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A proposed framework for developing an Energy Efficiency Design Index (EEDI) for Warships

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What is the EEDI?

Energy Efficiency Design Index (EEDI)

- Purpose of EEDI is to reduce CO_2 production
- Functions indire fuel consumptic
- Currently only a cargo ships
- Evaluated at fix speed and disp

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EEDI Applied to Warships

Why consider it for Warships?

- The effects of pollution have been reco
  - Plastics from North America and Asia fou Pacific ocean.
  - Halon use in developed countries cause Antarctic.
  - CO_2 production includes warships as we are on everyone – global warming and e
- Countries may have environmental pol
- First Sea Lord (UK) – Naval Platforms as far as possible.
- Even states or harbours can have spec

ROYAL NAVY

1SL ENVIRONMENTAL PROTECTION STATEMENT

I am committed to ensuring that our management of environmental protection can deliver, without weakening our operational resolve, our legislative and regulatory compliance obligations, minimise harm to the environment from our actions and manage the risks which the changing natural environment and its regulation poses to our operational capability.

We will comply with all applicable environmental legislation and remaining cognisant of emerging legislative changes, develop environmental requirements which aim to ensure that we can continue to operate globally into the future. Where internal regulations call for outcomes for the environment that are at least as good as statute we will only deviate from these outcomes by exception and where it is not reasonably practicable for us to do so. In making such determinations we will consider the residual risk that this places with operators and ensure these risks are understood and accepted at an appropriately senior level within the operating domain.

As technology and scientific understanding advance we will implement effective changes to ensure we remain efficient and continue to minimise the potential harm our activities can have on the environment. In this way, we should be seeking to enhance capabilities as well as improve our environmental performance.

By reporting and learning from our environmental incidents and monitoring environmental performance we shall take the necessary steps to minimise future occurrences and reduce our impact on the environment. We should all have the courage to challenge inadequate environmental practices, right across the business.

Those of us in senior management positions or in command shall lead by example and undertake environmental management as part of our normal business. It is the responsibility of all those in Navy Command to cooperate with the arrangements that are in place which enable us all to discharge the duties placed upon us.

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EEDI
As used on commercial vessels

- The solution formula gives an approximate value of:
  - Fuel consumed per tonne of cargo per mile or g / tonne-mile
- The complete formula is a follows:

$$\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME} **\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

- In summary the formula is: Sum of the engines x 75% power x Carbon factor x Specific Fuel Consumption (SFC)
- This is done for main and auxiliary engines with correction factors for PTI motors and shaft generators
- Key Issues
  - EEDI is for simple cargo vessels
  - Based on a cost/benefit arrangement
  - Only for one operating condition (75%)
  - Dredges and ferries currently exempt but will be included soon
- The EEDI is for the designer of the ship. However fuel consumption is also affected by operation and this is covered by the Ships Energy Efficiency Management Plan (SEEMP).

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EEDI
Applicability to warships - Issues

- EEDI is deterministic, at a single point
  - Which doesn't reflect reality
- EEDI is a product of the social & economic situation
  - In structure and detail – based on a current cargo ship revenue model
- An EEDI for warships is for a different socio-economic situation
  - Both structure and detail should be different – warships exercise a country's foreign policy and do not carry cargo
- The EEDI formula also directs the designer to select the smallest engines that meet the power requirements which pushes the SFC higher and also limits the margins of the ship (no spare power for growth) – Note 1

- Propose a probabilistic approach
- Assess more than just fuel consumption

Concept and Framework

The Concept: Variability is Central to Warships

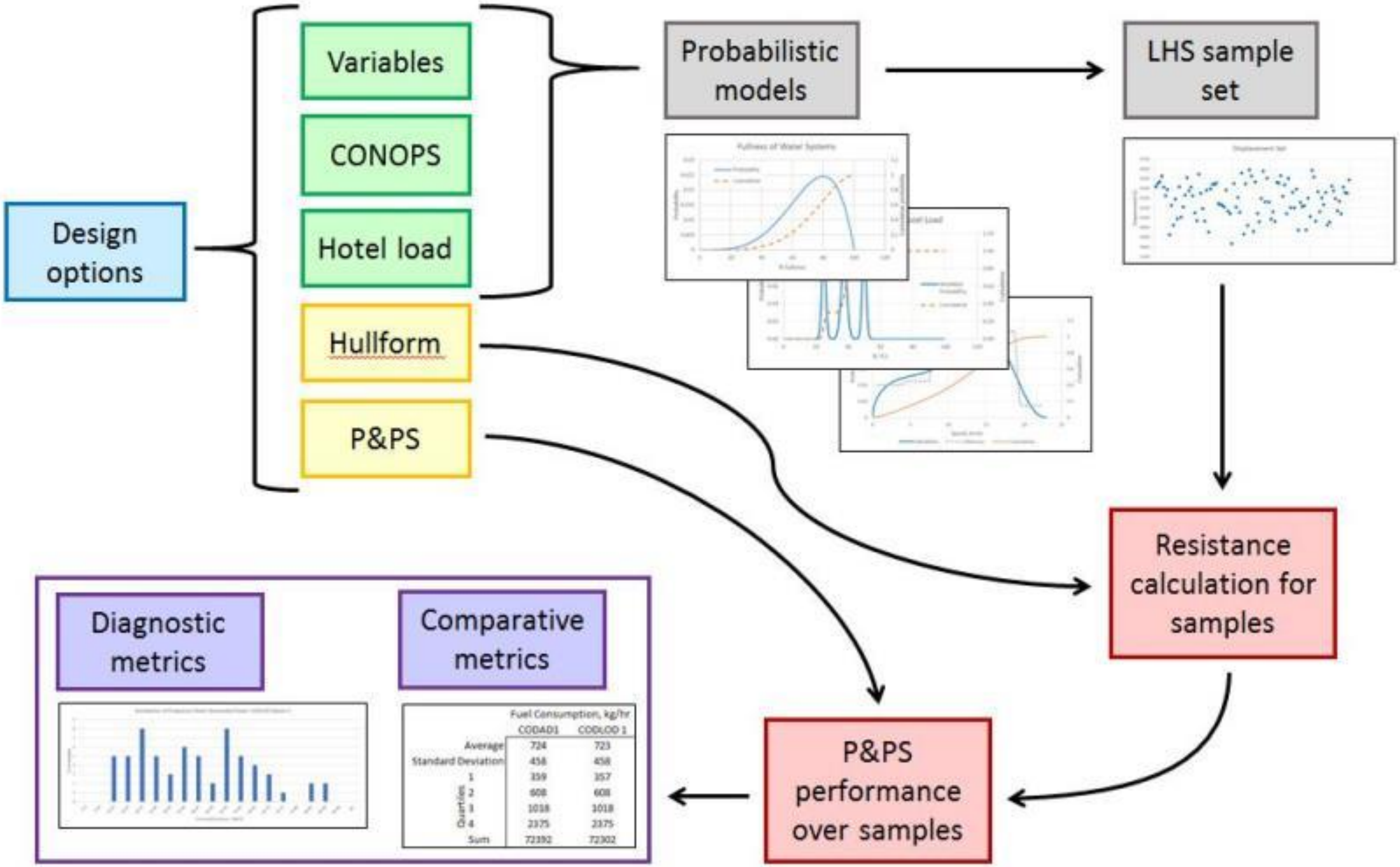
For a given hull and machinery, fuel burn depends on:

1. Displacement & draft
2. Fouling
3. Wind and waves
4. Ship speed
5. SFC curve for prime mover and auxiliary generators

- 1 and 2 depend on age & load state of ship & time at sea
- 3 is environmental
- 4 is operational
- 5 is a design choice

A very large variable space to assess!

