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“Are You Sure About That?”: Handling Uncertainty in an Early-Stage Ship Design Process

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ABSTRACT

UCL teaches ship design at postgraduate and undergraduate level, using a combination of spreadsheets and commercial computer aided ship design tools. These tools produce single values for a given input and so uncertainty is only incorporated via margins. Experience has shown that students do not develop an effective understanding of engineering uncertainty using the current tools and approaches. This paper describes ongoing work to develop an “add on” to the existing UCL toolset to allow the representation of various ship parameters as uncertainty distributions. This is with the aim of better understanding of uncertainty in ship design, primarily for ship design education but with broader applications for concept design tasks.

KEY WORDS

Design methodology; design education; uncertainty; margins

INTRODUCTION

UCL has taught ship design since 1967 when the RCNC course moved to the Department of Mechanical Engineering from the Royal School of Naval Architecture in Greenwich. The Naval Architecture and Marine Engineering (NAME) group, part of the Department of Mechanical Engineering (UCL, 2024a) teaches ship design at two levels; MScs in Naval Architecture or Marine Engineering; and a Maritime Design module as part the “Integrated Engineering Programme” (UCL, 2024b). The author has run the undergraduate module since its inception in 2018 and, after providing support for several years, took over the running of the postgraduate module in 2019. With a background in early-stage design methodology research, frequently presented to IMDC (Andrews & Pawling 2003, 2006, 2009, Pawling et al 2015) the author has sought ways to combine research and teaching interests. This paper briefly describes the UCL postgraduate course, focusing on observations regarding the way in which uncertainty manifests in the teaching of twentieth century students. The concepts of uncertainty, margins and design robustness are explored, and a possible approach illustrated via a modification to existing UCL design tools.

SHIP DESIGN TEACHING AT UCL

This paper mainly focusses on the postgraduate course, as it is a longer module (450 hours commitment) with time to explore design in detail. The course and some of the details of the various design tasks are described in more detail in Pawling et al (2018). The Ship Design Exercise (SDX) module follows six months of taught modules covering aspects such as ship stability, structures, resistance and powering (for naval architects); thermodynamics, power electronics and control (for marine engineers). Students on the course are generally industry sponsored but may be early in their employer’s graduate schemes so have little practical experience. The module sees the cohort split into small groups of 2-4 naval architects and marine engineers. Design requirements for each group are generally warships and service vessels and they are characterized by being challenging and relatively open. Table 1 provides some examples of recent design requirements. The SDX requires the students to integrate the subject specific technical knowledge gained during the MSc into a coherent design. Emphasis is placed on decision making and justification, and the understanding of influences and interactions in the design.

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Table 1: Examples of UCL MSc SDX design requirements

Year	Title	Summary
2020	Optionally Crewed Territorial Defence Vessel	A small, high speed vessel for patrol and defence of home waters against a numerically superior adversary.
2021	Family of Zero Emissions Island Ferries	An adaptable design for a Ro-Pax ferry serving island routes around the British Isles
2022	Seaplane Logistics Mothership	A ship to act as a hub for logistics seaplanes including large ground-effect machines.
2023	Adaptable Export Patrol Combatant	A trimaran vessel designed for export and to be completed in several roles via design and construction modularity.

A Typical UCL Design Model

Both undergraduate and graduate design exercises involve the construction of a parametric model composed of a number of line items for weight and space, with the general iterative structure shown in Figure 1.

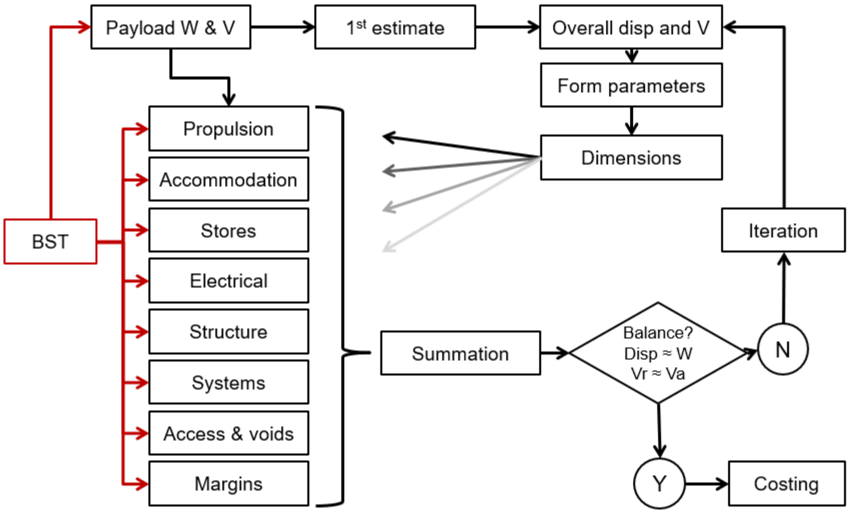
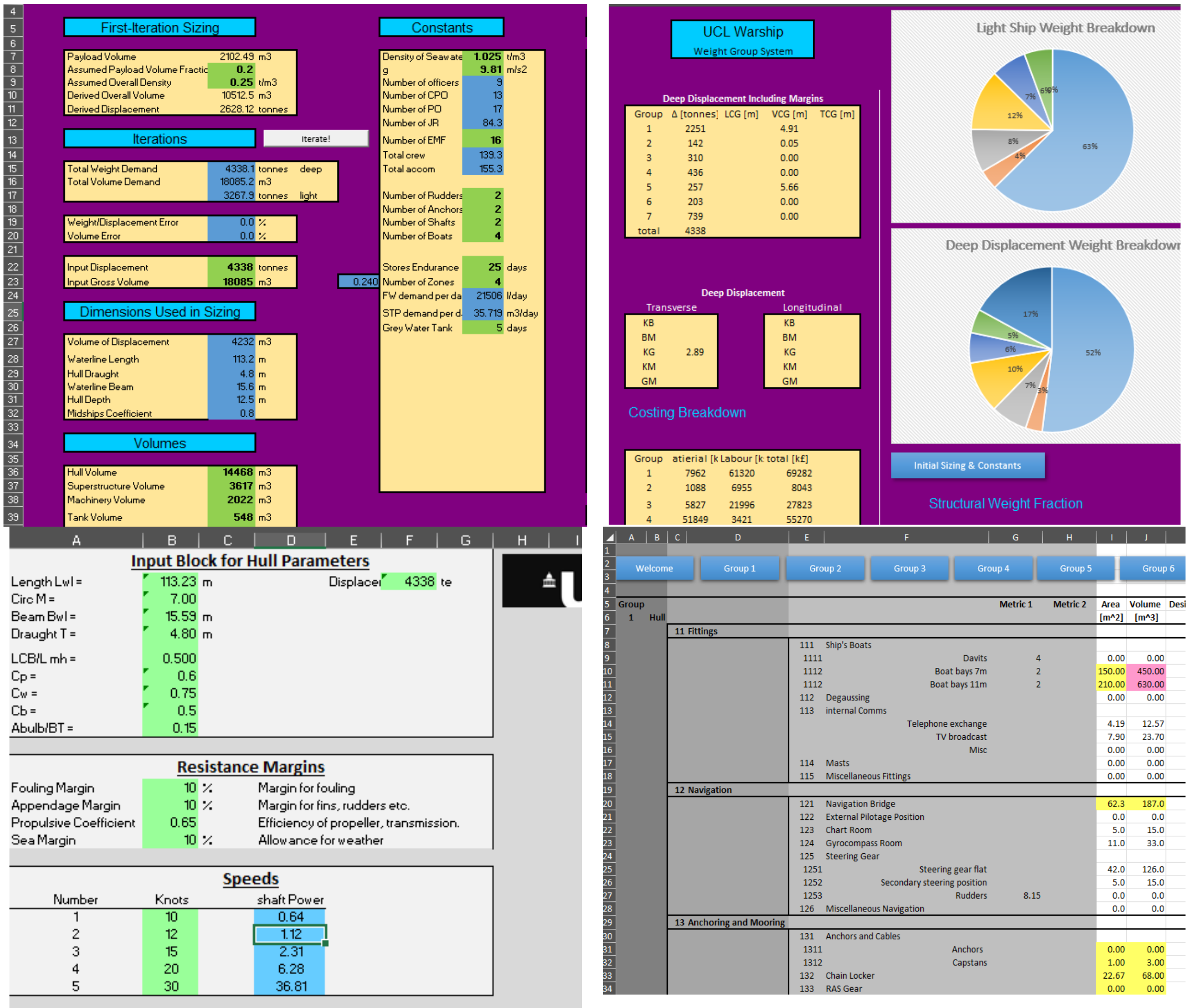


Figure 1: The general structure of a UCL student sizing model

This model is then used to examine different capability variants (cargo, speed, weapons etc.), and also the impact of different technology options, e.g. directed energy weapons or all-electric machinery. The students are provided with a template Excel file with the UCL Weight Breakdown System and various housekeeping functions such as the generation of summary tables already implemented. This spreadsheet becomes not only a design tool but also a method of managing work allocation between design team-members, integration with simplified analysis tools such as initial resistance estimates, prior to later development of Paramarine or Maxsurf design models. Screenshots of the spreadsheet are shown in Figure 2 overleaf.

