Greening the Fleet, Raising the Price?

Shipping Decarbonisation and UK Inflation Dynamics

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Agenda

- The Challenge
- Policies Landscape
- Previous Research
- Our Model
- Results
- Forward-Looking Directions

The Challenge

- Shipping accounts for about 3% of global GHG emissions (UNCTAD, 2023)
- While less polluting than other modes of transportation,
  - more than 80% of world trade is facilitated by vessels
  - world seaborne trade is increasing at an average rate of 3.3% since 2000 and will increase by 2.4% till 2029 (UNCTAD, 2024)
- International bodies and national governments are implementing policies for low/zero-emission operations
- Transition costs (alternative fuel engines, energy-saving technologies,...)
- Rising shipping costs

A Three-Tiered Regulatory Structure

Global (IMO): Sets baseline goals and universal rules for international shipping

↓

Regional (e.g., EU): More aggressive targets to accelerate the transition

↓

National: Drive domestic fleet decarbonisation, foster innovation through funding and support infrastructures

Global Level

Revised GHG Strategy (2023)

- Net-zero emissions by/around 2050

Mandatory Technical and Operational Measures

- EEDI (since 2013): Minimum energy efficiency standards for new ships
- EEXI (late 2022 / early 2023): Benchmarks efficiency of existing fleet
- CII (from January 2023): Requires data collection for ships over 5,000 gross tonnage and assigns annual ratings

Economic Measures (MEPC 83, 2025)

- Carbon pricing mechanism with two-tier credit trading:
  - \$380/tCO2e penalty for emissions above limits
  - \$100/tCO2e penalty for emissions between base tier and Direct Compliance Target

EU Level

EU Emissions Trading System (effective January 2024)

- Requires shipowners to purchase or be allocated carbon permits for their emissions
- Coverage details:
  - 100% of emissions for intra-EU voyages
  - 50% of emissions for voyages between an EU and a non-EU port
  - 100% of emissions when ships are at berth in EU ports

FuelEU Maritime Regulation (effective January 2025)

- Objectives:
  - Limit GHG intensity of energy used by shipping
  - Employ a Well-to-Wake approach for measuring fuel energy efficiency
- Target (relative to the 2020 baseline): 80% reduction by 2050

UK Level

The UK's strategy aligns with international efforts when implementing tailored domestic measures

UK Maritime Decarbonisation Strategy

- Provides pathway to zero fuel lifecycle GHG emissions for the domestic maritime sector by 2050

Alignment with IMO GHG Strategy

- Targets at least 30% reduction in fuel lifecycle emissions by 2030 and at least 80% reduction by 2040 (relative to 2008 levels)

Integration with Domestic Policy

- Domestic maritime emissions will be incorporated into the UK Emissions Trading Scheme starting in 2026

Shipping Cost and Inflation

- Various environmental regulations contribute to higher shipping costs
- Studies show a link between shipping costs and inflation
- Magnitude varies, shaped by import dependence and monetary policy strength

Key Findings

- Herriford *et al.* (2022) (US): A 15% rise in shipping costs increases US core PCE inflation by 0.1 ppt after a year
- Isaacson and Rubinton (2022) (US): During the COVID-19 period, shipping cost surges raised US import price inflation by 3.6–5.9 ppt
- Carrière-Swallow *et al.* (2023) (Global): A one-standard-deviation increase in shipping costs lifts headline inflation by 0.15 ppt over 12 months
- Michail *et al.* (2022) (EU): Inflation effects intensify when freight rates exceed critical thresholds

Carbon Pricing and Inflation

- Carbon pricing policies show effects on inflation, primarily through increases in energy prices

Key Findings

- Moessner (2025) (OECD study): A $10 increase in ETS prices is associated with:
  - 0.8 ppt increase in energy CPI inflation
  - 0.08 ppt increase in headline inflation
- Konradt *et al.* (2024) (EU study): A 30 €/ton increase in effective carbon tax leads to:
  - Immediate 0.05 ppt rise in headline inflation
  - Peak effect of 0.1 ppt after two years
- EU "Fit-for-55": With effective carbon prices potentially reaching 150 €/ton by 2030, annual Euro area inflation could rise by 0.2–0.4 ppt
- Konradt *et al.* (2024) & Moessner (2025): Overall effects on headline CPI have been generally modest

Inflation Volatility

Empirical Facts

- Higher inflation increases volatility (Friedman-Ball hypothesis) (Kim, 2013)
- Greater volatility fuels inflation (Cukierman-Meltzer effect) (Berument *et al.*, 2009)

Modelling

- Approaches: moving standard deviation, ARCH/GARCH, stochastic volatility, stochastic volatility in mean, change-point models
- Multivariate Autoregressive Index models capture time variation and common factors

Sources of Volatility

- Global developments significantly affect domestic inflation and its volatility
- Country-specific drivers are equally important

Characteristics of Volatility

- Inflation volatility can be persistent and asymmetrically responsive to shocks (e.g., Omotosho, 2012)
- Change-point models provide insights into level and regime switches (Koop and Potter, 2007; Eisenstat and Strachan, 2016)

Research Gap

How shipping decarbonisation policies affect the UK inflation volatility

> 80%
All Imports & Exports by Volume

> 50%
All Imports & Exports by Value

Cost Increases
Pass-Through to Consumers

Macroeconomic Instability
Monetary Policy & Financial Markets

Model Specification

- GARCH-MX model captures both autoregressive behavior and volatility clustering
- Conditional volatility σ_t^2 represents inflation uncertainty
- The GARCH-MX:
  - Provides feedback relationship between inflation and uncertainty
  - Captures economic indicators with anticipated effect on inflation
  - Provides robust framework to assess how shipping cost shocks spread through inflation volatility

Model specification:

$$\begin{cases} Y_t = \mu + \varphi Y_{t-1} + \vartheta_1 X_t + \vartheta_2 \sigma_t^2 + \varepsilon_t \\ \sigma_t^2 = \omega + \alpha \varepsilon_{t-1}^2 + \beta \sigma_{t-1}^2 + \gamma Z_{t-1} \end{cases},$$

Y is the 12-month CPI inflation change (dependent variable)
X is the vector of control variables
Z captures the impact of shipping costs
ε is the error term