Approach Framework



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Latin Hypercube Sampling to reduce sample space

10	x	x	x	x	x	x	x	x	x	x
9	x	x	x	x	x	x	x	x	x	x
8	x	x	x	x	x	x	x	x	x	x
7	x	x	x	x	x	x	x	x	x	x
6	x	x	x	x	x	x	x	x	x	x
5	x	x	x	x	x	x	x	x	x	x
4	x	x	x	x	x	x	x	x	x	x
3	x	x	x	x	x	x	x	x	x	x
2	x	x	x	x	x	x	x	x	x	x
1	x	x	x	x	x	x	x	x	x	x
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

◀ Full factorial

IMPRACTICAL – Too much data

▼ Random May be inaccurate

10	x									
9								x		
8										
7				x			x			
6										
5			x			x				
4										
3			x							
2			x							
1				x						x
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

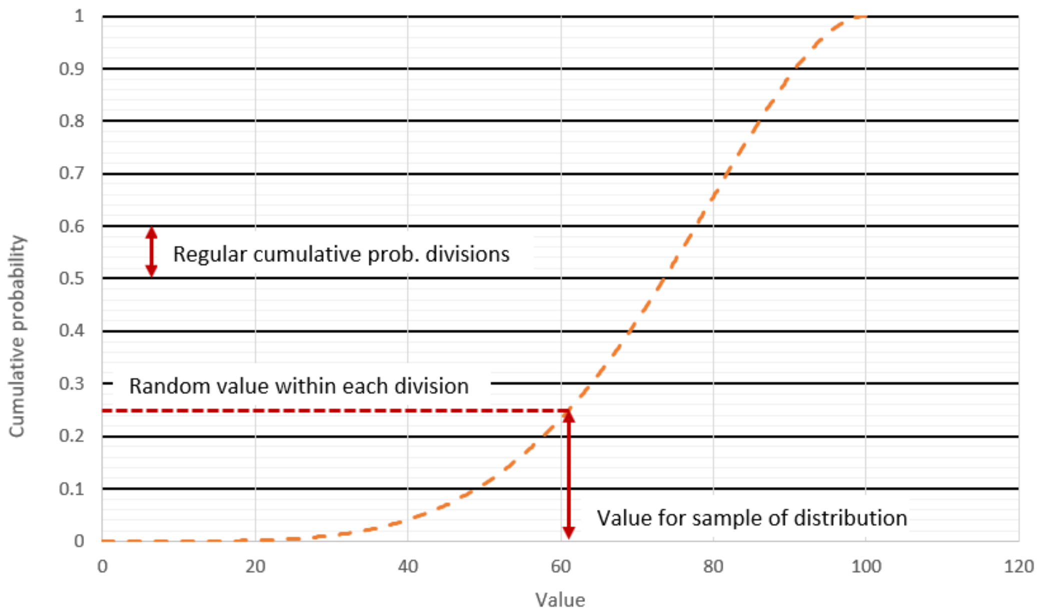
▼ LHS Good compromise

10				x						
9			x							
8								x		
7										x
6		x								
5					x					
4									x	
3							x			
2	x									
1						x				
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

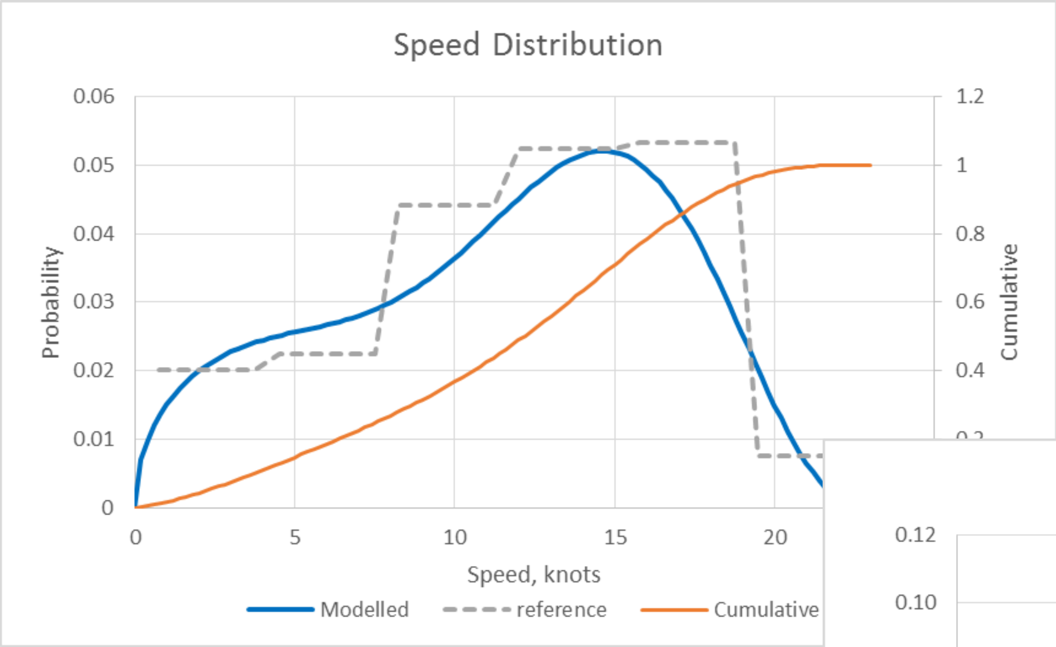
Selecting values to ensure coverage

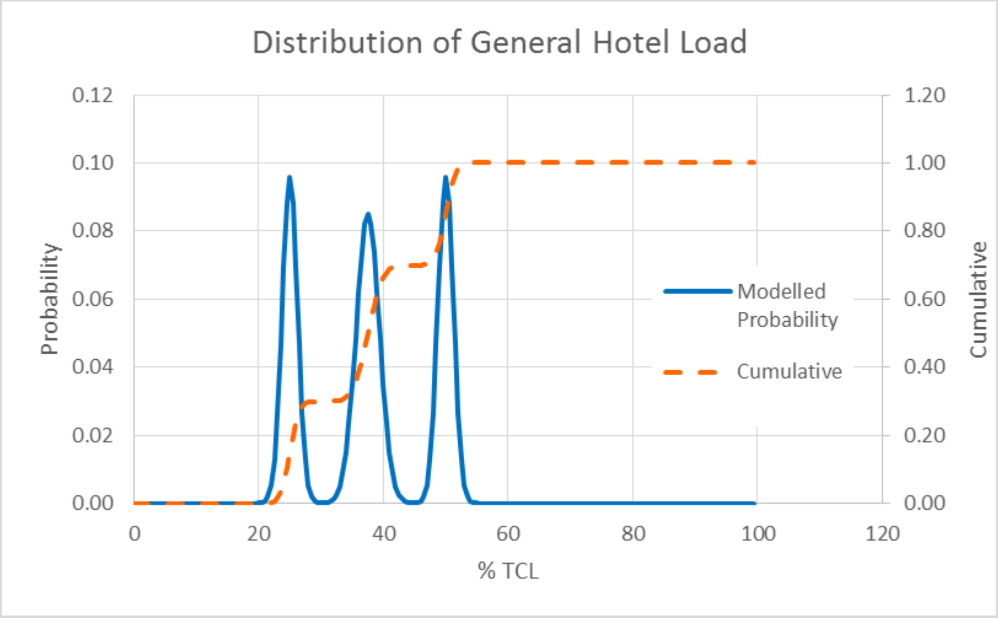
- **Variables X and Y represented as cumulative probability distribution**
- **Can be data or theory derived**
- **Select samples from evenly divided cumulative probability**

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
10				x						
9			x							
8								x		
7										x
6		x								
5					x					
4									x	
3							x			
2	x									
1						x				