MARGINS, UNCERTAINTY AND ROBUSTNESS IN SHIP DESIGN

Within the UCL SDX, general uncertainty in design is handled in a relatively simplistic manner. Margins are added to weight, space and other characteristics. Stability is generally assessed in the extremes of deep and light load, and many systems such as propulsion or electrical generation will be designed to meet the worst-case scenario. Students are expected to consider more general operational scenarios, but there is not a formalised process to specify what these should be, other than some very specific cases (e.g. harbour load is a specified condition for electrical generation).



First-Iteration Sizing

Payload Volume	2102.49	m3
Assumed Payload Volume Fractic	0.2	
Assumed Overall Density	0.25	t/m3
Derived Overall Volume	10512.5	m3
Derived Displacement	2628.12	tonnes

Iterations

Total Weight Demand	4338.1	tonnes	deep
Total Volume Demand	18085.2	m3	
	3267.9	tonnes	light

Weight/Displacement Error	0.0	%
Volume Error	0.0	%

Input Displacement	4338	tonnes
Input Gross Volume	18085	m3

0.240

Dimensions Used in Sizing

Volume of Displacement	4232	m3
Waterline Length	113.2	m
Hull Draught	4.8	m
Waterline Beam	15.6	m
Hull Depth	12.5	m
Midships Coefficient	0.8	

Volumes

Hull Volume	14468	m3
Superstructure Volume	3617	m3
Machinery Volume	2022	m3
Tank Volume	548	m3

Constants

Density of Seawate	1.025	t/m3
g	9.81	m/s2
Number of officers	9	
Number of CPO	13	
Number of PO	17	
Number of JR	84.3	
Number of EMF	16	
Total crew	139.3	
Total accom	155.3	
Number of Rudders	2	
Number of Anchors	2	
Number of Shafts	2	
Number of Boats	4	
Stores Endurance	25	days
Number of Zones	4	
FW demand per da	21506	l/day
STP demand per d	35.719	m3/day
Grey Water Tank	5	days

UCL Warship
Weight Group System

Deep Displacement Including Margins

Group	Δ [tonnes]	LCG [m]	VCG [m]	TCG [m]
1	2251		4.91	
2	142		0.05	
3	310		0.00	
4	436		0.00	
5	257		5.66	
6	203		0.00	
7	739		0.00	
total	4338			

Deep Displacement

Transverse

KB	
BM	
KG	2.89
KM	
GM	

Longitudinal

KB	
BM	
KG	
KM	
GM	

Costing Breakdown

Group	atierial [k	Labour [k	total [k£]
1	7962	61320	69282
2	1088	6955	8043
3	5827	21996	27823
4	51849	3421	55270

Structural Weight Fraction

Group			Metric 1	Metric 2	Area [m^2]	Volume [m^3]	Desi
1 Hull							
11 Fittings							
	111 Ship's Boats						
	1111	Davits	4		0.00	0.00	
	1112	Boat bays 7m	2		150.00	450.00	
	1112	Boat bays 11m	2		210.00	630.00	
	112 Degaussing				0.00	0.00	
	113 internal Comms						
		Telephone exchange			4.19	12.57	
		TV broadcast			7.90	23.70	
		Misc			0.00	0.00	
	114 Masts				0.00	0.00	
	115 Miscellaneous Fittings				0.00	0.00	
12 Navigation							
	121 Navigation Bridge				62.3	187.0	
	122 External Pilotage Position				0.0	0.0	
	123 Chart Room				5.0	15.0	
	124 Gyrocompass Room				11.0	33.0	
	125 Steering Gear						
	1251	Steering gear flat			42.0	126.0	
	1252	Secondary steering position			5.0	15.0	
	1253	Rudders	8.15		0.0	0.0	
	126 Miscellaneous Navigation				0.0	0.0	
13 Anchoring and Mooring							
	131 Anchors and Cables						
	1311	Anchors			0.00	0.00	
	1312	Capstans			1.00	3.00	
	132 Chain Locker				22.67	68.00	
	133 RAS Gear				0.00	0.00	

Input Block for Hull Parameters

Length Lwl =	113.23	m
Circ M =	7.00	
Beam Bwl =	15.59	m
Draught T =	4.80	m
LCB/L mh =	0.500	
Cp =	0.6	
Cw =	0.75	
Cb =	0.5	
Abulb/BT =	0.15	

Displacer 4338 te

Resistance Margins

Fouling Margin	10	%	Margin for fouling
Appendage Margin	10	%	Margin for fins, rudders etc.
Propulsive Coefficient	0.65		Efficiency of propeller, transmission.
Sea Margin	10	%	Allowance for weather

Speeds

Number	Knots	shaft Power
1	10	0.64
2	12	1.12
3	15	2.31
4	20	6.28
5	30	36.81

Figure 2: Screenshots of the template sizing tool, clockwise from top left; iteration to numerical balance; summary tables and charts, typical weight entry table; resistance estimation

Fixed Design Margins

The use of various types of margins is an important part in any engineering design activity, however these margins have different conceptual meanings. Design and build margins are used to account both for possible changes that *may* occur with the design but also for weight growth that *will* occur during detail design but is not captured in the early-stage design estimates. In the theoretical case of perfect and complete detailed data collection and perfect and completely detailed design models, this latter type of design and build margin would not be needed, or at least could be limited to that required due to mechanical variation (e.g. plate rolling). Growth margins are also applied to prevent design limits being exceeded through life.

UCL ship design education employs several types of design and operational margins, and these are summarised in Table 2. These are ultimately derived from UK naval practice and experience in the post war period. For example, the “Board Margin” refers to the RN Admiralty Board who would authorise additional equipment to be added during the ship’s life (Brown, 1991), whilst the electrical load margin originates in the rapid growth of shipboard electronics in the post-war period (Gates & Rusling, 1982). Growth margins for UK warships were derived from historical experience of 0.5% per year between major refits (Brown, 1991). It can be seen that these are all linear, additive margins that simply make the initial design larger, heavier and more expensive, firstly to account for changes in detail design and build and then to account for changes through life.

Table 2: Typical UCL MSc SDX margins

Group	Name	Weight %	Space %
		Design and Build Margin	
1	Hull	5-10	0
2	Personnel	0-5	5-10
3	Ships services	5-15	2-10
4	Propulsion	4-10	0-2
5	Electrical services	5-10	0-10
6	Payload	5-25	5-25
7	Variables	4-7	4-7
Board margin, for additions through life		2-10% light weight @ no 1 deck	5% volume
Growth margin, for unattributed growth through life		5% light weight	
Sea margin, to prevent overloading engine		25% on shaft power	
Fuel margin		5% on fuel tankage	
Electrical load margin, for design and build		25% on design load	
Electrical growth margin, for additions through life		20% on design load + design margin	

Simply adding linear margins to design characteristics is not the only solution, and can cause problems with compounding margins (Hockberger, 1976). A ship with excessive stability margins may in fact be too stable early in life or in some light load conditions. A generator with the total margins applied in the traditional UCL approach will be lightly loaded much of the time, with consequences for efficiency and reliability. This was illustrated in Lyster and Pawling (2019) where a Monte-Carlo analysis applied to a statistical model of ship through-life operations showed that the conventional approach of designing for the worst-case, or a set of specific loadings, was poorly matched to the wide range of possible displacements and load cases that would occur once the total range of variability was incorporated into the model. This is illustrated in Figures 3 and 4 which show the probability distributions of displacement and fuel consumption for a light frigate / OPV type vessel.

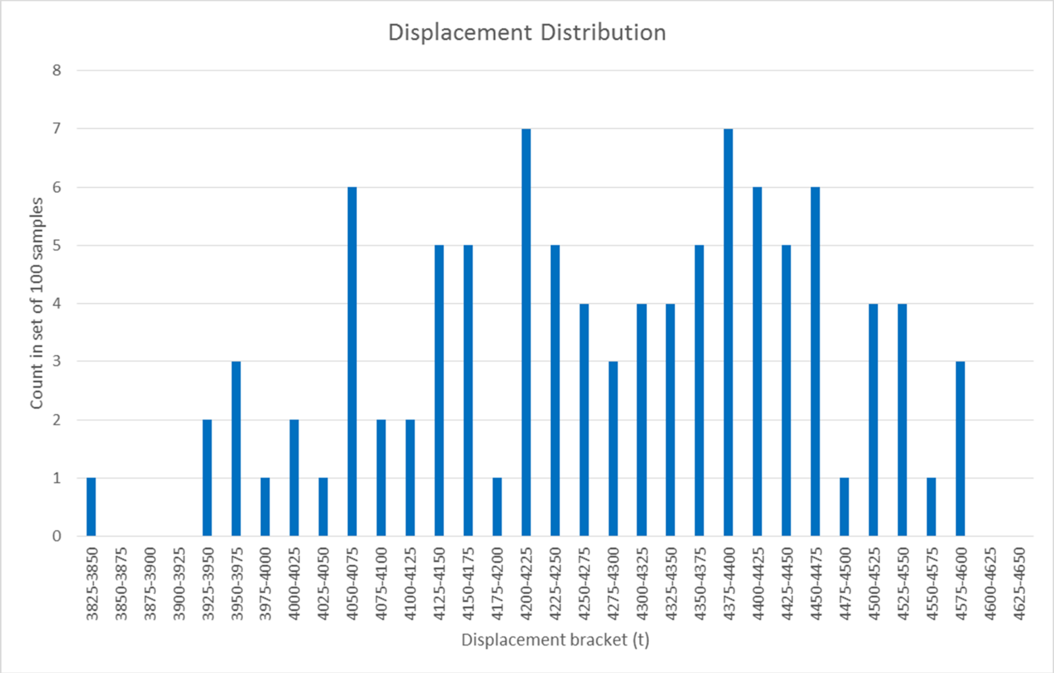


Figure 3: Probability distribution of displacement over ship life (Lyster & Pawling, 2019)