Independent Variables and Data

- Shipping cost proxies: BDI, BDTI, BCTI
- Control variables:
  - Monthly Unemployment Rate Change
  - Monthly Aggregate Demand Change
  - Monthly Aggregate Supply Change
  - Monthly Growth Rate of M4 Change
- Data sources: Office for National Statistics (UK), Clarksons Research Services
- Log-transformations employed to ensure stationarity
- Conversion to monthly frequency via Chow-Lin method
- Period: Jan 2001–Dec 2023 (276 monthly obs)

Summary Statistics

Variable	Mean	Std. Dev.	Maximum	Median	Minimum
12-Month CPI Inflation Log-change	**0.0043**	**0.1723**	0.6942	-0.0026	-0.8750
BDI Log-return	**0.0017**	**0.2273**	0.8519	0.0170	-1.0125
BDTI Log-return	**-0.0025**	**0.1724**	0.6474	-0.0068	-0.5781
BCTI Log-return	**-0.0025**	**0.1590**	0.5013	-0.0113	-0.8418
Unemployment Rate Log-change	-0.0006	0.0209	0.0834	0.0000	-0.0541
Monthly Aggr. Demand Log-change	0.0013	0.0128	0.0919	0.0015	-0.1012
Monthly Aggr. Supply Log-change	0.0012	0.0134	0.1080	0.0017	-0.1344
Monthly Growth Rate of M4 Log-change	-0.0011	0.8003	2.9000	0.0000	-2.3

Table: *Summary Statistics.* The table reports the sample descriptive statistics for the dependent and independent variables. It is interesting to observe that the mean inflation over the sample period is low, below 0.005, while its the standard deviation is quite high. We observe similar characteristics for the shipping indices' log-returns.

Unit Root Test Results

Variable	ADF p-value	ADF Stat.	KPSS p-value	KPSS Stat.
12-Month CPI Inflation Log-change	4.65E-05	Stationary	0.1	Stationary
BDI Log-return	4.01E-08	Stationary	0.1	Stationary
BDTI Log-return	1.39E-11	Stationary	0.1	Stationary
BCTI Log-return	7.22E-27	Stationary	0.1	Stationary
Unemployment Rate Log-change	1.54E-04	Stationary	0.1	Stationary
Monthly Aggr. Demand Log-change	1.80E-06	Stationary	0.1	Stationary
Monthly Aggr. Supply Log-change	5.60E-06	Stationary	0.1	Stationary
Monthly Growth Rate of M4 Log-change	5.75E-17	Stationary	0.1	Stationary

Table: *Unit Root Test Results.* The table reports the unit root tests and the corresponding p-values for the ADF and KPSS tests for stationarity. Both tests suggest strong rejection of the unit root hypothesis, supporting stationarity. Results from breakpoint tests confirm the stationarity of the variables even under structural breaks.

Model Estimation

Variable	Coefficient	p-value
Mean equation		
μ (Constant)	0.0022	0.0031
Y_{t-1} (Past Inflation Log-change)	0.0721	**0.001**
$X_{1,t}$ (Monthly Growth Rate of M4 Log-change)	-0.0004	**0.0521**
$X_{2,t}$ (Unemployment Rate Log-change)	0.0079	**0.0935**
$X_{3,t}$ (Monthly Aggr. Demand Log-change)	0.0932	**0.0876**
$X_{4,t}$ (Monthly Aggr. Supply Log-change)	-0.0656	**0.0798**
σ_t^2	0.0891	**0.005**
Variance equation		
ω (Constant)	1.07E-05	0.4897
ε_{t-1}^2 (Past Squared Error)	0.1500	0.0311
σ_{t-1}^2 (Past Volatility)	0.6000	**0.0051**
Z_{t-1} (Past Shipping Cost – **BCTI**)	**0.5632**	**0.0001**
Adjusted R^2		0.8384
Log-likelihood		**1060.38**
Akaike information criterion		**-8.1503**

Discussion and Implications

- Inflation change is statistically significant
- Traditional macroeconomic controls
  - Growth Rate of M4 Change
  - Unemployment Rate Change
  - Aggregate Demand and Supply Changes

  are significant at the 10% level
- Inflation uncertainty significantly affects inflation changes
- Lagged conditional variance confirms that inflation volatility is persistent
- Shipping cost proxy BCTI shows strong positive impact on inflation volatility
- Findings suggest that higher maritime costs, such as those induced by decarbonisation policies, may contribute to broader macroeconomic instability and heightened inflation volatility

Next Steps

Scenario Analysis of Policy Impact

- Simulate how increases in shipping costs driven by decarbonisation policies affect inflation volatility

Advance Model Specifications

- Extend to stochastic volatility models that better capture long-run trends and time-varying uncertainty (e.g., UCSV)

Future Research Directions

- Validate results using alternative shipping cost proxies, such as container shipping rates
- Explore different measures of inflation

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Research Hub

The Economics of Shipping Decarbonization: Carbon, Production, Cost, and Allocative Efficiencies

