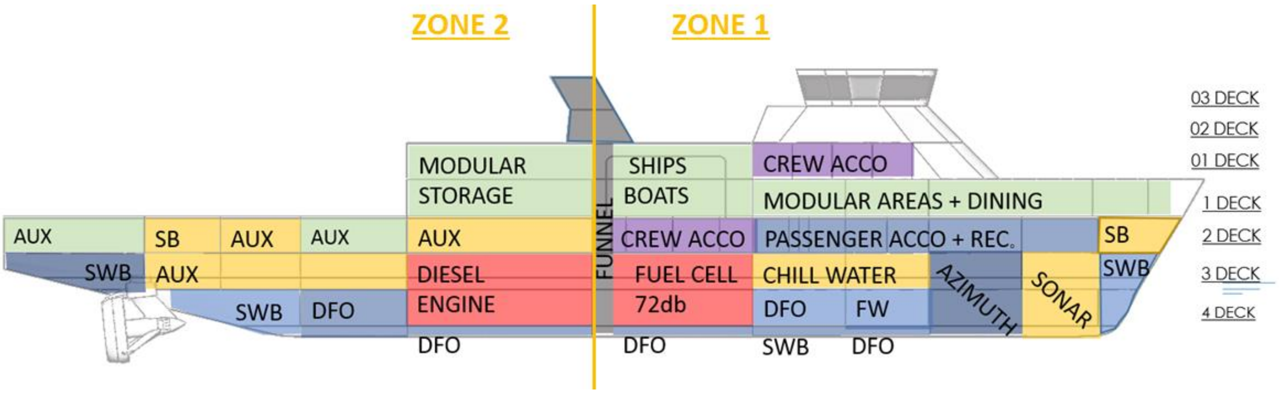


Figure 16: General profile of HYDRA, showing main functional areas and machinery locations (Bilde, 2017)

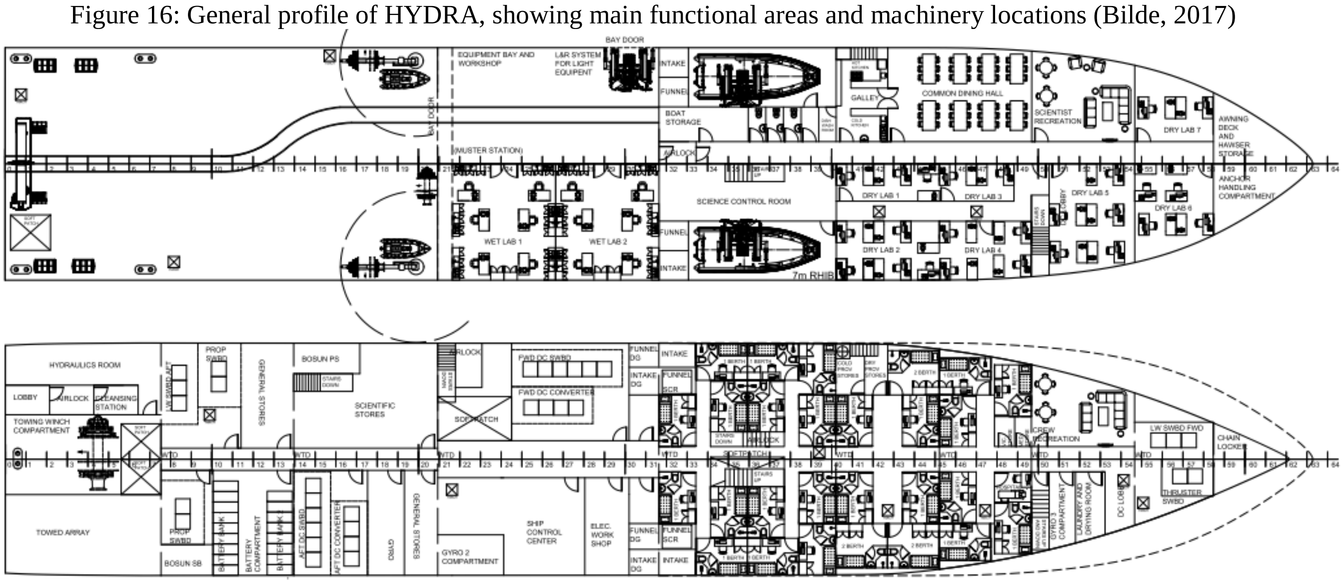


Figure 17: No 1 and No 2 deck of the HYDRA research option (Bilde, 2017)