Example probability distributions





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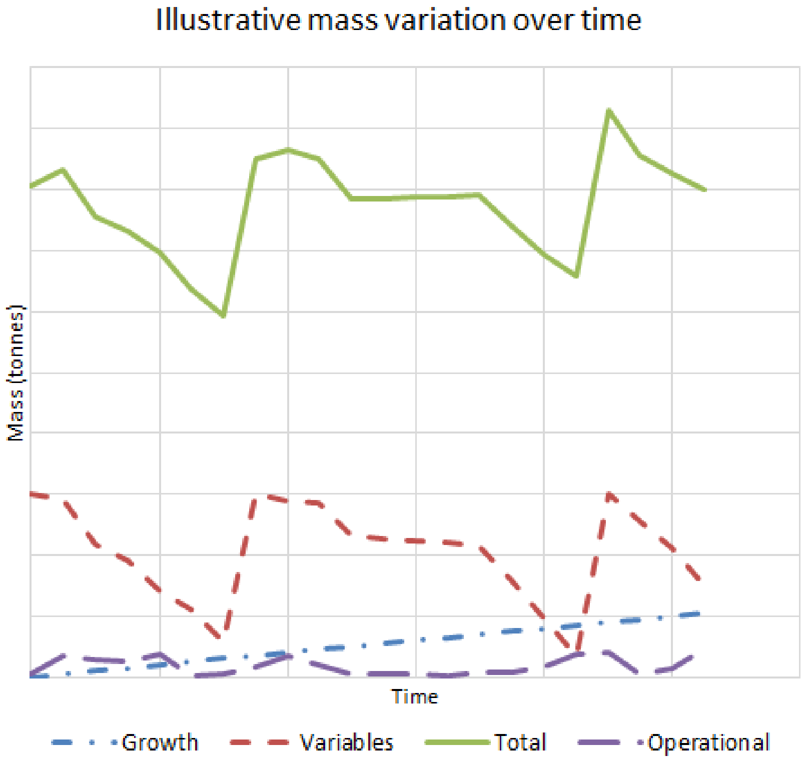
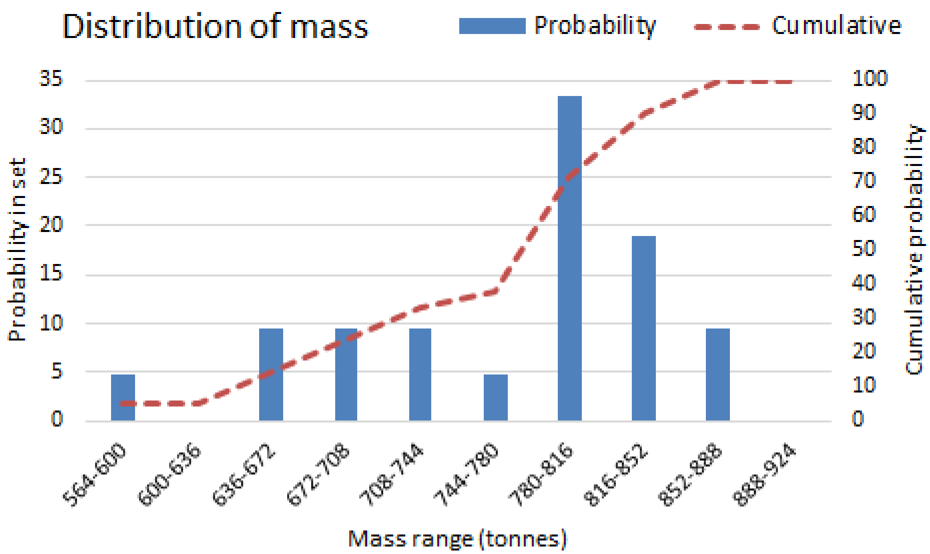
Probability distributions from models & data





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Calculating displacement

Growth mass (from year)