Clean Maritime Assembly 2025

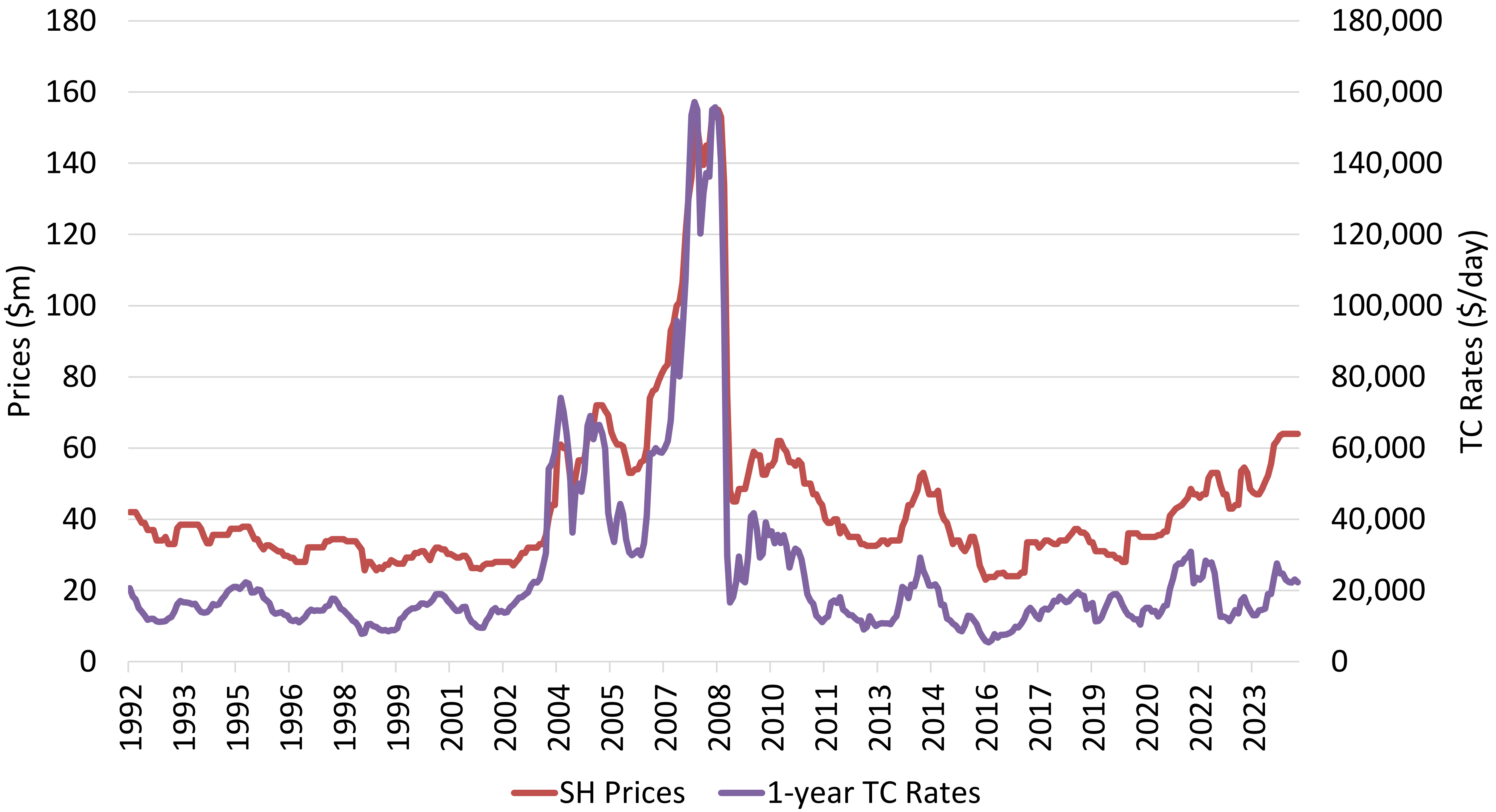
26 June 2025

Dr Yao Shi and Dr Ioannis C. Moutzouris

Research aims

- The literature has focused on the technological challenges
  - Shipping energy efficiency or carbon emission efficiency indices are largely physical-thermal measures, such as EEDI, EEXI, and CII.
- We relate the economic and technical performances of vessels with carbon emissions
  - How much do vessels earn per ton of CO2 emitted?
  - How changes in labor, fuel, and capital costs affect vessels' performance?
- We estimate the technical and allocative efficiencies, which enables us to
  - Differentiate the effects of economic resource allocation from technical improvements on (i) the energy demand and (ii) the total cost of owning and running a ship
  - Compare the price and productivity of energy to the prices of labor and capital
- This allows us to examine the effects of potential economic/market-based measures

Highly volatile and capital-intensive industry



Source: Clarksons' Shipping Intelligence Network

Methodology – carbon, production and cost efficiencies

- Stochastic frontier analysis measures efficiency relative to the frontier
  - Measures an input or output compared to its optimal value – holding everything else constant
- The efficiencies range between 0 and 100%, with 100% being on the frontier

Carbon efficiency: $min(CO2|given\ output\ and\ other\ inputs)$

Production efficiency: $max(transport\ work|given\ energy\ and\ other\ inputs)$

Cost efficiency: $min(total\ cost|given\ output\ and\ inputs)$

Methodology – allocative efficiency

- The allocative efficiency compares an input’s productivity with its price
- While the carbon and production efficiencies focus on the technical and operational capacity, the allocative efficiency incorporates **market price information** and investigates how **resources can be allocated** more efficiently
- A **positive** value indicates that an input is **overused**, i.e., it has **low** productivity relative to its price
- A **negative** value indicates that an input is **underused**, i.e., it has **high** productivity relative to its price