Table 8: A summary of the naval architectural technical aspects examined in the HYDRA design

Technical Area	**Outline**
Resistance	Resistance estimation using regression methods; comparison of methods & evaluation of consistency
Propulsion	Maintenance strategy & removal routes, working with the marine engineer
Hullform design	Hullform design in Paramarine or Maxsurf; lines plan generation
Complementing	Complement estimation and rank / task structure
Architecture & arrangement	Layout functional concept; zoning; arrangement detailed to individual space & major equipment level
Structures	Midships bending moment & shear force evaluation; midships section design (including grillage selection); identification of risks & uncertainties
Stability	Intact stability in all loading conditions, beginning & end of life; damaged stability to selected design standards; calculations in Paramarine
Manoeuvring	Evaluation using Paramarine of circle & zig-zag manoeuvres
Seakeeping	Evaluation using Paramarine, motions typically assessed at; bridge; flight deck; boat davits
Costing	Unit Production Cost (UPC) for core vessel & options; operating costs / required freight rate for commercial vessels; market comparison
Compliance with URD	Statement of compliance / non-compliance with each entry in the URD; mitigation strategies for non-compliance

Table 9 summarises the marine engineering technical modelling and analysis activities carried out in the MSc Marine Engineering component of the SDX. As with the analyses in Table 8, several are carried out independently by the marine engineer, but there are some notable aspects, such as the propulsion system selection, where the two disciplines are expected to work together and to make the decision based on the whole-ship implications. Figure 18 provides a line diagram of the IFEP electrical propulsion and distribution system for HYDRA.

Table 9: A summary of the naval architectural technical aspects examined in the Marine Engineering MSc

Technical Area	**Outline**
Complement estimation	Historical data is available, but a detailed breakdown is expected
Environmental legislation	Consideration of appropriate environmental legislation
Fuel choice & consumption	Quantitative & qualitative (technical risk) comparison of fuel options & sizing of tanks
Propulsion system architecture	Consideration of multiple architectures & justification for selection, including working with the naval architect to capture whole-ship impact
Prime mover sizing	Sizing of prime movers, including part-load considerations
Electrical load analysis	Development of electrical load chart
Fault current analysis	Calculation of fault current on each electrical bus & switchboard
Electrical harmonic analysis	Analysis of harmonic distortion in rotating electrical machines
Removal routes & maintenance	Maintenance strategy & removal routes, working with the naval architect
Hotel systems design	Definition of system architecture & sizing of main components for: Chilled water systems, HVAC systems, Fresh water systems, Black & grey water systems, Exhaust treatment systems, High & low pressure sea water systems