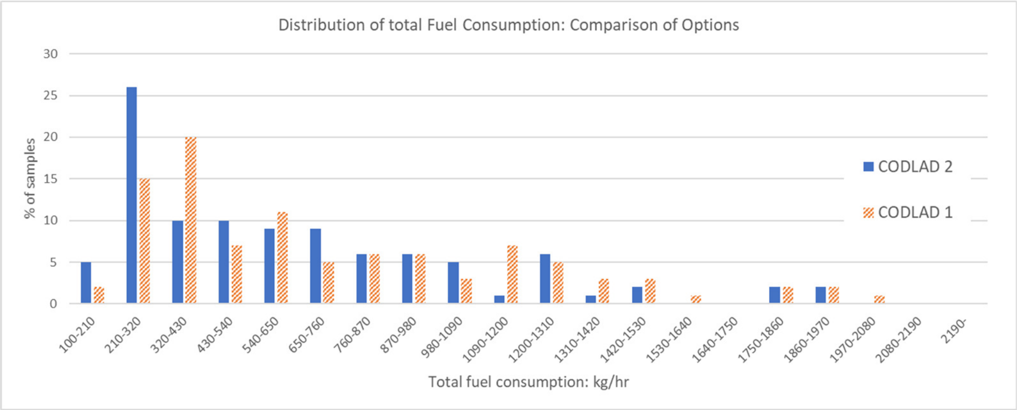


Figure 4: Probability distribution of fuel consumption for different machinery types applied to a statistical through-life model (Lyster & Pawling, 2019)

Design and build margins can however be consumed by uncertainty due to new technologies not developing as first estimated. As exceeding design margins can have undesirable consequences, the appropriate margin to be applied can be related to not just the novelty and confidence in a design estimate, but also the acceptable risk (ISAWE, 2001). Both design and through life margins can be regarded as similar in some respects to the safety margins applied when calculating loads, as they ensure a system remains within a safe (or low risk) region. However, risk here is a broad case including financial and programmatic risk rather than only structural failure or stability problems. As risk is probability multiplied by consequence, this suggests margins should be selected using an approach that examines a range of consequences for different margin choices, as different outcomes may be permitted; as noted by Brown (1991) RN practice was that the vessel had to meet its performance requirements with all design and build margins consumed, but growth margins were permitted to degrade performance but not safety. The importance of considering a range of possible outcomes increases if margin policy is derived from historical designs, technologies and operational practices which may not be appropriate for modern systems. An example is a fuel-cell based generator system. Given the higher UPC for fuel cells compared to diesel engines, oversizing the generator is undesirable. But if a large fuel cell generator is composed of multiple smaller modules, it becomes possible to remove the growth margin by allowing for easy addition of more modules later in life.

Uncertainty

Uncertainty and variation in design can take many forms and have many implications, and it is not truly captured by simple linear margins added to properties such as weight and space. Hockberger (1976) used a probabilistic approach to describe design margins in general, with the demand and supply both being probability distributions as illustrated in Figure 5.

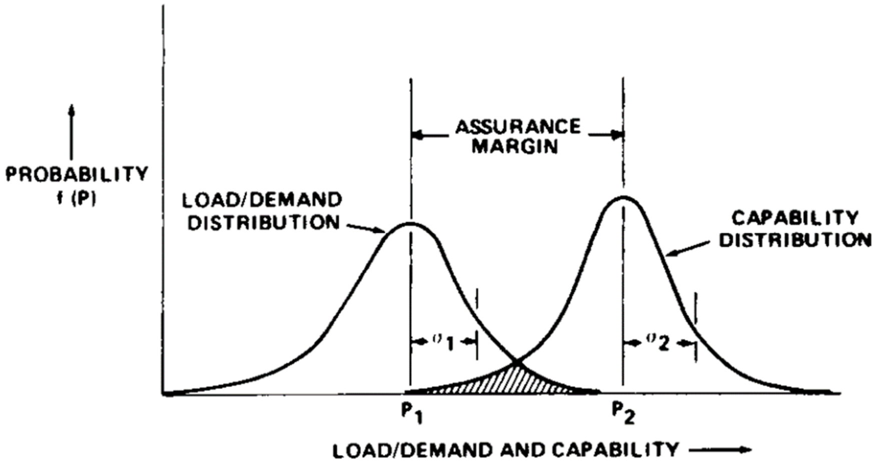


Figure 5: Representation of design demand and capability as probabilisty distributions with associated range of uncertainty (Hockberger, 1976)

Uncertainty can be inherent in the mathematical models used in ship design, as the final product produced via detailed design may vary from estimates due the vast range of possible detail solutions that can be produced to meet the same high-level requirements. Some items such as recreation spaces may also be regarded as “rubber” in that they can expand to fill available space or be compressed if the design is cramped. Table 3 illustrates this with a sample of cabin areas for five ships (all service vessels), for the same rate of cabin on that ship, normalised to the smallest example for that ship, with variations as high as 90% on the smallest size. The distribution of the ratios-to-smallest is summarised as a histogram in Figure 6.

Table 3: Example of variation in cabin sizes for the same rate

Ship	Cabin Sizes, Normalised to Smallest				
A	1	1.5	1.9		
B	1	1.2	1.1		
C	1	1.2	1.1	1.3	
D	1	1.2	1.1	1.2	
E	1	1.2	1.2	1.2	1.1

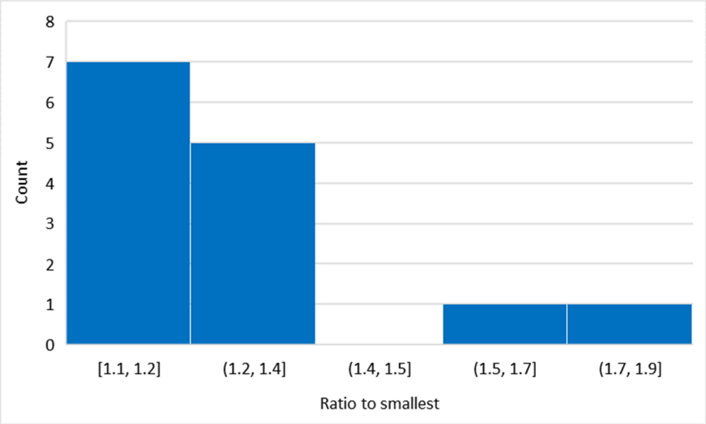


Figure 6: Histogram of ratios-to-smallest cabin

Much of the design data in the UCL database is derived from multiple datapoints with subsequent curve fitting and this type of model leads to an uncertainty of plus or minus some percent, as illustrated in Figure 7 for a generic linear diesel generator. Based on specific machinery data, the Excel trendline (using the default least-squares method built into Excel) is only around +/-20% accurate to any specific item. Figure 7 also shows the error between the linear estimator and individual data points as a histogram, with a maximum error of +/-32%.

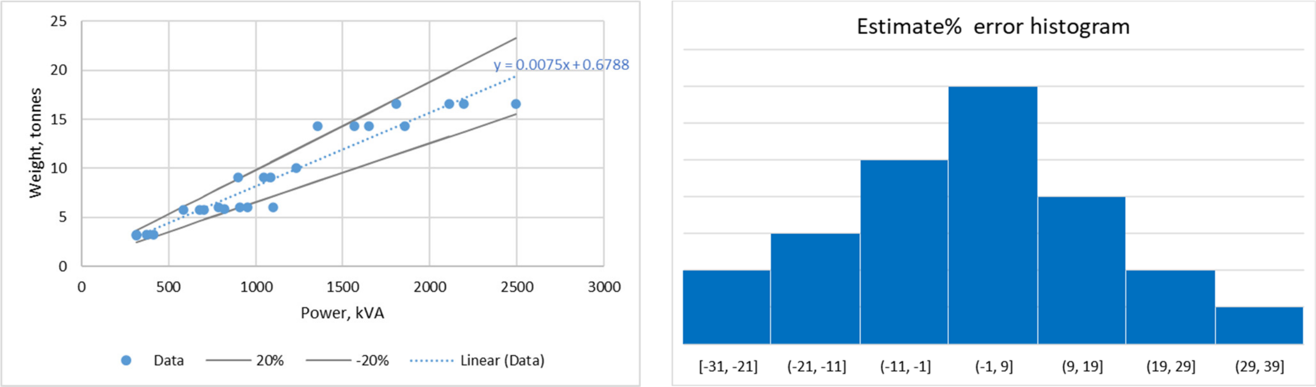


Figure 7: Example of a UCL single line sizing algorithm and error distribution

Uncertainty can also manifest as a type of prediction, i.e. a new technology might be expected to become cheaper or lighter as it is refined, thus having a wider "-%" than "+%". Porche et al (2004) described the use of BetaPERT distributions, more typically used to describe uncertainty in task durations for project management, to evaluate the effect of uncertainty in propulsion machinery technology. Figure 8 below shows such a distribution applied to the case where a trendline has been fitted to a set of data points.