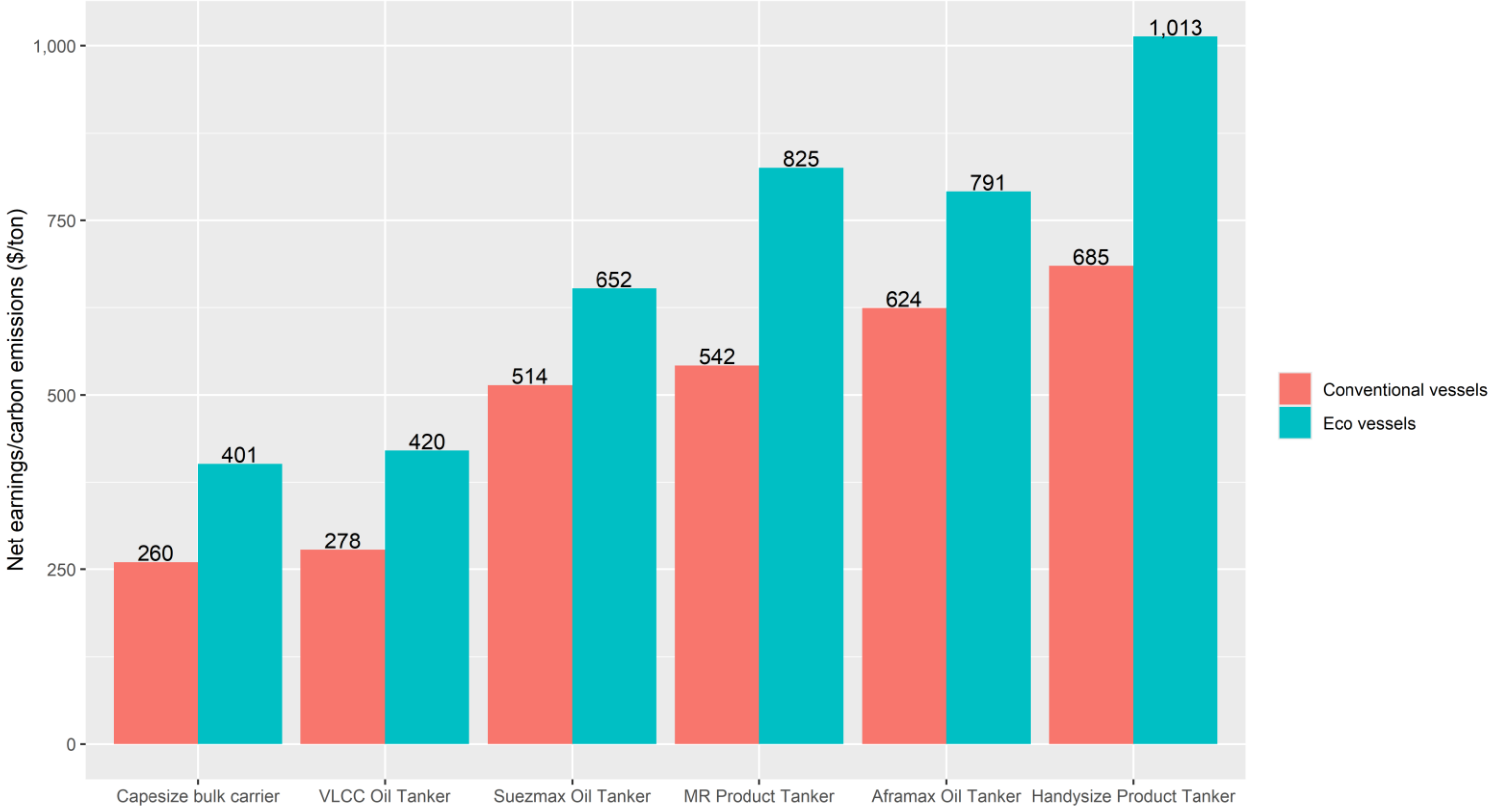
Inputs and outputs

- Inputs in shipping:
  - Energy consumption (E) or carbon emissions (CO_2)
  - Capital: newbuilding vessel prices (K)
  - Operation: labour/crew costs (L)
- Outputs of shipping:
  - cargo volume (V) * distance (D)
  - Time charter earnings (TC)

Data description

- Panel data:
  - 15 vessel types (dry bulkers, tankers, containerships) from 2021 to 2024 (annual frequency) from Clarksons' SIN (the biggest source of shipping data)
  - Capex, Opex, Earnings, fuel costs, speed, fuel consumption, etc.
- Cross-sectional data:
  - 664 individual vessels in 2023 from Clarksons' WFR
- Supplementary data:
  - Shipping loan rates from Dealogic/Marine Money
  - Monetary values adjusted based on the US Consumer Price Index
  - Labour prices are adjusted according to the International Labor Organization
- To the best of our knowledge, it is the first time that such granular dataset has been employed for the economic dimension of shipping sustainability

Net earnings per unit of carbon emissions by eco status



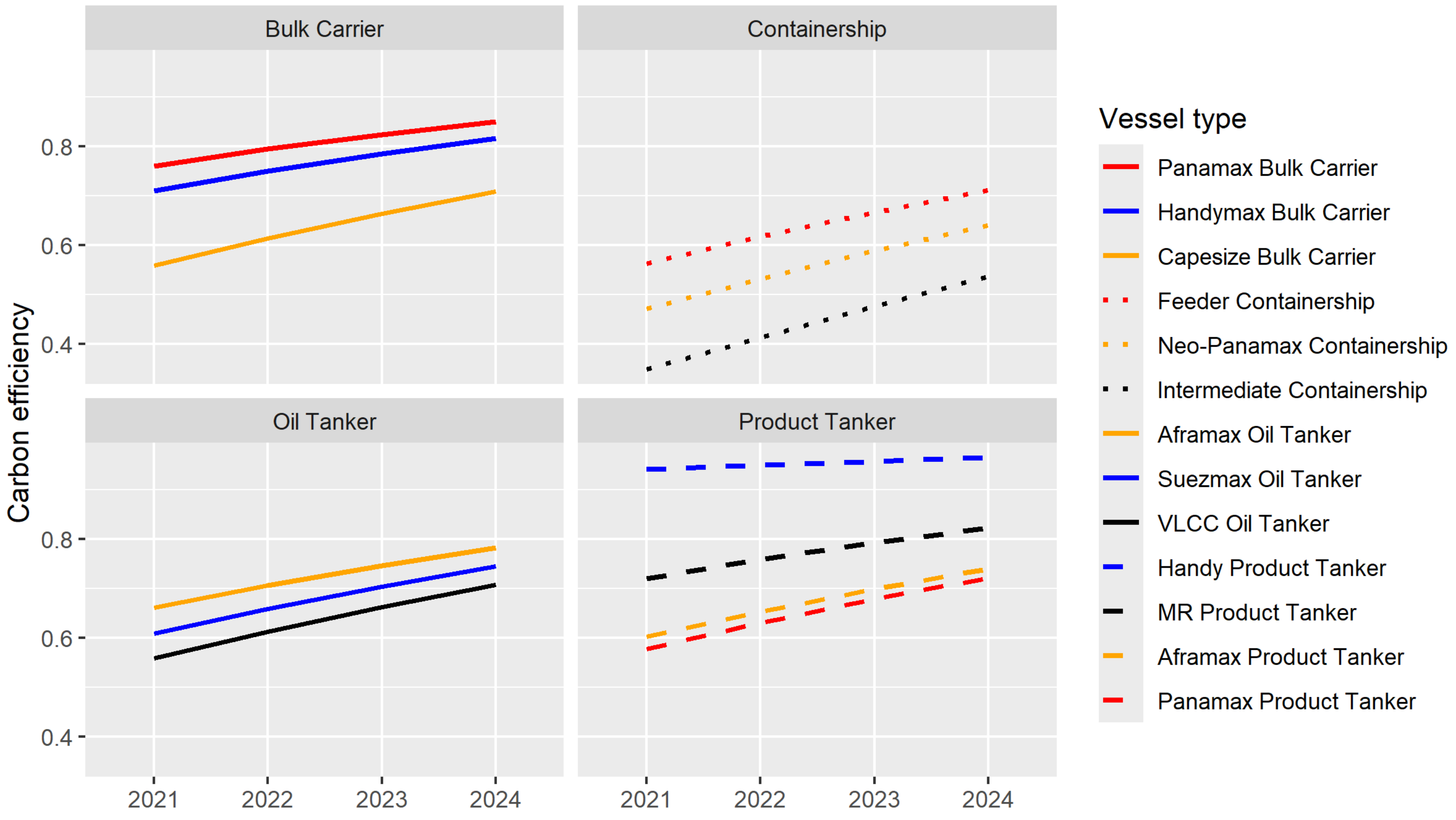
- ❑ Eco-vessels earn significantly more income per unit of CO2 emissions
    1. Emit less tons of CO2
    2. Earn a premium rate compared to non-eco ones
- ❑ Overall, larger vessels earn less per unit of CO2 emissions

Note: The carbon emissions values in the figure are obtained by taking the average of the carbon intensity from LPG, LNG, LSFO and HSFO. "eco vessel" refers to all ships with a 2-stroke engine which have an electronically controlled fuel injection system.