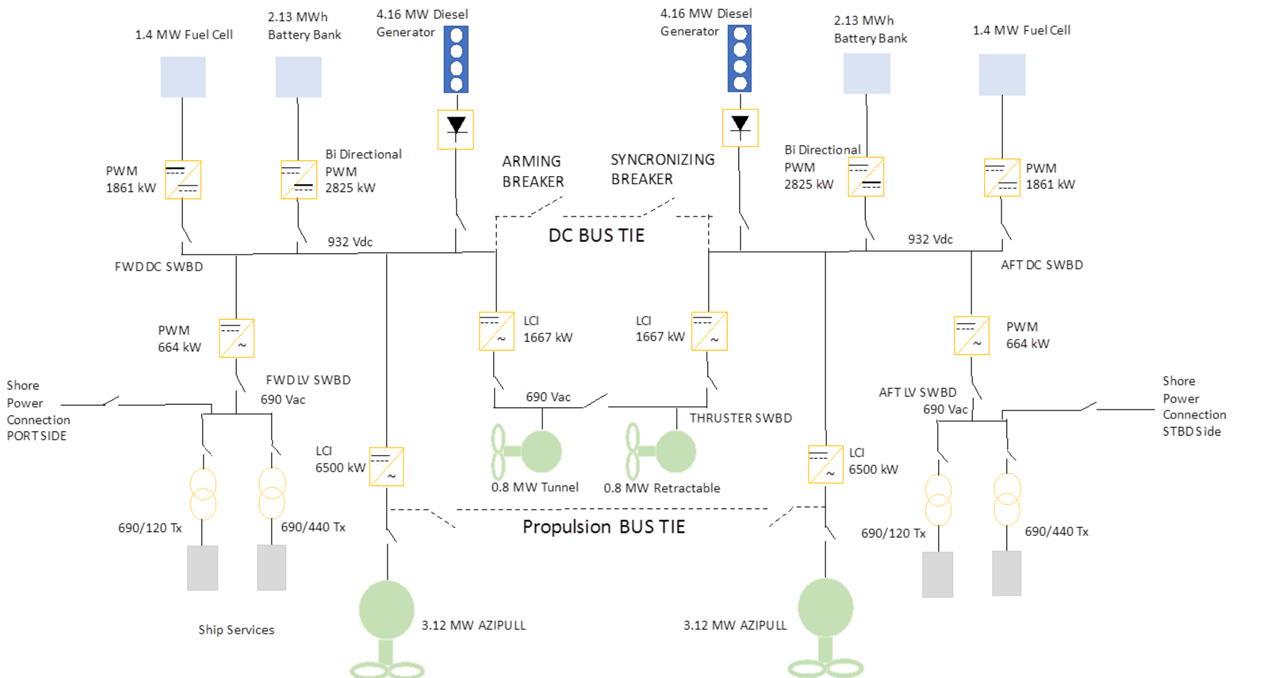


Figure 18: HYDRA power and propulsion system line diagram (Hunt, 2017)

4 SHIP DESIGN IN THE OCEAN ENGINEERING MINOR

4.1 *The IEP*

The Integrated Engineering Programme (IEP) is a multidisciplinary modular teaching framework with eight core engineering disciplines and a range of specialisms, similar to the major / minor degree structure used in some countries. There is a strong emphasis on group and individual design activities as a core part of the teaching. This design education both contextualizes the detailed technical education and also integrates input from industry on "real world" engineering problems for the students to examine.

The IEP Ocean Engineering minor consists of one three-month module in each of the first, second and third years of the course. The first year "Ocean Engineering Fundamentals" provides an introduction to ships and maritime industries, the basic analytical methods of naval architecture, and a practical design-build-test exercise for a small ROV. The second year "Offshore and Coastal Engineering" module turns to the ocean environment, with a port facilities design exercise. The third year "Maritime Design" module was developed by the first author, based in part on the legacy UCL undergraduate ship design exercise.

4.2 *The Maritime Design Module*

In keeping with the design-oriented nature of the IEP programme, the Maritime Design module revolves around a Maritime Design Exercise (MDX) featuring the development of a concept design for a container ship (with additional ship types to be added in future iterations of the module) although as with the MSc course, the OPV DX is used to introduce the students to the design process in a highly simplified form with a constrained problem space. In the MDX, the students are provided with a requirement set that is more open than the OPV DX, but less so than the MSc SDX. Table 10 summarises the design requirements.

Table 10: The initial requirements provided to students in the Maritime Design module

Requirement	Notes
Role	Feeder, trans-oceanic, general purpose etc.
Capacity	A wide range of capacities of interest.
Speed	A wide range of speeds of interest.
Route	Operating area of interest.
Special study	Special studies to differentiate designs, such as: icebreaking, gas fuel, ConRo, etc.

The students produce arrangement drawings, preliminary estimates of weights, stability, powering, emissions and cost, along with a 3D printed model of the design. This module has a strong emphasis on individual work, with a limited number of technical lectures and several free-form workshop sessions aligned with various activities in the design process.