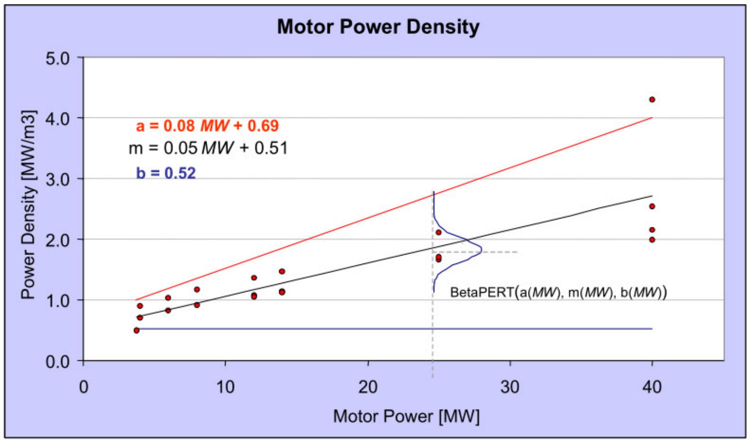


Figure 8: An example of a trendline fitted to data being the "most likely" value in a Beta distribution (Porche et al, 2004)

The Beta distribution was adopted by Porche et al as it can be used to represent a three-point estimate, itself being a simple way of describing the error or uncertainty in a numerical evaluation. In particular a Beta distribution, for the same three inputs (minimum, maximum, most likely value), weights the most-likely value more heavily. This approach can be particularly useful in comparing various options, such as electric motor technologies as shown in Figure 9, where both general trends and the potential for different technologies to have very similar outcomes can be shown.

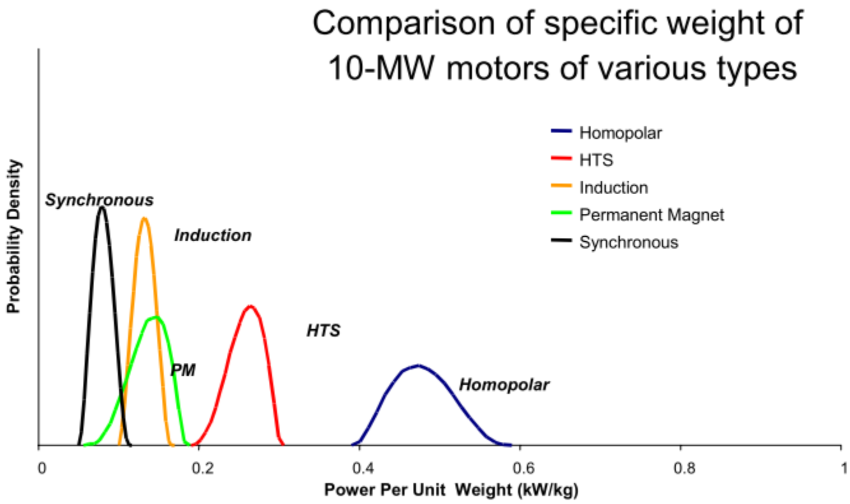
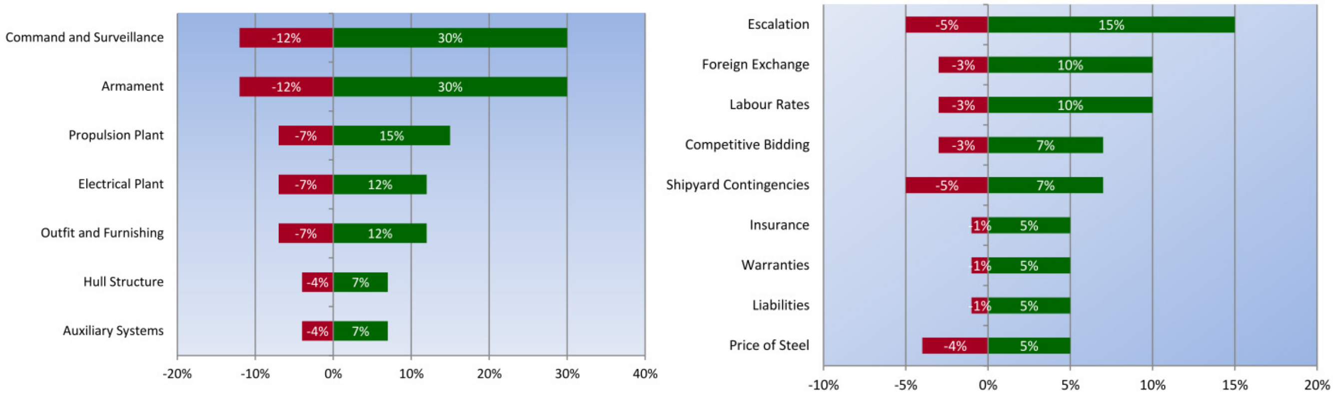


Figure 9: Representation of different motor technologies having different power density and different uncertainty ranges (Porche et al, 2004)

Whilst most mathematical and procedural methods for incorporating uncertainty have focused on the detail design and component level, e.g. structural design (Claus & Collette, 2018) or planing craft resistance (Brefort & Singer, 2018), other approaches have looked at higher level aspects, such as market and regulatory uncertainty has also been considered (Zwaginga et al 2021), (Puisa, 2015) extending to through life operation (Plessas et al, 2018). Olivier et al (2012) used a structured approach to capture subject matter expert input and develop a probabilistic model of ship cost at the weight group and total ship level. They illustrate the major difference between uncertainty inherent to the ship design ("epistemic factors") and uncertainty due to external factors ("aleatory factors"), with quite broad ranges as illustrated in Figure 10, where were then used to define the sample ranges in a Monte-Carlo analysis using a ship costing model. The importance of working with SMEs and stakeholders was also described by Brett et al (2022), in their comprehensive survey of the subjects of uncertainty and complexity in ship design.



Epistemic factors **Aleatory factors**

Figure 10: Broad ranges of uncertainty resulting from design and environmental factors (Olivier et al, 2012)

Whilst this paper focusses on the UCL postgraduate course, which mainly covers warship design, uncertainty and robustness were introduced to the undergraduate course, specifically concerning the assumed values of container or vehicle weight. Provided with data such as that illustrated in Figure 11, taken from Kristensen (2013), the students were expected to justify their assumptions for tonnes per unit cargo and discuss the likelihood and consequences of variations in service. Similarly, the students are provided with representative data on vessel utilisation and operational speed profiles and expected to consider scenarios where these differed from the theoretical optimum.

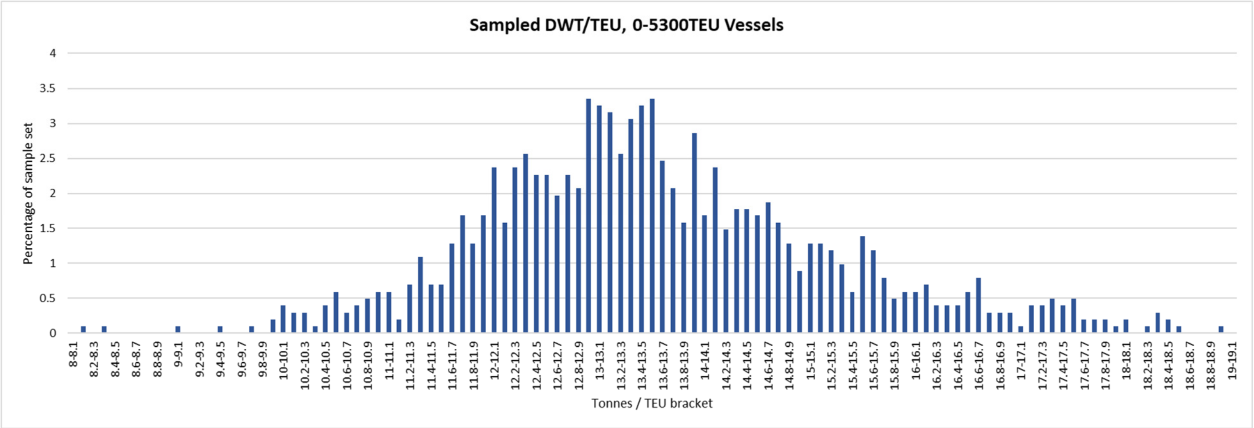


Figure 11: Example of variation in probability of occurrence with laden container mass in tonnes (n = 1013, digitised from Kristensen (2013), 0-5300 TEU range)

Robustness

Design margins and uncertainty also relate to the concept of robustness in design. The concept of robust design originated with Taguchi's robust design method, developed in Japanese manufacturing, which sought to create "a design that has minimum sensitivity to variations in uncontrollable factors" (Simpson, 2000). A graphical representation of design robustness is provided by Karl et al, (2011) and shown as Figure 12. This shows a notional design space with a surface representing possible solutions. On the left, a solution is shown that has been selected for peak performance. Whilst it easily meets the customer requirement, the steep shape to the local solution space means that any change in design or operational characteristics leads to its performance rapidly falling to below the requirement. To the right of the figure is an example of a more robust solution, which may not have such high performance, but will remain above the customer requirement for a range of design or operational characteristics.