+

Water systems fullness

+

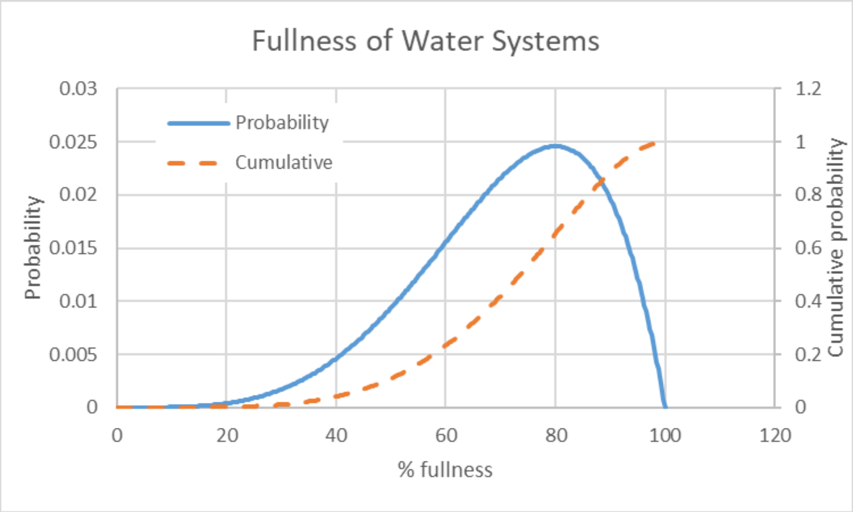
Stores level

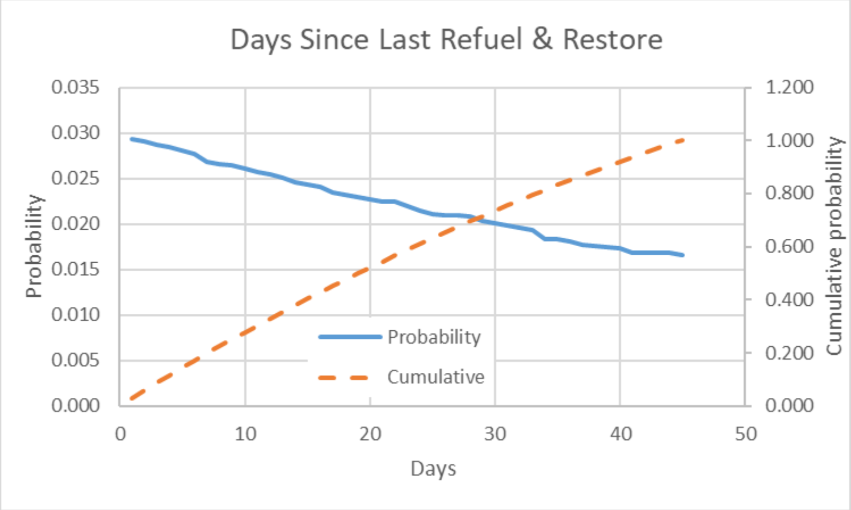
+

Fuel tanks fullness

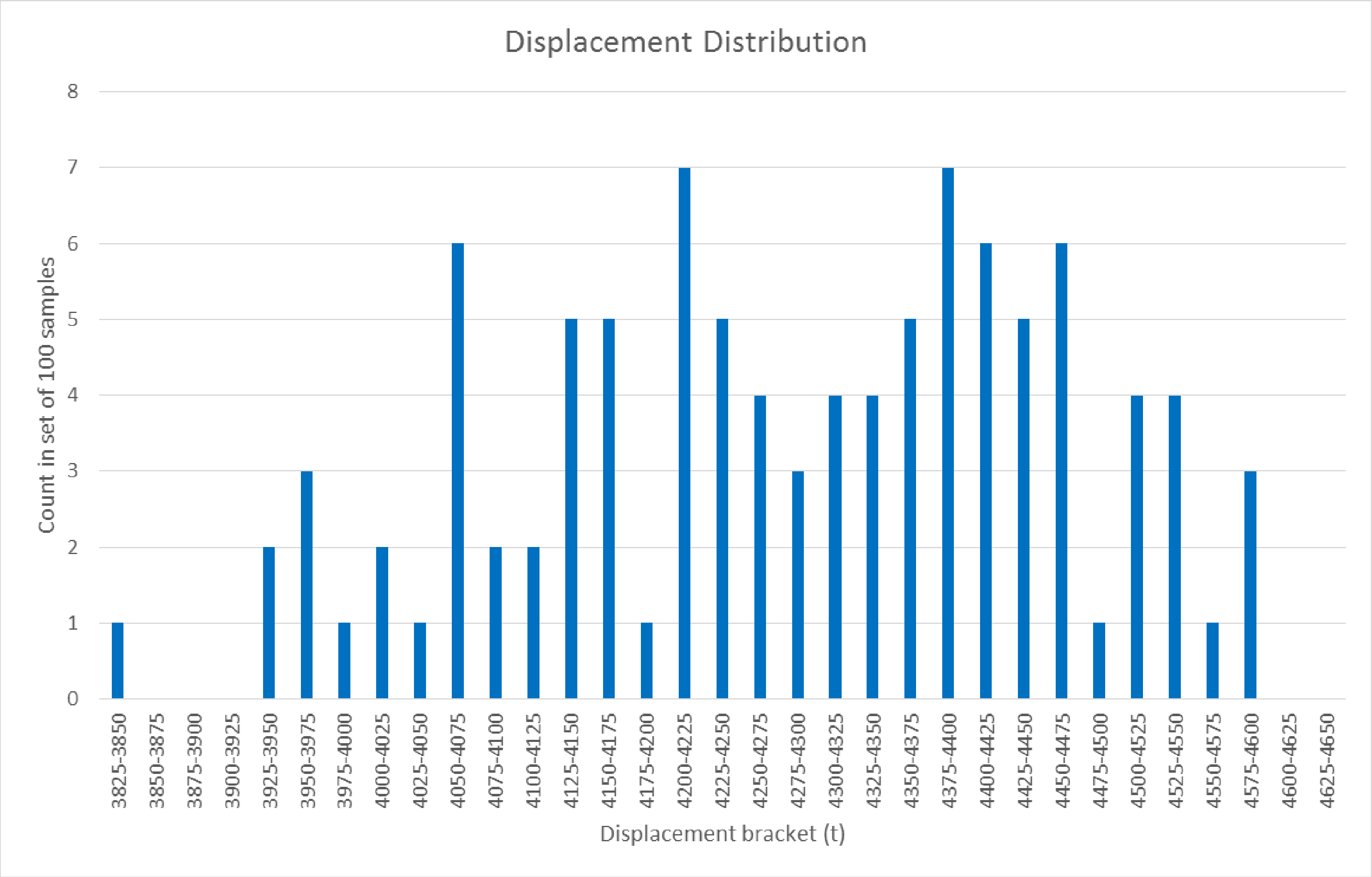
=

Displacement

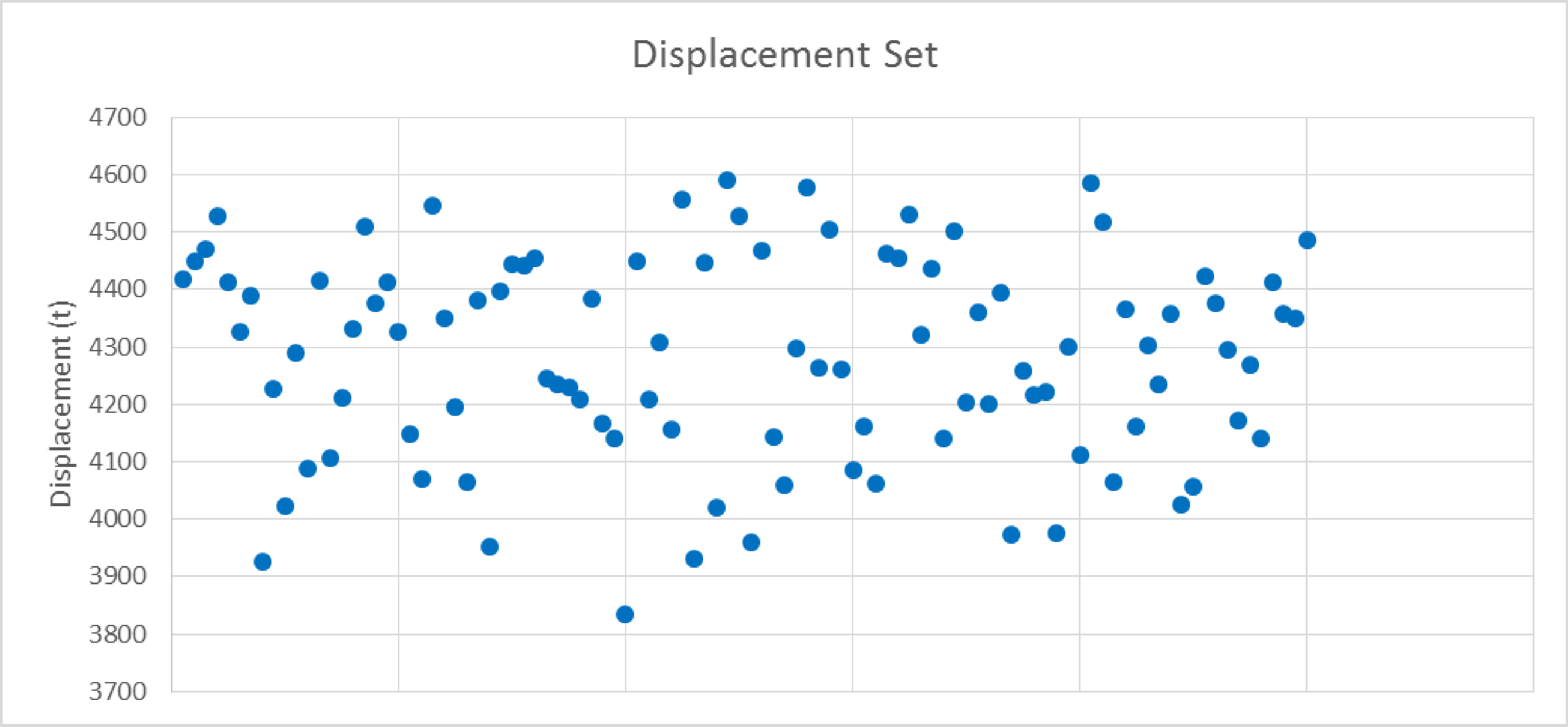




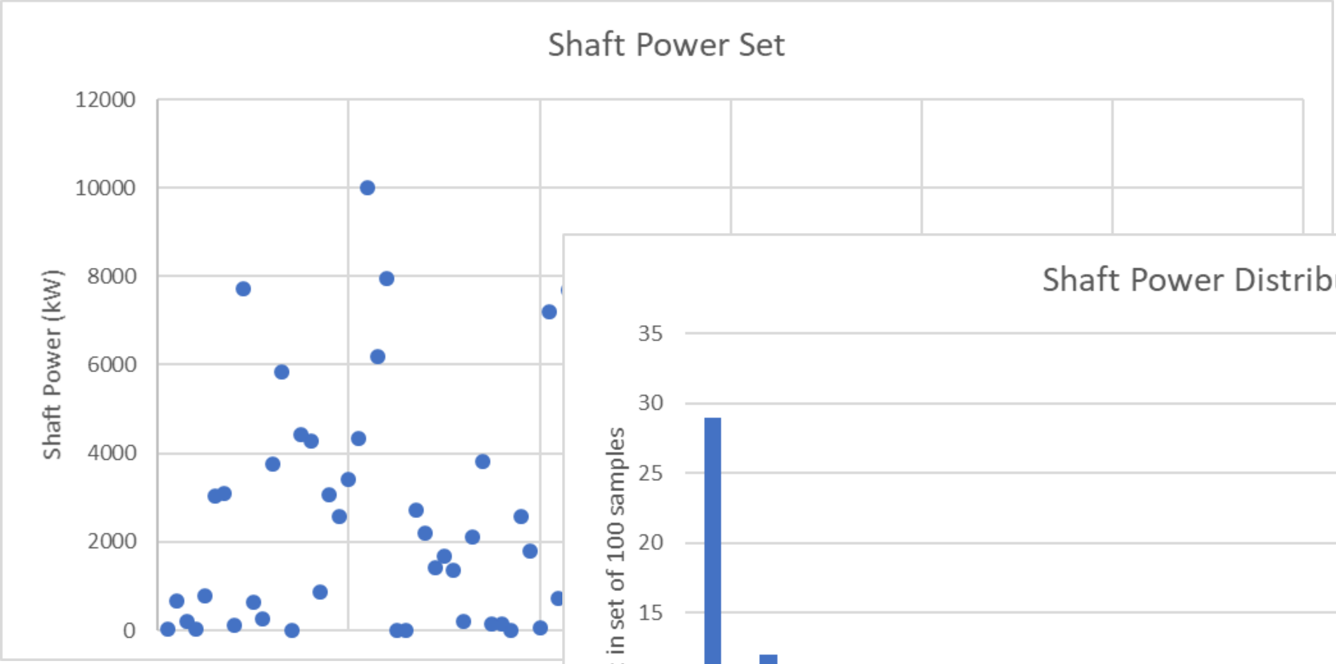
Resulting displacement distribution