Transport work per unit of carbon emissions

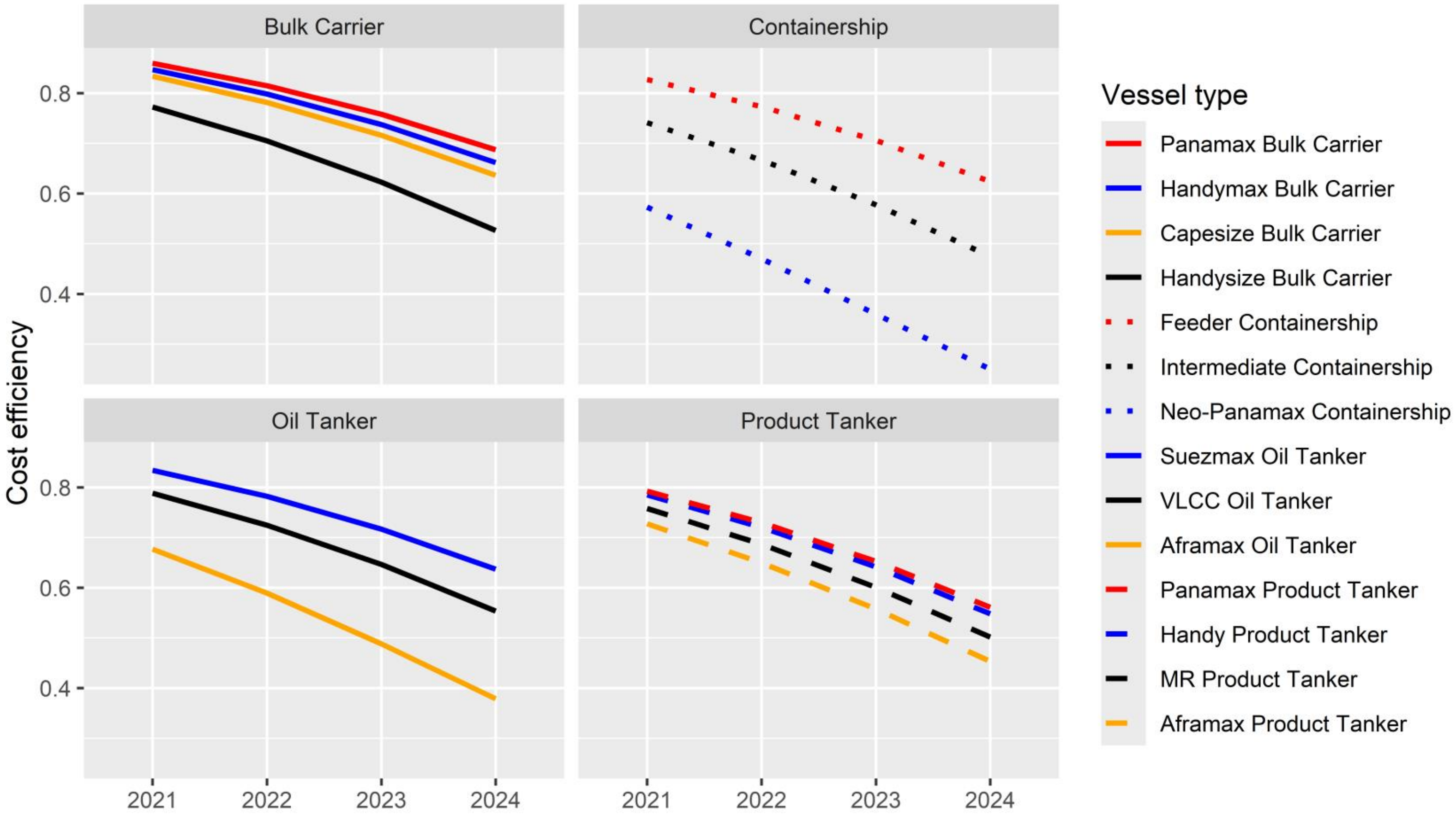
- On average, vessels produce a transport work of 0.07 million ton-miles per ton of CO2 emitted
- Larger vessels produce more transport work per unit of CO2 emissions

Carbon efficiency by vessel type and year



- Increased operational efficiency of vessels in that period, probably accelerated by the recent IMO measures
- Containerships are the least carbon efficient vessels
- Within a sector, smaller vessels are, in general, more carbon efficient than larger ones