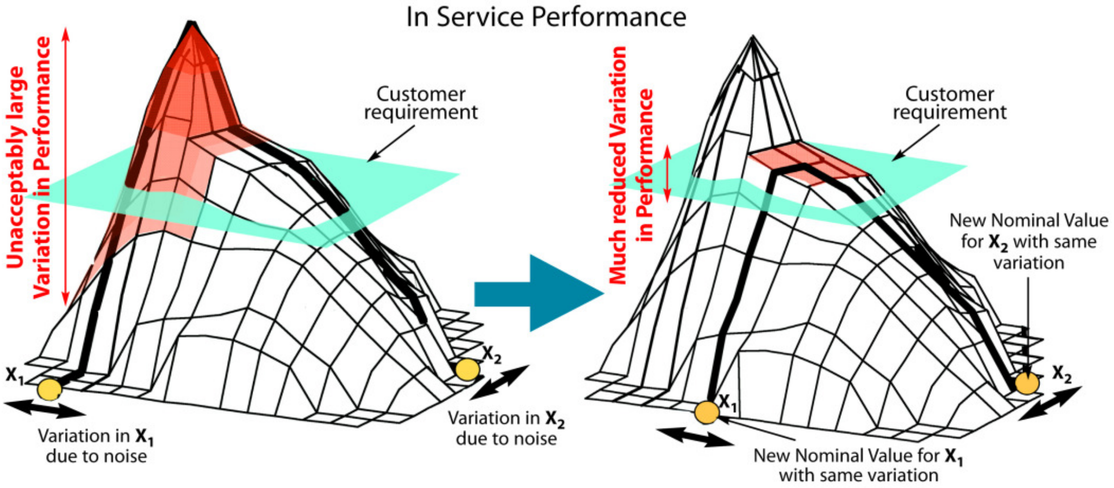


Figure 12: Example of highly optimised (left) and robust design (right) (Karl et al, 2011)

Summarising literature on robust design methods that would of interest in ship design, Puisa et al (2014) outlined four ways of dealing with uncertainty:

- Resistance: plan for the worst possible case of future situation – this is similar to the conventional approach used in the current UCL MSc SDX.
- Resilience: whatever happens in the future, make sure that the system can recover quickly – this is a key part of warship survivability, being the crew-centric concept of recoverability.
- Static robustness: aim at reducing vulnerability in the widest possible range of conditions.
- Dynamic robustness (or flexibility): plan to change over time in case conditions change.

Various mathematical approaches have been applied to the problem of robust design, including real options valuation (Puisa, 2015), the use of response surfaces providing meta-models of more complex engineering models (Karl et al, 2011), Epoch-era analysis (Gaspar et al, 2015) whilst the US Department of Defense's Engineered Resilient Systems (ERS) effort sought to improve the resilience and robustness of US defence procurement through the application of high-performance computing tools (Neches, 2012).

Adaptability and Changing Design Styles

The design of both warships and commercial vessels has changed in recent years, with cargo vessels, previously having been seen as the perfect example of a ship "optimised" for a single operational point, now having a much broader range of operational speeds (Banks et al, 2013) and in general a greater understanding of operational variation in the design, leading to changes in hull design for example or considerations of designing for adaptability through later refits (Puisa, 2015). The long operational life and rapidly changing strategic and technological environments mean adaptability has long been of concern for warship designers (Andrews, 2001) and recently warships have seen ever greater use of modularisation e.g. Doerry (2014), an approach introducing substantial uncertainty as to system weight and service demands, even if volume is constrained (Abbott, 1977).

Whilst some items in the UCL ship design database are derived from a technologically similar set of datapoints, such as a range of high speed marine diesel engines from one or two manufacturers, the majority of the scaling algorithms were generated using weight and space data from RN warships of the 1970s and early 1980s and so inherit the design style of those vessels. Pawling et al (2013) proposed a definition of "Style" in the engineering context of warship design as "a cross-cutting concept, where one decision explicitly influences a wide range of solution areas", with one example being how the approach to survivability will impact the number of bulkheads and detail design to resist shock. Some stylistic aspects of warship design have changed since this database was defined, such as the adoption of "Naval Ship Rules" and semi-commercial approaches, that do not explicitly call for heavier structure, but frequently lead to it. That warships are subject to change in their general style and proportions is well documented, e.g. Gates & Rusling (1982), implying a need to capture possible (but not certain) changes in general design style from current concept design algorithms.

THE PERCEIVED NEED FOR A NEW APPROACH IN THE SDX

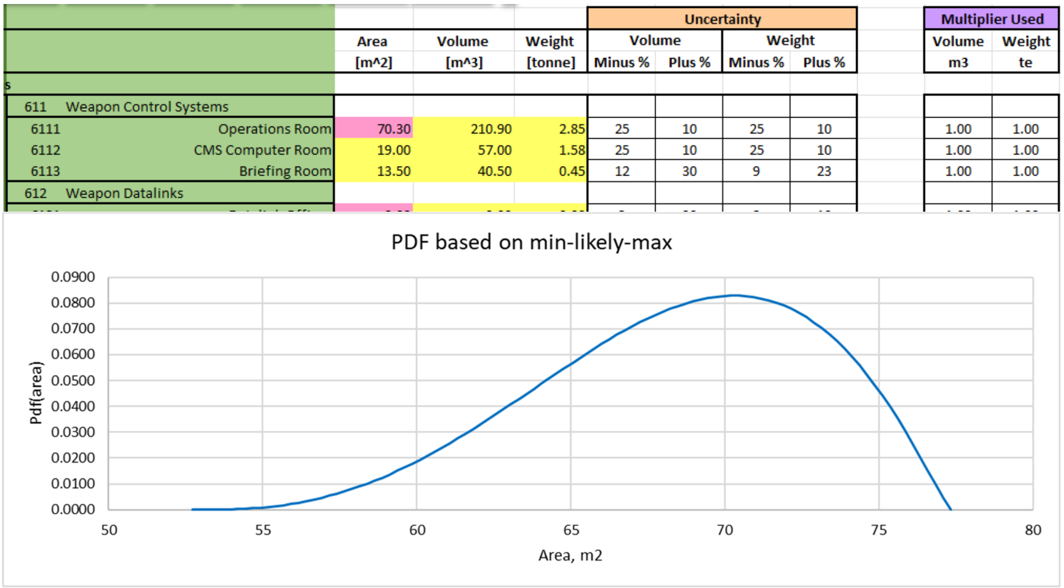
Whilst the UCL design process features several stages of option exploration and selection, ultimately it results in a single point design assessed over a limited set of operational conditions. Although students are expected to consider aspects such as uncertainty and robustness in their designs, and justify their choice of margins, it is generally difficult to ensure they do so purely through lecture material and discussion – if default margins are provided, students will usually adopt them. There is thus a need for a method and toolset for students to examine possibilities and determine margins as a structured part of the exercise. Another reason for introducing improved handling of uncertainty within an educational concept is an observed trend for many engineering students to view engineering as simply "applied mathematics", with any value calculable with high precision. It can be a challenge to assist students in internalising the changes in engineering systems with increasing detail, and the difference between a sizing algorithm applicable to a wide range and data representing single points, i.e. the importance of being "approximately right" rather than "precisely wrong".

Against this educational and engineering background, as the co-ordinator for the two UCL ship design modules, the author has been examining how concepts such as uncertainty, robustness and margin selection can be better examined in the course, through the use of software tools. The author has previously presented some aspects of software tools for ship design education (Pawling et al, 2015), with specific attention to teaching general arrangements design. Nine properties were identified as being important for tools to be usable by students. Based on these, the approach has been to take the existing Excel spreadsheet templates and add additional functionality;

1. Wide availability:
2. Low learning and familiarisation overheads:
3. Fast operation:
4. Not type ship based:
5. Task focused:
6. Not automated:
7. Integration of models, datasets and evaluation:
8. Flexible levels of detail:
9. Appropriate levels of precision:

THE MODIFIED MODEL

The existing UCL MSc ship sizing template Excel sheet was modified with additional characteristics for each line item and VBA macros to carry out various studies. The most visible change is that the weight, space, cost etc. defined for each item becomes the "most likely" value in a beta distribution, with a percentage +/- defined for each item. This is illustrated in figure 13 below.