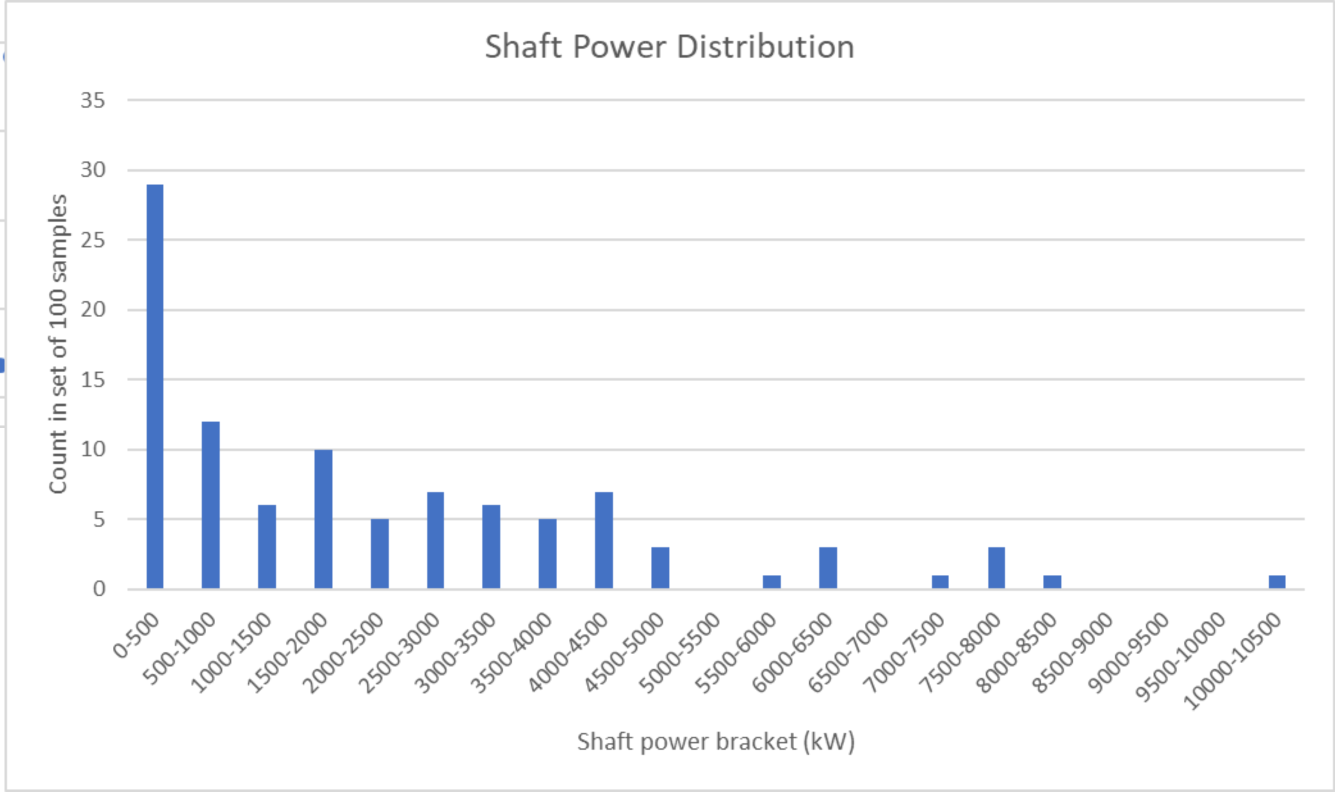


Resulting displacement set



Resulting shaft power set & distribution





Analysis

Apply a proposed machinery set to the shaft & hotel power sets

Assess %MCR & SFC distributions

Example:

CODAD 1 configuration

- 2 x MAN 16V28/33D STC driving 2 shafts
- 4 x 12V 4000 M24S gensets hotel load only