Cost efficiency by vessel type and year



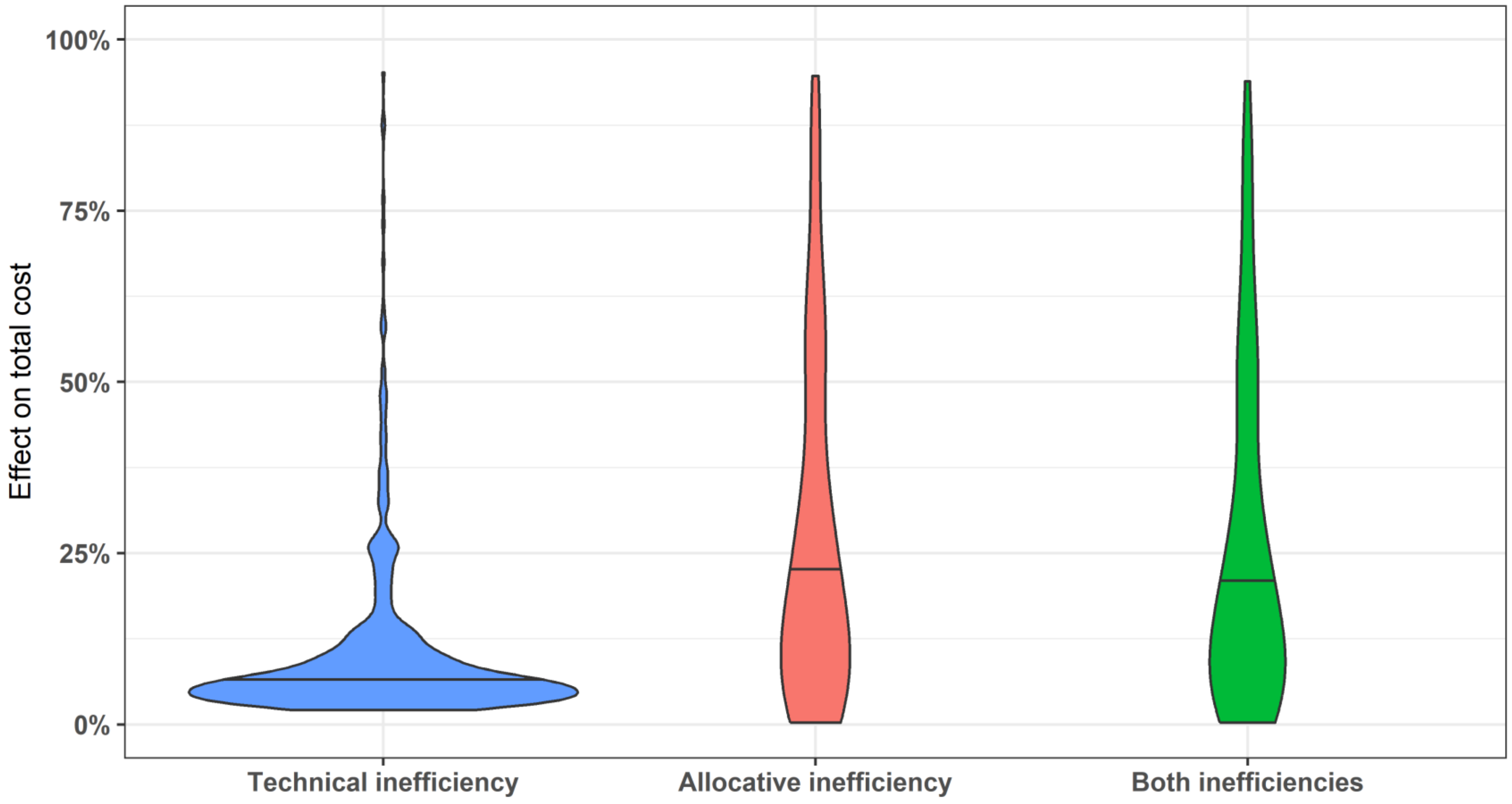
- Cost efficiency significantly decreases over time, probably due to the stricter environmental regulations
- It becomes more costly for shipowners to provide the same levels of productivity

Technical and allocative inefficiency results

	Technical inefficiency	Allocative inefficiency	Both inefficiencies
Labour	7.1%	255.9%	278.0%
Energy	6.1%	-36.5%	-32.6%
Capital	5.9%	57.7%	70.6%

- Our results suggest that vessels must increase their labor, energy and capital inputs by around 6-7% to match the maximum production level on the technical efficiency frontier
- The -36.5% allocative inefficiency indicates that energy is a relatively cheap input for the output it produces
  - Scope for increased fuel costs, e.g. in the form of a carbon levy
- The 58% capital figure may be due to the excess capex related to environmental regulations which, however, does not generate enough income to justify the investment

The inefficiency effects on vessels' total costs



- The two inefficiencies combined result in a close to 20% increase in vessel's total costs
- For the median vessel, technical inefficiency has increased its total cost by ca. 6%
- Allocative inefficiency has much more varied effect on vessels' costs
- For the median vessel, costs have increased by ca. 22%

Policy recommendations

❑Regulations on shipping decarbonisation need to account for economic and financial aspects. Suggestions include:

- Introduce stricter regulations to further improve vessel carbon efficiency, such as carbon prices or emission trading schemes.
- Such measures should be implemented with caution, considering the current earnings per ton of CO2 emitted.
- Design different policies for various vessels according to their size and cargo type.
- Gradually introduce higher compliance standards to green fuels.
- Provide financial incentives to encourage widespread adoption of greener fuels.
- Enhance investors’ access to capital via more attractive interest rates for green investments.

Q & A

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HYDRO-Port: Safety Management and Risk Assessment of Liquid Hydrogen Bunkering and Storage in Ports

UK National Clean Maritime Research Hub Wave 1 – Flexible Funding
July 2024 – December 2024

Dr. Sean Loughney
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Partners (Co-Is):

LJMU	Prof. Jin Wang, Dr. Eddie Blanco-Davis and Joe Ford
Lloyd's Register	Dr. Paul Davis
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Safe Energy Systems	Simon Waddington

Outline

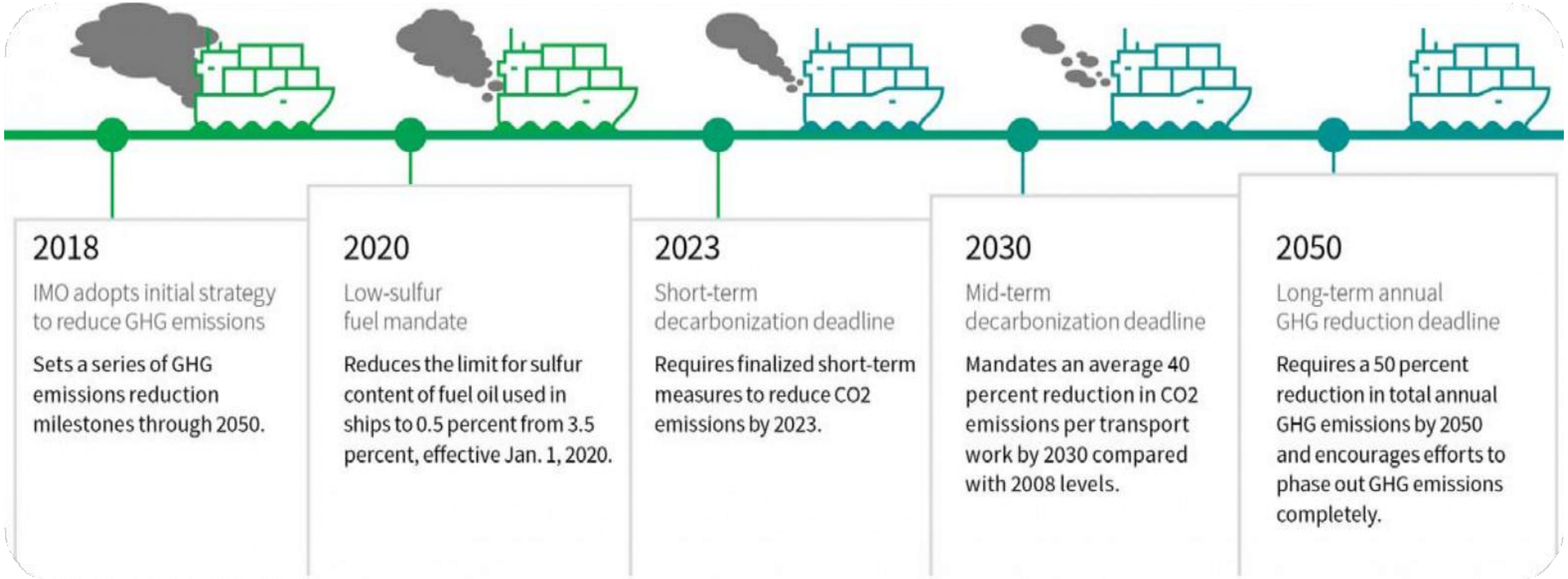
- Project Aim
- Background
- Multi-criteria decision methodology for most suitable alternative fuel
- Dispersion analysis
- Dynamic risk model development and integrity framework
- Conclusions and further research
- Project deliverables