					Uncertainty				Multiplier Used	
		Area [m^2]	Volume [m^3]	Weight [tonne]	Volume Minus %	Volume Plus %	Weight Minus %	Weight Plus %	Volume m3	Weight te
611	Weapon Control Systems									
6111	Operations Room	70.30	210.90	2.85	25	10	25	10	1.00	1.00
6112	CMS Computer Room	19.00	57.00	1.58	25	10	25	10	1.00	1.00
6113	Briefing Room	13.50	40.50	0.45	12	30	9	23	1.00	1.00
612	Weapon Datalinks									

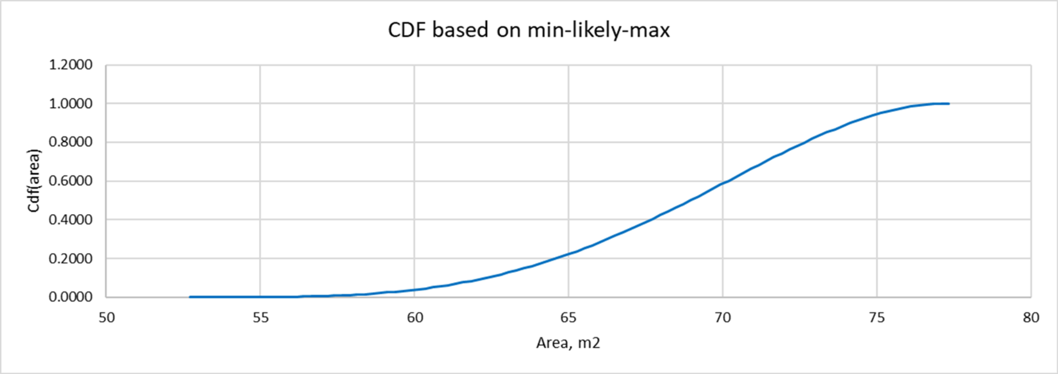


Figure 13: Top: modified table with +/- percentages for weight and volume. Middle: Resulting Beta Probability Density Function (PDF). Bottom: Cumulative Density Function (CDF).

Sampling was carried out using the Cumulative probability Density Function (CDF). For a required number of samples, the CDF was sampled at a random point within each sample window. Figure 14 below illustrates a sample taken at 0.275 within the sample window 0.2-0.4 (i.e. the window resulting from a sample number of 5).

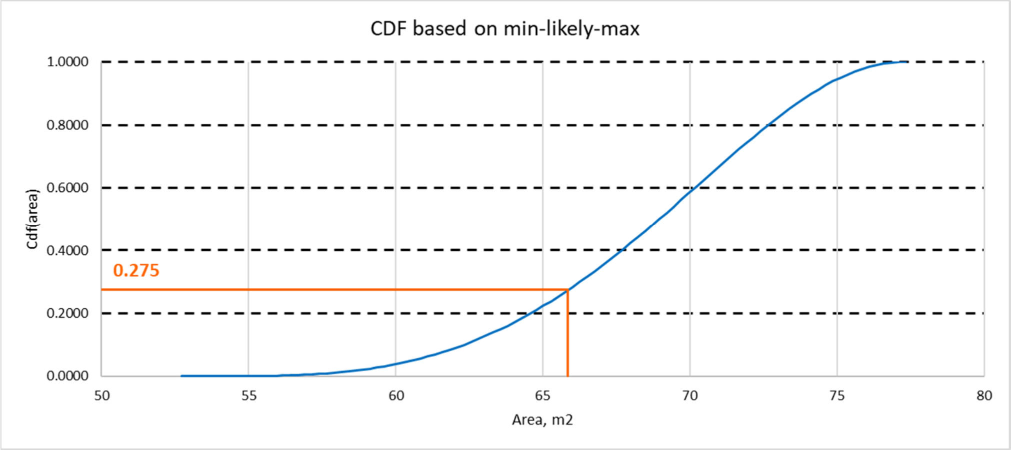


Figure 14: Example of a sample taken from a CDF

At the time of writing, the following studies have been implemented using VBA macros:

MOST LIKELY Run: This macro sets the values to their most likely value and balances the design.

MAX Run: This macro sets all values to their maximum value and balances the design.

MIN Run: This macro sets all values to their minimum value and balances the design.

X% Run: This macro sets all values to their Xth percentile value and balances the design. Currently this is set to the 50th percentile. The aim of this function is to allow students to quickly identify a "most likely" outcome.

Weight Group X Sensitivity Study: This macro conducts a simple sensitivity study for a selected weight group "X", varying each item from its minimum to maximum value and recording the impact on the design. The aim of this function is to assist students in determining which items have the most impact on the overall design.

Special Item Study: This macro conducts a sensitivity study on specified variables. This is intended for variables such as hullform coefficients, specific fuel consumption etc. It requires more input from the user as they must specify the sheet and cell in which the variable is located.

System Sensitivity Study A: Deterministic: This macro conducts a complex sensitivity study on multiple items, using the mid-point of each range within the CDF.

System Sensitivity Study B: Random: This macro conducts a complex sensitivity study on multiple items, using a random point within each range of the CDF. System sensitivity studies are defined in a tabular structure illustrated in Figure 15. Up to six line items can be defined. There is no restriction on the number of samples, other than user preference for run time.

Selected Items for System Sensitivity

Item #	Item Name	Item Group	Samples
1	DG size 1	5	5
2	Electric Motors	4	5
3	GT GB	4	5
4	EM GBs	4	5
5	DG size 2	5	5
6			

Figure 15: Definition of the system sensitivity study

The tool currently uses a simple full factorial approach, examining every combination of every item. The tool generates 2 to 3 options per second, with typical run times for a study summarised in the table below. Keeping run times short is important to ensure student use, as unless they are directly assessed on the use of the tool, any activity that takes too much time will generally be deprioritised. The UCL design exercise emphasises interactivity and the explorative "sketching" model of concept design described by Pawling and Andrews (2011) where the design model is used to explore alternatives and aid in discussion. In this model of design, time spent developing and running models should be reduced as much as possible, as it can be an impediment to understanding.

Table 4: Typical run times for the tool

Items	Samples per Item	Run Time (minutes)
1	4	<1
	5	<1
2	4	<1
	5	<1
3	4	<1
	5	1
4	4	2
	5	5
5	4	7
	5	21
6	4	28
	5	105

EXAMPLE DESIGN STUDY

To demonstrate the functions currently implemented, the sizing model was populated with data representing a generic frigate, with the broad characteristics outlined in Table 5.

Table 5: Principal particulars of the example design

Combat Systems	Baseline (most likely option)	
1 x 127mm and 2 x 30mm guns	Deep displacement	4338 tonnes
20 short range and 16 medium range SAM	Light displacement	3268 tonnes
Single face AESA radar	Internal volume	18088 m3
12 long range SSM	Waterline length	113.2m
10 tonne helicopter with hangar	Waterline beam	15.6m
3 x 1.5 tonne UAV	Depth amidships	12.5m

2m 7m and 2 x 11m boats	Draught amidships	4.8m
Hull sonar	UPC	398 M£
Triple torpedo tubes	Max speed	29.5 kn
Decoys	Cruise speed	15 kn
16 x Embarked personnel	Complement	139
Machinery	CODLOG – twin shaft, single boost GT with splitter gearbox	

Example Single Weight Group Sensitivity Study

In this study the tool sets all weights to their “most likely” value, then for each item in the selected weight group performs two runs – one with that item set to its maximum value, and one with it set to the minimum. Comparison charts are produced showing several metrics; the ratio of item change (in tonnes and m^3) to overall ship change; the total range of variation (in tonnes and m^3 and as a percentage of the group totals); the percentage of the group total that that particular item makes up. These are presented in bar charts as shown in Figures 16-19 for weight group 2 (personnel).