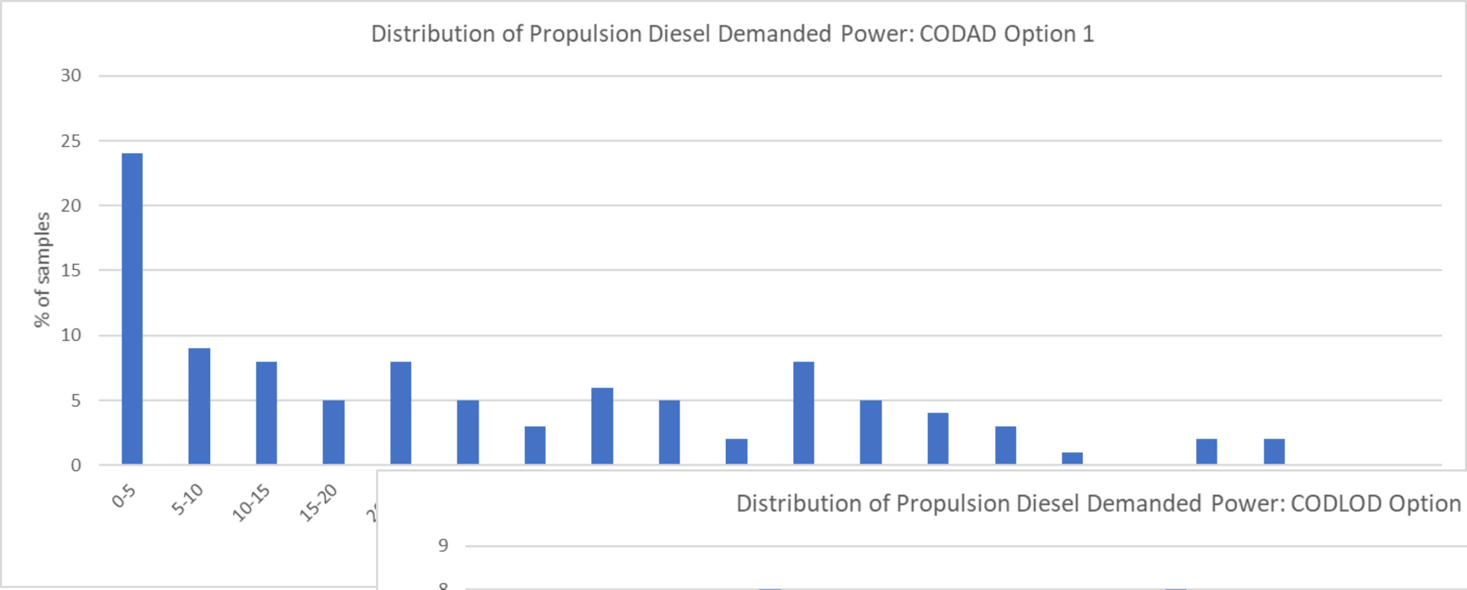
CODLOD 1 configuration

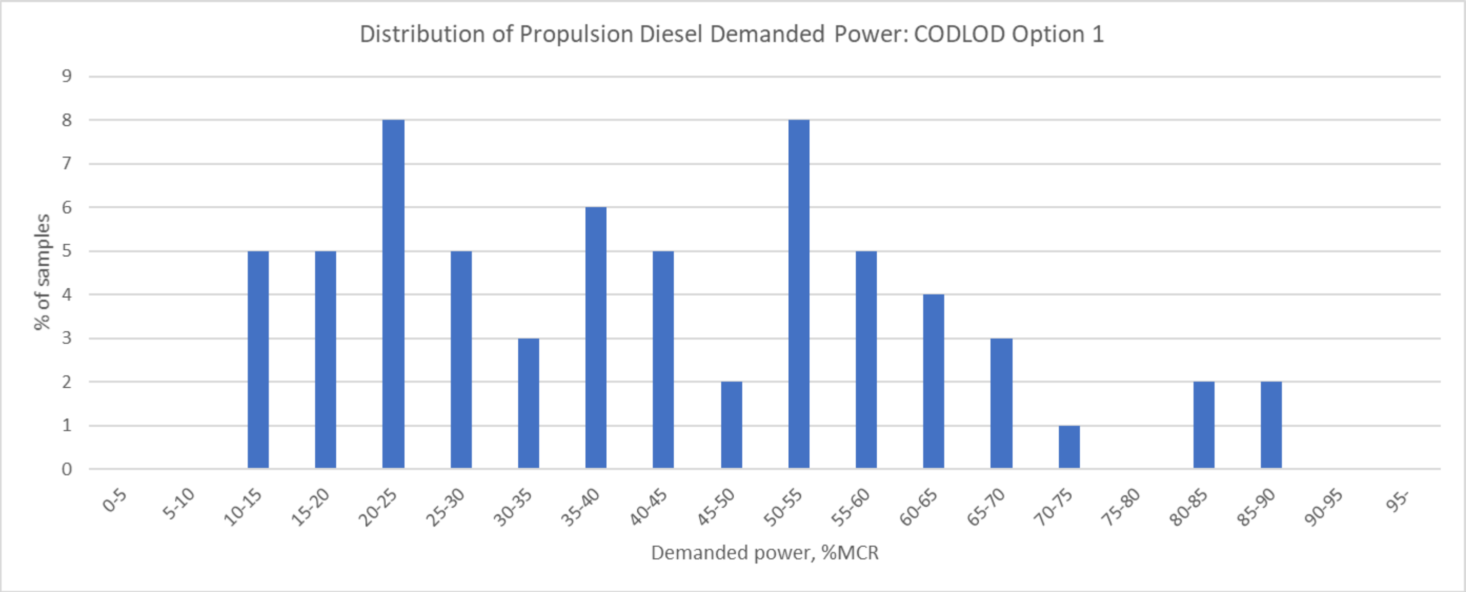
- 2 x MAN 16V28/33D STC driving 2 shafts
- 4 x MTU12V4000M24S gensets hotel load and creep
- 2 x 466kW creep motors

MCR – Maximum Continuous Rating (of each engine)

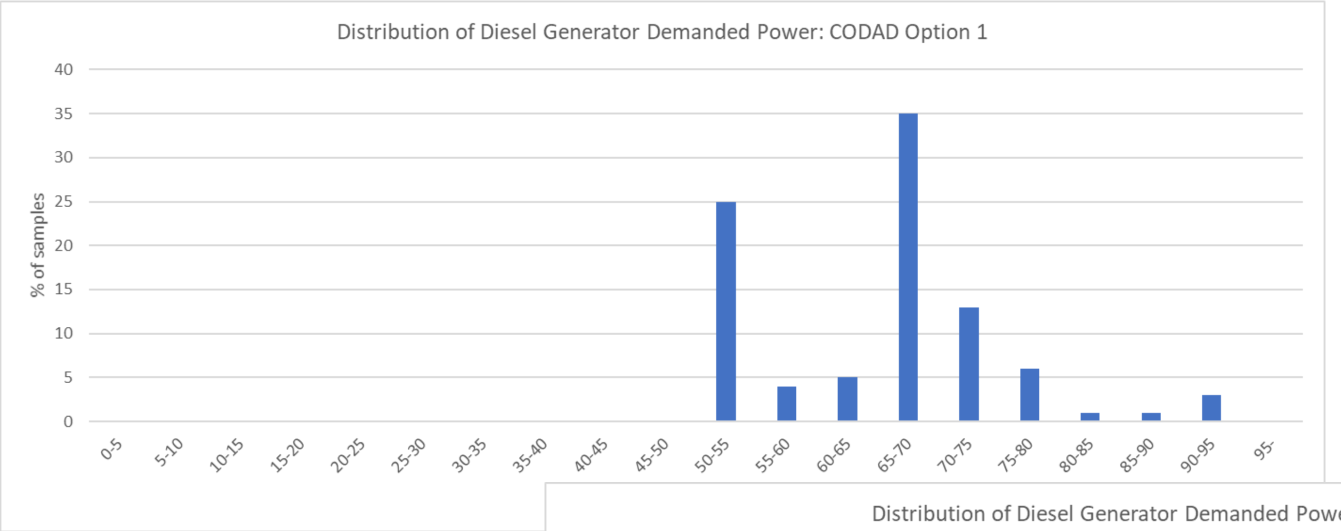
SFC – Specific Fuel Consumption - g/kWh (of each engine)