Aim & Objectives

The aim of this research project is to assess and evaluate the risks associated with the storage and use of Hydrogen in the port of Liverpool.

- O1 – To evaluate existing alternative fuels and determine the most effective for use for Shore-to-Ship power generation.
- O2 – To determine and evaluate the risks associated with stored alternative fuels and appraise standard requirements of port safety management systems, for Liquid Hydrogen (LH2).
- O3 – Develop a dynamic integrity management framework to assess alternative fuel infrastructure safety for storage and transfer in ports.
- O4 – Apply the risk and safety management assessment results in a port case study adjacent to a populated city region.

Background



- During the 21st Climate Change Summit in Paris in 2015, the International Maritime Organization (IMO) pledged to adopt necessary measures to reduce Green House Gas (GHG) emissions from shipping.
- Several research studies and maritime classification society outlooks argue that the true path to effective decarbonization of the shipping industry could only be achieved by adopting low-carbon or zero-carbon alternative fuel sources.

Background

- According to an outlook published by the American Bureau of Shipping (2019a), achieving the IMO's long-term and short-term emission goals will require the development of low and zero-carbon fuels.
- It also emphasizes that the availability of these fuels and related infrastructure development will be vital to the shipping industry in meeting IMO's emission reduction targets.
- Psaraftis (2021) have reinforced the claim of ABS pertaining to the importance of zero-carbon alternative fuel's role in IMO's 2050 GHG emissions ambitions.
- However, maritime sector stakeholders exhibit a reactive nature to decarbonization compared to a proactive approach.

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Background

- Much of the recent research published (DNV-GL, 2019a; Thepsithar, 2020; Al-Enazi et al., 2021; Chiong et al., 2021b; Gray et al., 2021; Prussi et al., 2021; Ashrafi, Lister and Gillen, 2022) on alternate marine fuels have considered holistic approach to the alternative energy options available for shipping.

- These studies consider low/zero alternate carbon fuels for deep-sea, near coastal and inland-water applications.

- In large storage quantities, fuels such as LH2, ammonia or methanol would be more suited for vessels but would cause storage and bunkering availability issues for near coastal and inland-water applications.