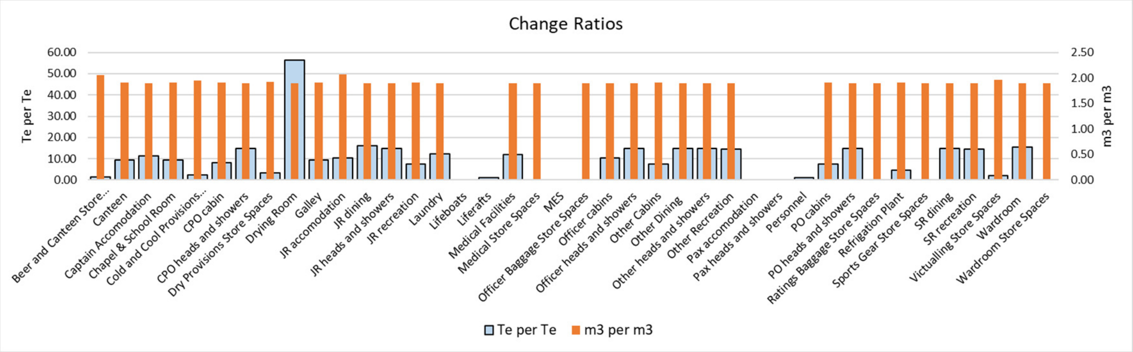


Figure 16: Ratios of item to overall ship change for group 2

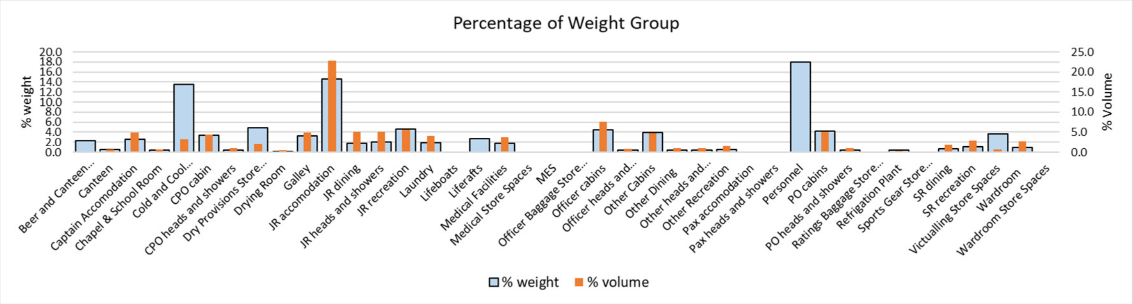


Figure 17: Composition of weight group 2 by percentage

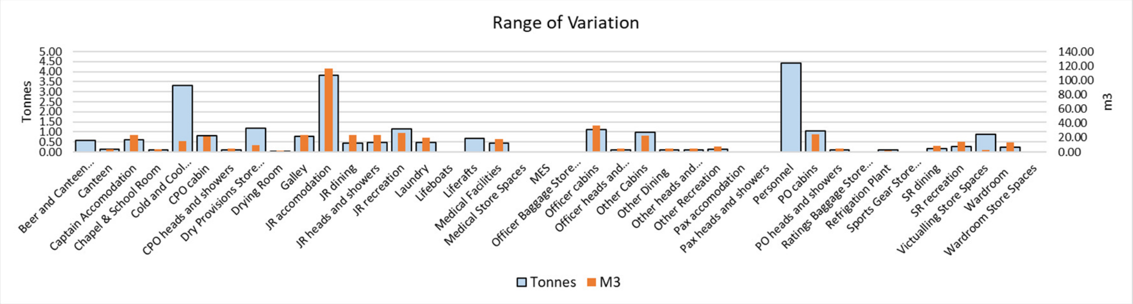


Figure 18: Total range of variation for each item

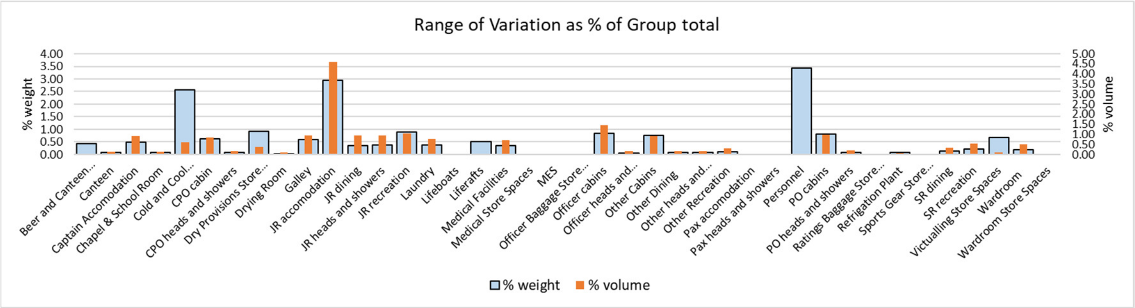


Figure 19: Total range of variation for each item as a percentage of the group totals

Example System Sensitivity Study

A trail was run on the main components of the propulsion system; gas turbines; diesel generators; electric motors and their power electronics. Figure 20 shows; a histogram of the deep displacements with the corresponding approximation of the CDF produced by compiling the runs. A generic beta PDF is also shown, generated by varying the specific components to their minimum and maximum values. Figure 21 shows the same plots for the overall ship volume. The current concept for use of the tool is that the CDF plots would be used to derive the design point to be used for analysis, based on a required level of certainty.

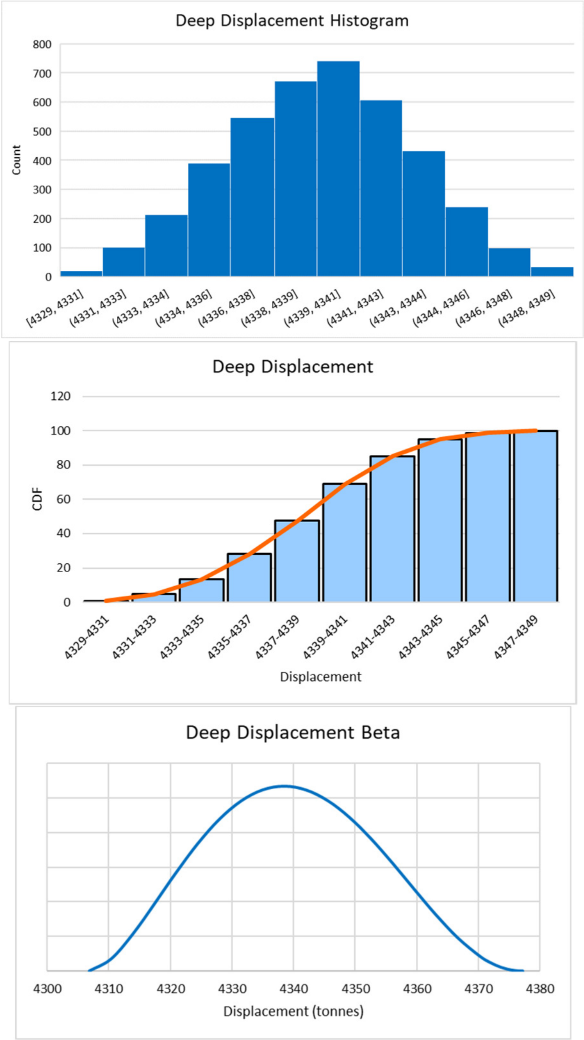


Figure 20: Displacement results

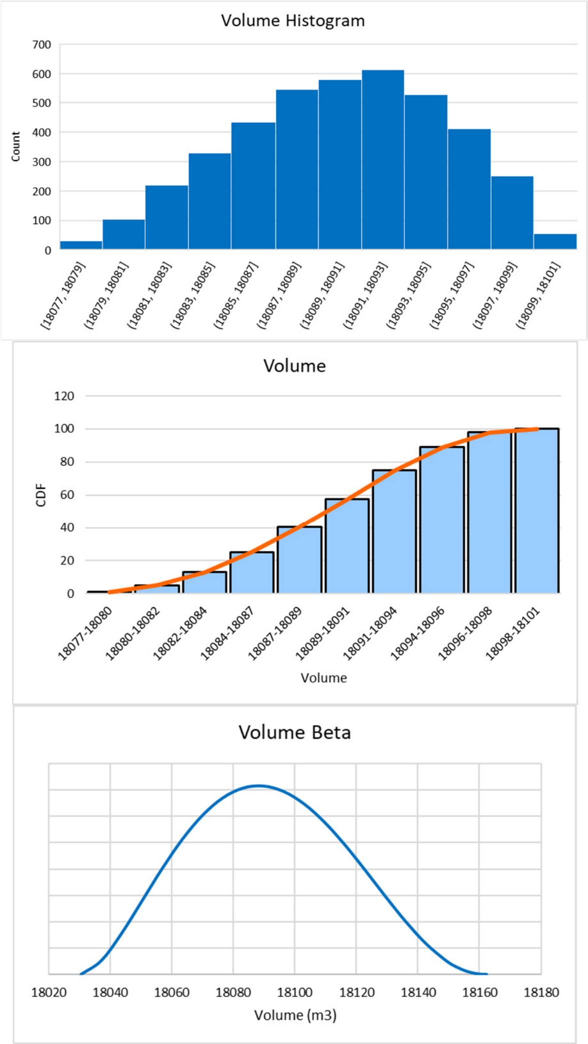


Figure 21: Volume results

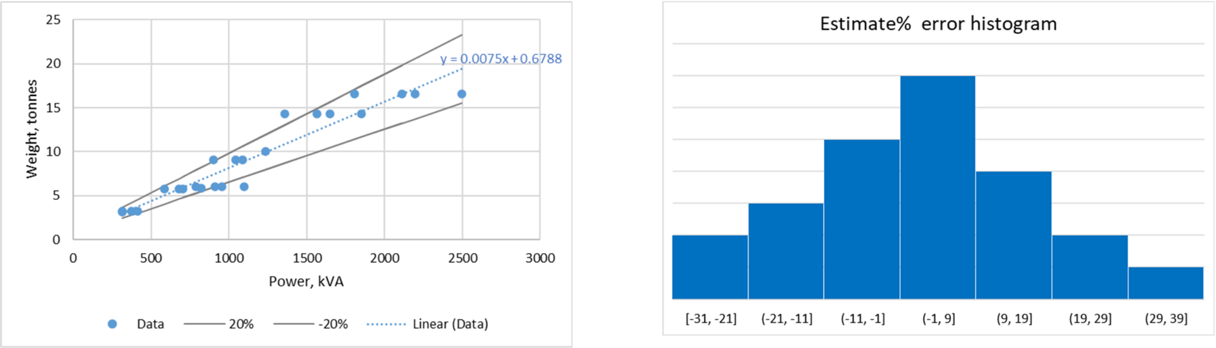
Figures 20 and 21 show that the overall distribution is not necessarily well represented by a simple beta, or by a normal distribution (as would be expected as per the central Limit theorem). However, it should be remembered that this study only examined a small set of the many line items in the sizing model.