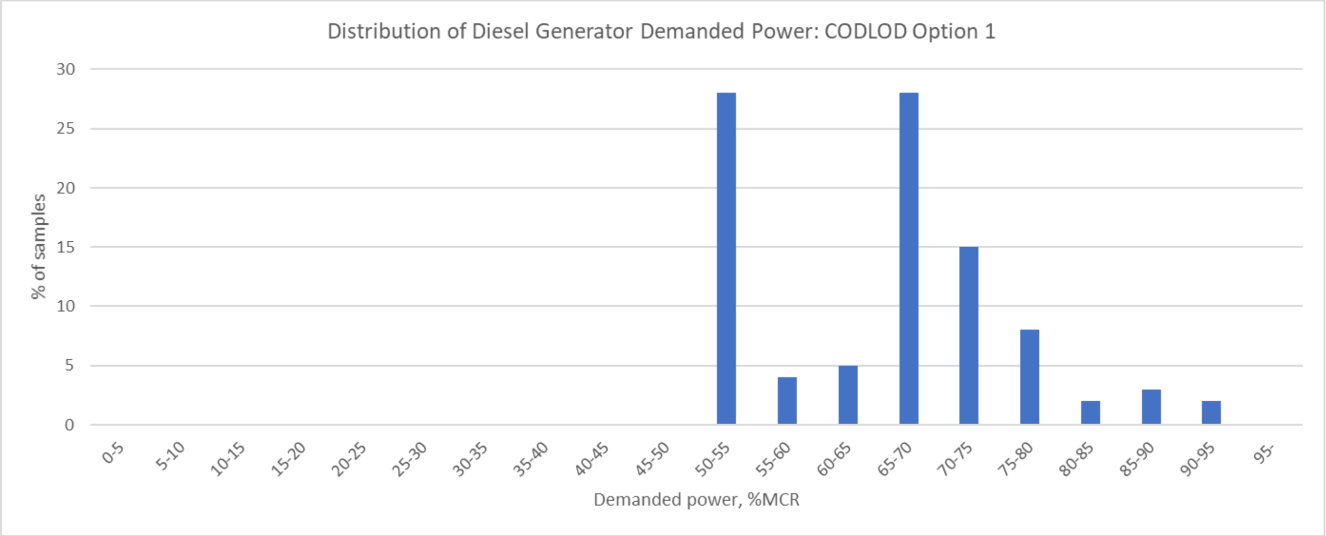
Comparing engine loadings





Comparing diesel genset loadings





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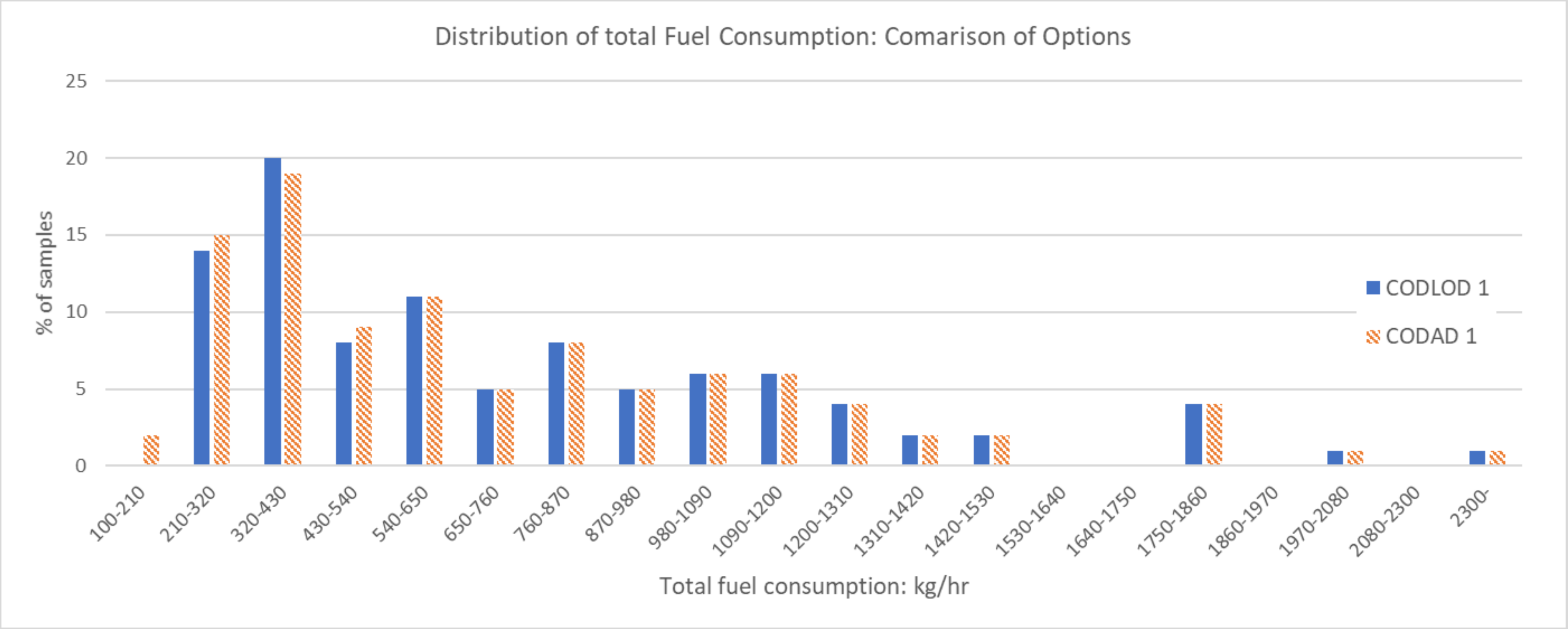
Comparing fuel consumption/hr



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Metric comparisons

		Fuel Consumption, kg/hr	
		CODAD1	CODLOD 1
	Average	724	723
	Standard Deviation	458	458
Quartiles	1	359	357
	2	608	608
	3	1018	1018
	4	2375	2375
	Sum	72392	72302

Savings in fuel at low speeds

- Big changes to a small number are small numbers

Improvement of loading of main engines may be a better metric

		Engine Loading, %		Generator Loading, %	
		CODAD1	CODLOD 1	CODAD1	CODLOD 1
	Average	28.0	41.6	67.3	67.3
	Standard Deviation	24.2	19.9	12.7	12.6
Quartiles	1	5.7	23.3	55.4	54.4
	2	22.9	39.8	66.9	68.2
	3	48.3	55.8	70.7	72.9
	4	87.3	87.3	99.0	99.0

Further options

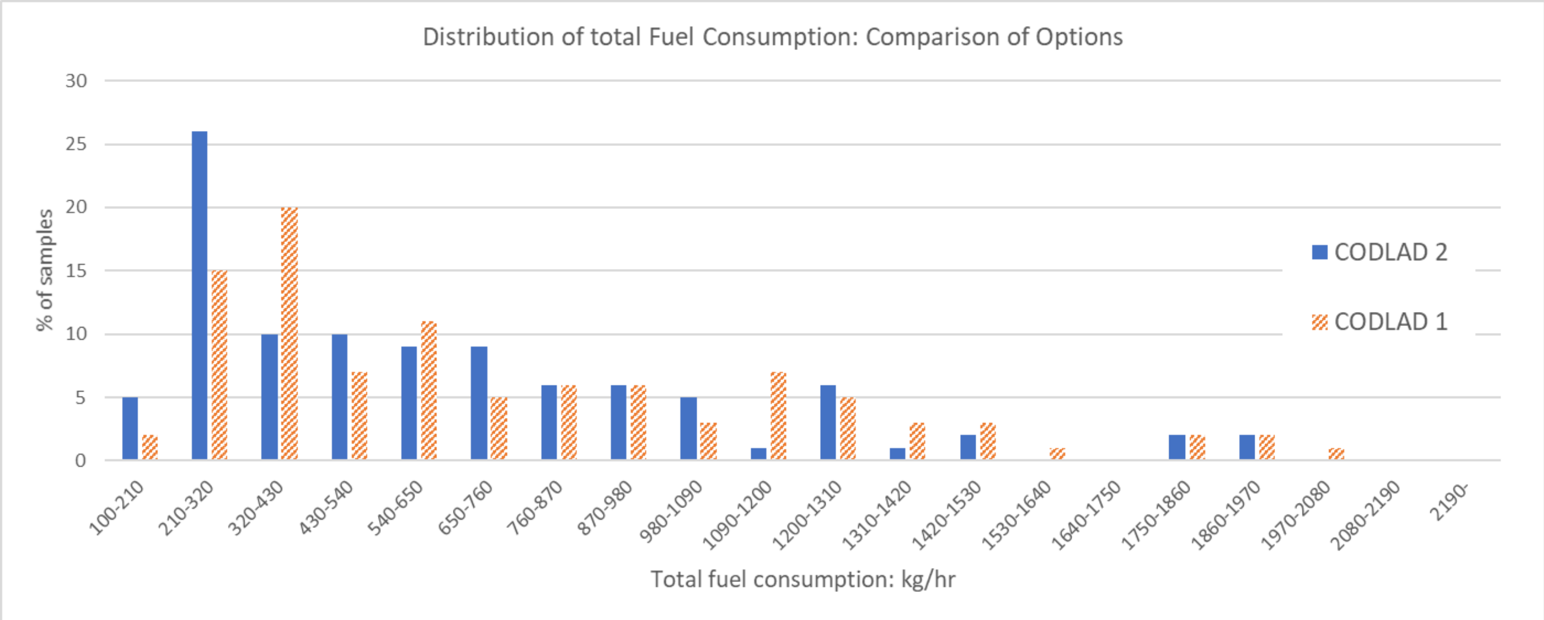
CODLAD 1 configuration

- 2 x MAN 6L32/44CR driving 2 shafts
- 4 x MTU16V4000M40B gensets hotel load and propulsion
- 2 x 3550kW motors