4.3 *Challenges in the Maritime Design Module*

One of the primary challenges of the modular IEP course is that, particularly in the later years of the course, students may opt for a specialist minor module without having previously studied that topic. A chemical engineer may decide to only do the third year Maritime Design course without having the first and second year courses which introduce stability, for instance. Another challenge is that specialist CAD software and workstations may not always be available to support the high level of individual work – and the compact three-month timetable highlights the fact that time spent learning design tools is time not spent learning design.

These challenges have impacted on the teaching of the maritime design module in two main ways. Firstly, it limits the depth of technical detail that can be taught and assessed – the students receive summary lectures on stability, powering etc. but they cannot be expected to analyse these to the same level of detail as a dedicated course with dedicated facilities and software. The module is instead focused on the process of design; of integrating different technical assessments in an iterative decision making process under conditions of uncertainty and imperfect knowledge (i.e. Figure 3). Secondly, technical modeling and analysis tasks have to either be simplified enough that the students can construct their own models using Microsoft Excel; or alternatively make use of simplified or constrained software tools, again written in Excel.

Table 11 summarises the key modelling and analysis activities and tools used in the MDX. Notable is the requirement to detail the general arrangement drawing by hand. This serves two purposes; to reduce dependence on specialist CAD software and as a (proposed) means for students to develop the discipline needed to produce clear drawings in future.

Table 11: Modelling and analysis tools in the MDX

Task	Tool	Description
Initial sketches	Excel ISDX tool & hand sketches	The ISDX historical-data based tool is used for initial sketches of possible design solutions.
Numerical sizing	Spreadsheet model	A process & data document is provided to the students and they must construct the iterative sizing model themselves. Individual research is required to complete the dataset.
Costing & economics	Spreadsheet model	As above. Individual research is required to complete the dataset
Emissions analysis	Spreadsheet model	As above. Individual research is required to complete the dataset.
Hullform design	Type-ship based Excel tool	A developed version of the hyperbolic waterlines based approach described by Calleya et al (2015)
Resistance estimation	Type-ship based Excel tool	Spreadsheet implementations of Holtrop & Mennen method.
Intact small angle stability	Hand / Excel calculation	Using hydrostatic outputs from the hullform tool.
Intact large angle stability	Type-ship based Excel tool	A regression-based tool using a database of ship hulls, developed by Ali (2003).
Damage stability	Hand / Excel calculation	A single-hold midships damage case using the added mass or lost buoyancy methods.
Layout (block level)	Excel based tool	A developed version of the OPV DX tool shown in Figure 2.
Layout (detail)	Hand drawing	Hand drawing over printed block drawings; a scaled grid is provided in the printed drawings to assist in area calculations.

4.4 *Decision Making and Uncertainty in the Maritime Design Module*

As has been noted throughout this paper, a key aspect of ship design education – independent of the level of technical/analytical detail that may be taught – is in making and justifying decisions, particularly under conditions of incomplete data, changing requirements and uncertain futures. This has led to some specific features of the Maritime Design exercise, including; sketching; options exploration; data provision; and design margin exploration.

The ISDX used in the UCL Naval Architecture and Marine Engineering MSc courses is incorporated into the MDX as part of a market survey / literature survey activity. After receiving their outline ship specifications, the students are tasked with researching the routes, ship sizes and technological or emissions requirements and generating initial "sketch" designs based on historical data and a simplified layout. In addition to the use of historical data (with later comparison to the developed design), this introduces students to the need to sketching (in the methodological sense) as a crucial ship design activity, as described by Pawling and Andrews (2011).

In the legacy UCL undergraduate container ship design exercise, the students were required to develop a simplified parametric sizing model, then conduct an economic design exploration to determine the "optimum" combination of ship speed and capacity for the lowest freight rate, before developing the chosen option. This is retained in the MDX, but with the addition of through-life considerations in a (pseudo) risk based approach influenced by the real options analysis described by Puisa (2015) and scenario planning such as that carried out by Shell (Shell, 2017). Students must propose possible future ranges for fuel prices and technological availability and compare design options for their adaptability (and subsequent financial risk) across these multiple scenarios. This activity also encourages students to investigate efficiency and emissions reduction technologies and their impact on the design, such as those investigated in the Shipping in Changing Climates (SCC) project (Calleya et al, 2016). This wider-ranging study effectively replaces the parametric survey used in the MSc SDX.