SPECIFYING UNCERTAINTY RANGES

For this approach to be used in the design exercise, guidance will be required regarding the choice of uncertainty ranges. This should be linked to some characteristic to allow a reasoned selection. Some references may describe uncertainty using +/- values. These can range from specific components to entire weight groups.

From Data

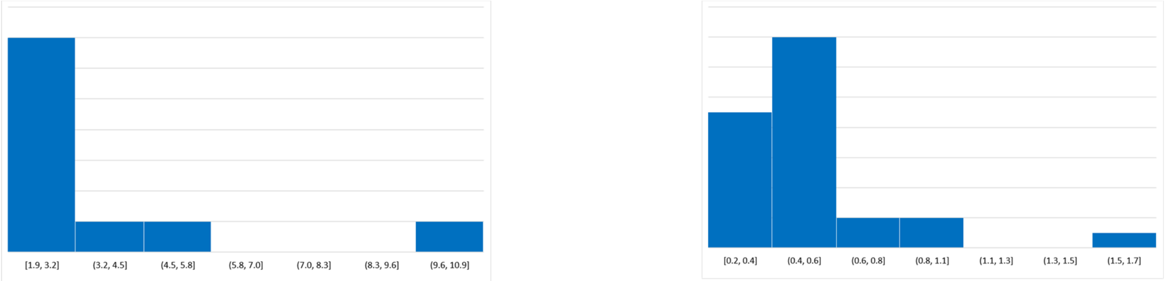
As noted previously, UCL sizing algorithms derived from multiple date points have an inherent uncertainty, and this can be provided in the existing design database. Histograms of the error between the actual values and fitted curve can be used to determine the most appropriate +/- values to generate the min and max inputs to the beta distribution. This is illustrated for the case of diesel generator weight in Figure 22.



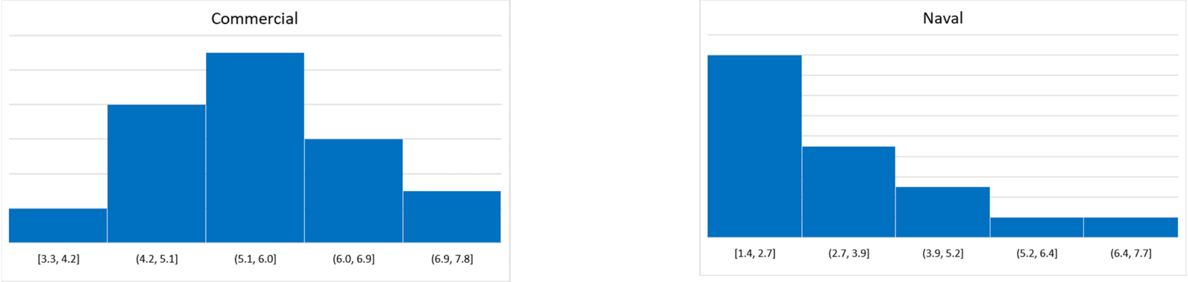
Basis data, fitted curve and example limits **Histogram of errors between fitted curve and input data**

Figure 22: Example uncertainty range for a fitted curve

To support the development of the new design tool, similar histograms have been developed based on reference papers containing historical values such as Kehoe et al (1983). A range of general arrangement drawings for commercial and naval ships have also been analysed to determine possible distributions for the area of certain spaces, some of which are shown in Figure 23. The figure also compares the area per rating for accommodation sizes in commercial and naval vessels in the database and whilst there is some overlap in the values, the distributions are quite different. This is due to the dominance of offshore support vessels and research vessels from the 1990s onwards in the commercial ship database, all being designed to broadly similar standards of crew comfort, whilst the warships database contains ships as old as the 1970s designed RN Type 22 frigate (with mess decks for accommodation) and as modern as the RNZN Otago class OPV (with cabins).



Operations rooms, area per operator **Galleys, area per crewmember**

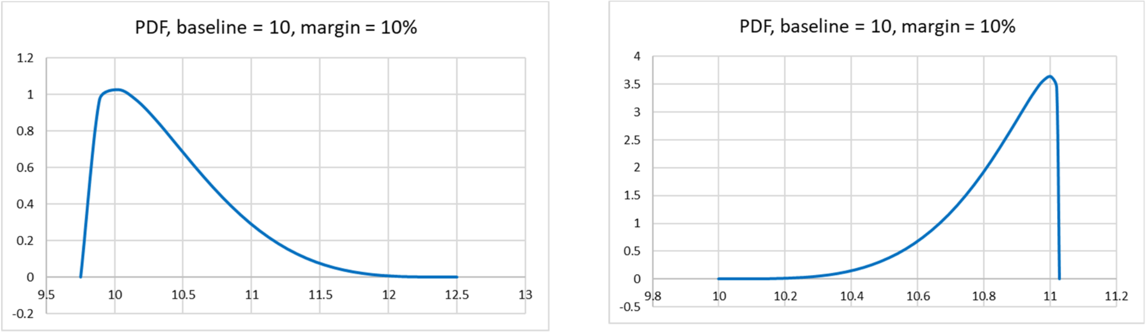


Ratings accommodation, area per rating, commercial **Ratings accommodation, area per rating, naval**

Figure 23: Example histograms for spaces extracted from general arrangement drawings

From Design Margins

The recommended weight and space margins summarised in Table 2 may also be used to generate a beta distribution, under some assumptions. If a weight margin is assumed to be the value that captures 90% of all possible outcomes (for example) then it is possible to define a Beta distribution that reflects this. Figure 24 shows how this might be represented for the assumption that the baseline value is the most likely value (left) or that the margin value is most likely (right). The margin value has a CDF of 90% in both cases. This approach has the advantage of aligning with the existing approach to design margins.



PDF assuming baseline value is most likely **PDF assuming margin value is most likely**

Figure 24: PDFs derived from existing margins and assumption that margin = 90% cumulative probability

From Confidence Levels

Linking uncertainty values with standardised definitions of confidence, is attractive for a teaching environment as the definitions can be clearly stated and understood. The NASA Technology Readiness Levels (Manning, 2023) are already used within both the SDX and its sister Submarine Design and Acquisition Course at UCL, but do not have any formal margins or uncertainty values associated with them. Past NASA programmes have shown that novel concepts can experience huge weight growth as the design develops (NASA, 1971) however, a ship would usually not be entirely composed of new technologies so TRL-linked weight margins or uncertainty levels should be selected for the specifics of shipbuilding rather than aerospace. Pedatzur (2016) proposed specific ship weight margins associated with the Bonen scale – a similar concept to TRL – and stage of the design. These are shown in Table 6 below and could be used to generate a PDF as per other weight margins. The Bonen scale having four levels listed below.

Level 1—Duplicating an Existing System
Level 2—Upgrading an Existing System
Level 3—Development of a New System
Level 4—Technological Breakthrough

Table 6: weight margins based on design stage and Bonen scale (after Pedatzur (2016))

Complexity and risk level according to the “Bonen Scale”	Stage of the project			
	Feasibility study	Contract design	Detailed design	Construction
Level 1	5%	4%	2%	1%
Level 2	10%	8%	5%	2%
Level 3	15%	12%	8%	4%
Level 4	25%	15%	10%	5%

DISCUSSION AND CONCLUSIONS

Within the UCL SDX, general uncertainty in design is handled in a relatively simplistic manner via margins added to various characteristics, and a limited set of operating conditions to be analysed. It has proven difficult to ensure students consider the concept of uncertainty in their design, either at the whole ship or system level, and this has, ironically, been made more difficult by the greater numerical precision easily available with modern tools. This paper has described a work-in-progress on developing new tools and approaches to address this issue. Whilst a need for a different approach to educating future engineers about uncertainty in design has been identified, the tool demonstrated is only viewed as a step along the way. As the ship design exercise represents one quarter of the total credits for the MSc some caution is warranted when making changes to the tools or material. This paper is intended as part of the discussions on the way to improving ship design teaching at UCL. Implementation of an Excel based uncertainty model using the beta distribution at individual line-item and component level has proven relatively straightforward. More complicated is the development of the supporting material, such as recommended numerical uncertainty values associated with concepts such as TRL and the phase of the design process.

FURTHER WORK

Currently the tool performs a simple analysis, generating all possible combinations of the selected items. This full factorial approach does not scale to larger numbers of samples or components of a system without an unacceptable run time. A further development would be to incorporate a method such as Latin Hypercube Sampling to generate a statistically representative set of results over a large range of design components. As a typical UCL sizing sheet would contain around 250 individual line items this would be a challenge to cover the entire design within a run-time acceptable to maintain the desired level of interactivity. However, it would permit the extension of single-system analyses to cover more components.

Additional visualisations and aggregations of results will be required for deployment, as experience with other UCL-developed tools has shown that students frequently output the results from multiple runs with the tool, to compare and discuss with teammates. A further area of development is to automate the process of generating the complete definition of a beta distribution from only a baseline and additive margin. The beta distribution is defined by three input parameters; minimum, maximum and most likely, so a method is required to derive the values such that the CDF reaches the required value (e.g. 90%) at the margin, as shown in Figure 24. Currently this is done by a pre-calculated set of ratios arrived at by numerical approximation.

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