CODLAD 2 configuration

- 2 x MAN 6L32/44CR driving 2 shafts
- 4 x Bergen C25:33L8A gensets hotel load and propulsion
- 2 x 3550kW motors

CODLAD option comparison



	Fuel Consumption, kg/hr	
	CODLAD 1	CODLAD 2
Average	747	640
Standard Deviation	482	418
Quartiles 1	352	303
Quartiles 2	622	535
Quartiles 3	1082	853
Quartiles 4	2417	1938
Sum	74723	64050

	Engine Loading, %		Generator Loading, %	
	CODLAD 1	CODLAD 2	CODLAD 1	CODLAD 2
Average	39.8	39.8	75.5	75.6
Standard Deviation	26.1	26.1	13.1	14.6
Quartiles 1	18.5	18.5	65.3	63.3
Quartiles 2	34.7	34.7	77.8	78.3
Quartiles 3	63.3	63.3	85.6	86.1
Quartiles 4	92.5	92.5	100.0	99.2

Analysis - Some key aspects

Modern naval platforms are designed for efficiency

- Diesel engines are a COTS design with military modifications – high efficiency
- Propellers, shafting and gearboxes are designed for high efficiency
- HVAC has been recognised as being a major hotel load and is being made more efficient
- Other hotel loads have been changed to improve efficiency – e.g. variable speed drives for cooling pumps.
- Combat systems have become more efficient with less reliance on chilled water systems

However the system must be designed and operated correctly for maximum efficiency and lowest emissions

  - Operating 2 diesel generators each at 25% load will be very inefficient as they are well away from their optimum SFC whereas operating just 1 DG at 50% load will have it at a more efficient set point.
  - However for security and redundancy on naval platforms it is necessary to run 2 DG sets. – KEY REQUIREMENT FOR OPERATION

- **Design and Operation need to work together.**

Analysis of all propulsion plant options

Can apply a proposed machinery set to the shaft & hotel power sets

Assess %MCR & SFC distributions

Example:

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- 2 x MAN 16V28/33D STC driving 2 shafts
- 4 x 12V 4000 M24S gensets hotel load only

CODLOD 1 configuration

- 2 x MAN 16V28/33D STC driving 2 shafts
- 4 x MTU12V4000M24S gensets hotel load and creep
- 2 x 466kW creep motors

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CODLAD Option Comparison

Distribution of total Fuel Consumption: Comparison of Options

30

		Engine Loading, %		Generator Loading, %	
		CODAD1	CODLOD 1	CODAD1	CODLOD 1
Average		28.0	41.6	67.3	67.3
Standard Deviation		24.2	19.9	12.7	12.6
Quartiles	1	5.7	23.3	55.4	54.4
	2	22.9	39.8	66.9	68.2
	3	48.3	55.8	70.7	72.9
	4	87.3	87.3	99.0	99.0

Quartiles	2	[illegible]	[illegible]
	3	1082	853
	4	2417	1938
Sum		74723	64050

Conclusion
and
Further Investigations

Furthering Investigations (EEDI & SEEMP)

Design and Operation are inter-related

- This study has successfully demonstrated that the concept of Monte Carlo simulations is a good approach for an EEDI for warships.
- However vessel design is just 1 of 2 criteria for reducing CO_2 emissions.
- The operation of the ship is the second.
  - A Ships Energy Efficiency Management Plan (SEEMP) is the ship's operation component of energy efficiency and needs to considered in conjunction with propulsion plant design.
- EEDI and SEEMP combined provide: Design + Operation = Lowest CO_2
- Result is an overall CO_2 reduction strategy

Going forward the navies of the world need to develop a unified approach to CO_2 reduction with a naval EEDI and SEEMP.

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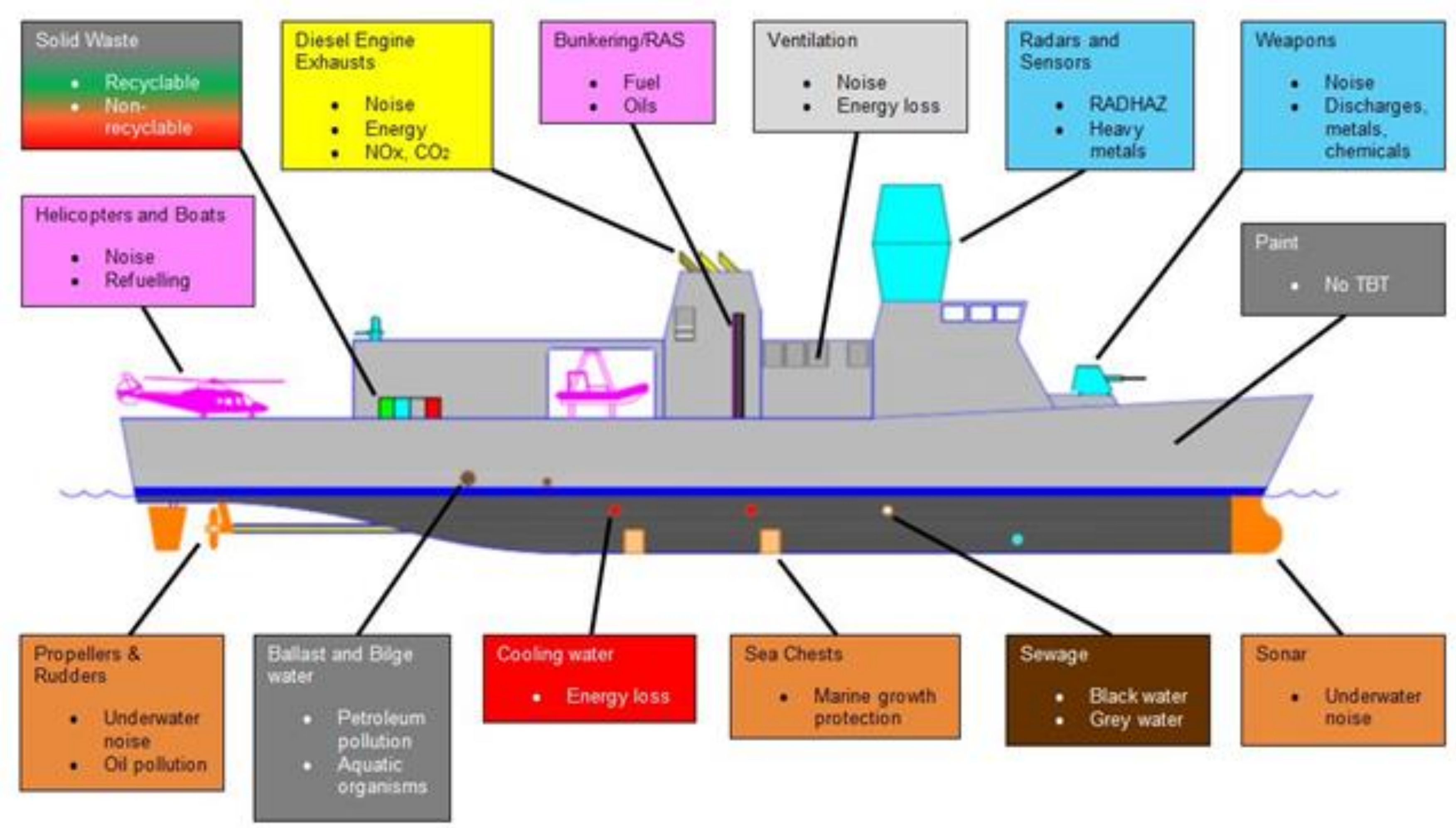
Future Work

Holistic Approach for Pollution Prevention on Warships



Thank you for your time
Any questions?