The approach to design data provision in the MDX is different to that previously used in the MSc OPV DX and SDX; the students will be provided with a partial dataset, and expected to conduct individual research to obtain additional data. The data they are provided with will include items such as weight of distributed systems (which is difficult to find), but they will be expected to obtain data for major items of equipment by consulting manufacturers webpages, reference books etc. One objective of this aspect is to encourage students to approach sources of data critically, rather than prohibiting them outright (which may be unrealistic).

Design margins have traditionally been handled in student ship design exercises by the suggestion of certain percentages (and locations if appropriate), along with some narrative on the historical and engineering reasons for them to be used in ship design. However, this does not require students to actively engage with the rationale behind design margins, as they become simply a small modification to other numerical data. In the main container ship design exercise for the maritime design module, students are instead required to conduct design explorations, using their parametric models, to assess the impact on the design of using different levels of design margins, and particularly to assess the impact of estimates and assumptions, such as VCG, being incorrect.

5 CONCLUSIONS

This paper has described the ways in which ship design as a subject is taught through practice in the UCL MSc Naval Architecture and Marine Engineering courses, and the Integrated Engineering Programme Maritime Design module. A notable contrast between the four examples (ISDX, OPVDX, SDX and MMDX) is the degree of technical analysis that is expected from the students; the ISDX is very simple, and focusses specifically on the assessment of the use of historical data and identification of design drivers; in contrast the MSc SDX requires the students to both complete a high standard of technical modelling and analysis, and also explore design options and justify decisions to the customer (represented by academic staff). The undergraduate MMDX has the unique requirement that the students may not have completed previous naval architecture modules, so may have a very limited understanding of technical aspects such as stability. The greater technical knowledge of MSc students allows a design process with very broad URDs, which can be interpreted in a range of ways. For the undergraduate course, the design requirements must be more straightforward.

A common feature of all these design exercise, however, is the need for the students to compare options and make decisions, rather than simply follow numerical sizing methods. Both the main exercises – the MSc SDX and undergraduate MMDX – have explicit requirements for options exploration and downselection (e.g. the use of Equity; parametric survey; economic risk analysis). The decision making processes in these cases are supported by analytical methods and tools, but the students are operating under conditions of incomplete knowledge (and an incomplete requirement), so simplistic mechanistic approaches are insufficient, and the students are obliged to intellectually engage with the decision making. The SWOT and WSM approaches used in the HYDRA example are useful in that they can accommodate quantitative and qualitative approaches in a structured way – the key feature being that the decision making is rational and defensible.

A key feature of the HYDRA design is that it is multi-role, and it is proposed that this created a problem ideal for a holistic, integrative approach to teaching ship design. A design for a simple single role vessel may be generated through an effectively linear, mechanistic process, where the student is arguably simply a mechanism to transfer values from a databook to a spreadsheet. Setting design problems where students are obliged to consider multiple, preferably somewhat antagonistic requirements can be an approach to develop decision making approaches and skills in students.

It is important to consider what design tools are available to the students, both from the perspective of time and resources available for tutorials and technical support, and significantly with regards to the impact on their learning. Although it is desirable to introduce students to industry-standard software, the high fidelity and expansive capabilities of these packages can lead to students diving into great design detail, at the expense of visibility over the overall design. The undergraduate MMDX makes use of single-purpose Excel-based software tools, each with limited applicability, in an attempt to address these issues. However, this must be contrasted with the wider range of design types that may be investigated with the more sophisticated tools, so this is highlighted as an area of ongoing discussion.

6 DISCLAIMER

Although this paper describes current UCL ship design education, the wider conclusions for design education are the opinions of the authors.

7 ACKNOWLEDGMENTS

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