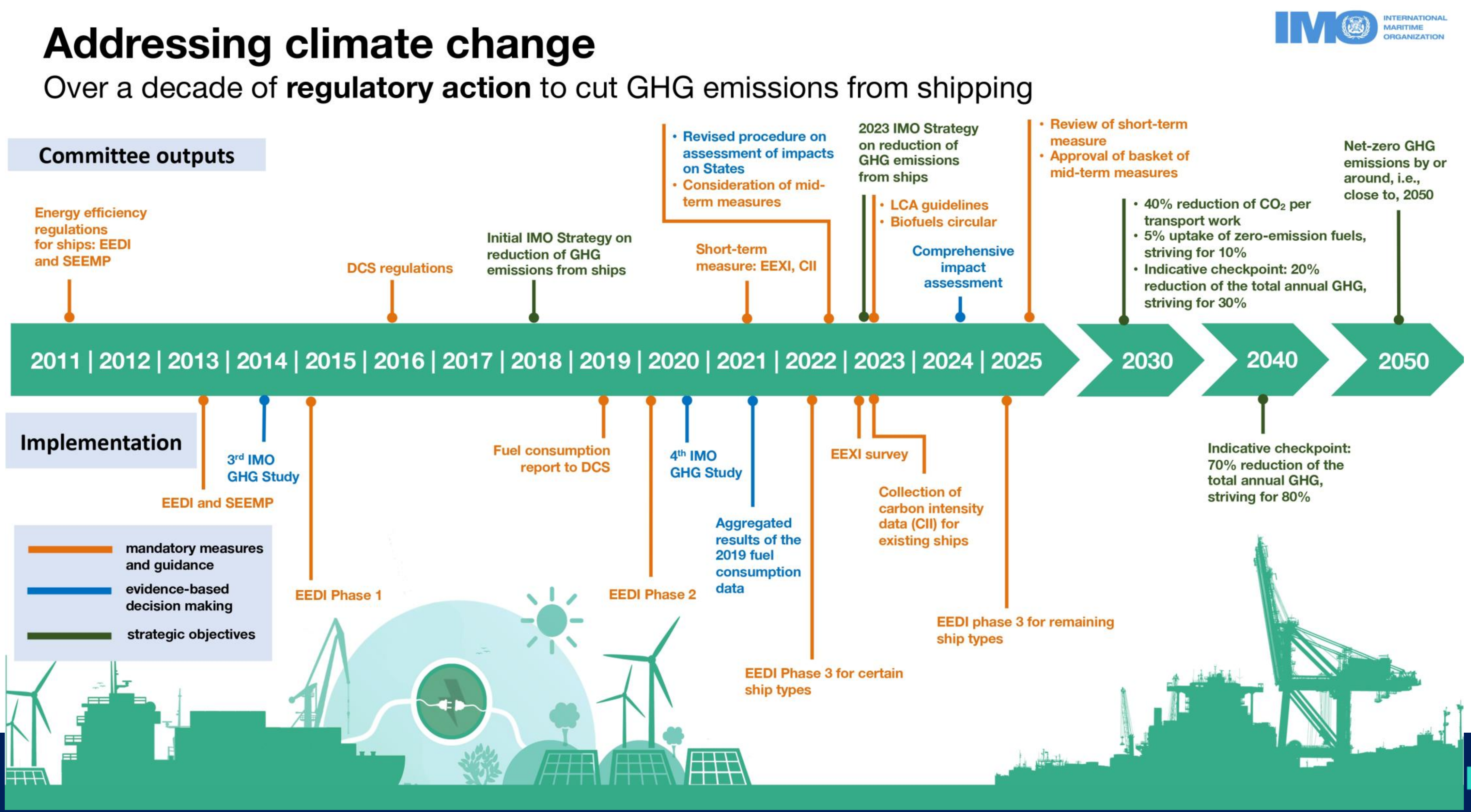
Background

- Although many studies have analysed alternate fuel options, none of these studies has specifically targeted deep-sea vessel applications, even though these vessels are responsible for over 80% of global GHG emissions from the maritime sector.

- Limited studies with a narrow scope of deep-sea applications (McKinlay, Turnock and Hudson, 2020; McKinlay, Turnock and Hudson, 2021; Ashrafi, Lister and Gillen, 2022) have been researched, but none of these studies has considered the technical, environmental, economic and social considerations of alternate deep-sea fuels.

- Lister and Gillen (2022), which evaluated alternative marine fuels through sustainability criteria. An in-depth systematic literature review utilizing secondary data and a detailed survey evaluated these fuels.
  - The study concluded that the most important criteria for alternate fuels would be regulatory compliance, followed by LCA performance, cost, air pollution potential, and safety. However, the study's relevance is applicable to fuel options that could meet the IMO’s 2030 emission targets and have not emphasized 2050 emission targets.

The 2050 Future Fuel Mix



Hydrogen

- The major challenge for hydrogen fuel would be the high production cost and the lack of bunkering infrastructure (DNV-GL, 2019b).
- On the other hand, the ABS (2021a) also identify that, among other challenges, advanced storage requirements and fire hazard mitigation are factors that require due attention.
- Hydrogen can be stored as a compressed gas or a cryogenic liquid at -253^{O}C.
- In gas form, hydrogen requires high-pressure tanks, and due to its low volumetric density, it would require 4 times the storage space compared to conventional fuels.

O1 - Alternative fuels assessment

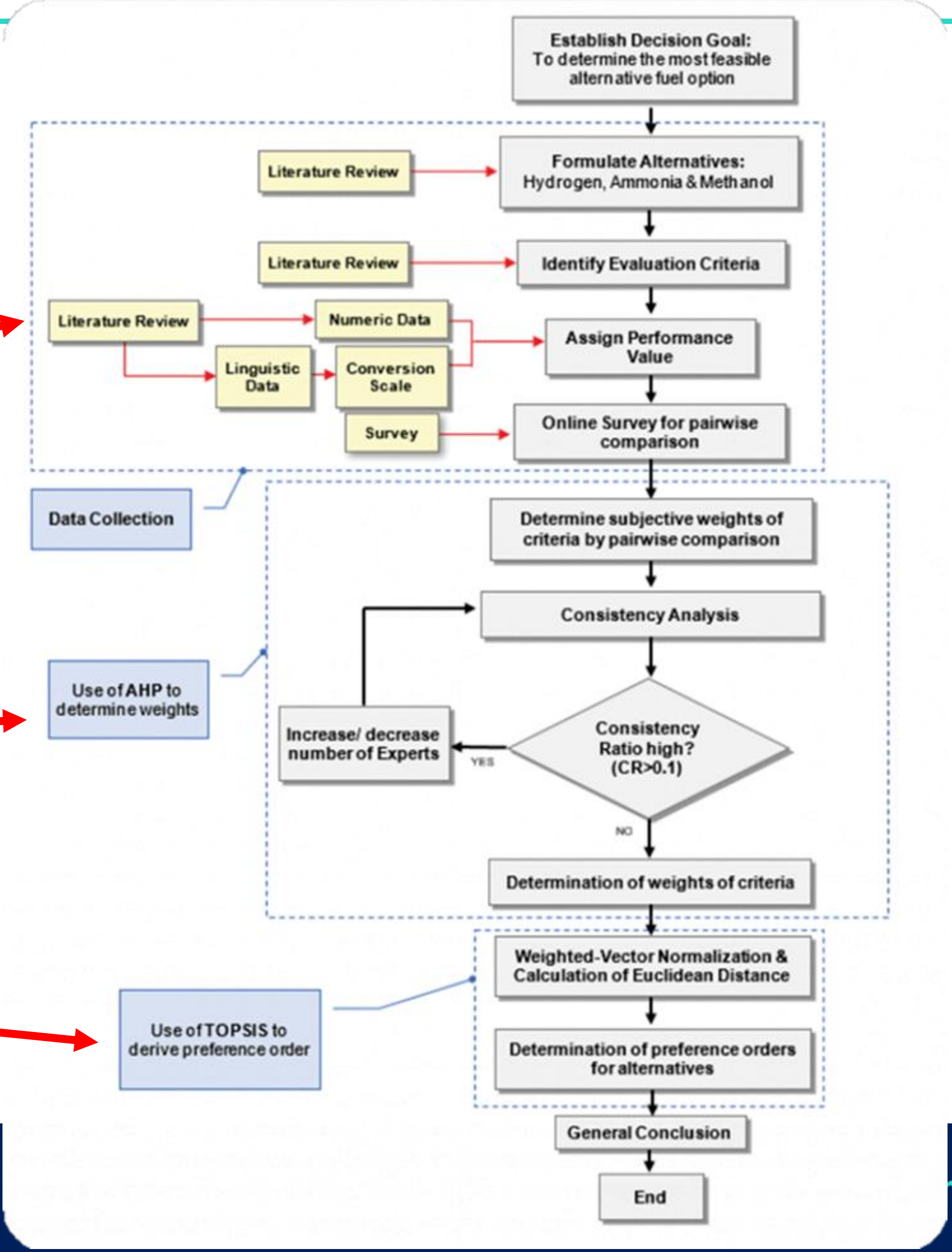
Methodological Framework

Data Gathering
- Primary Data:
  Survey of stakeholders

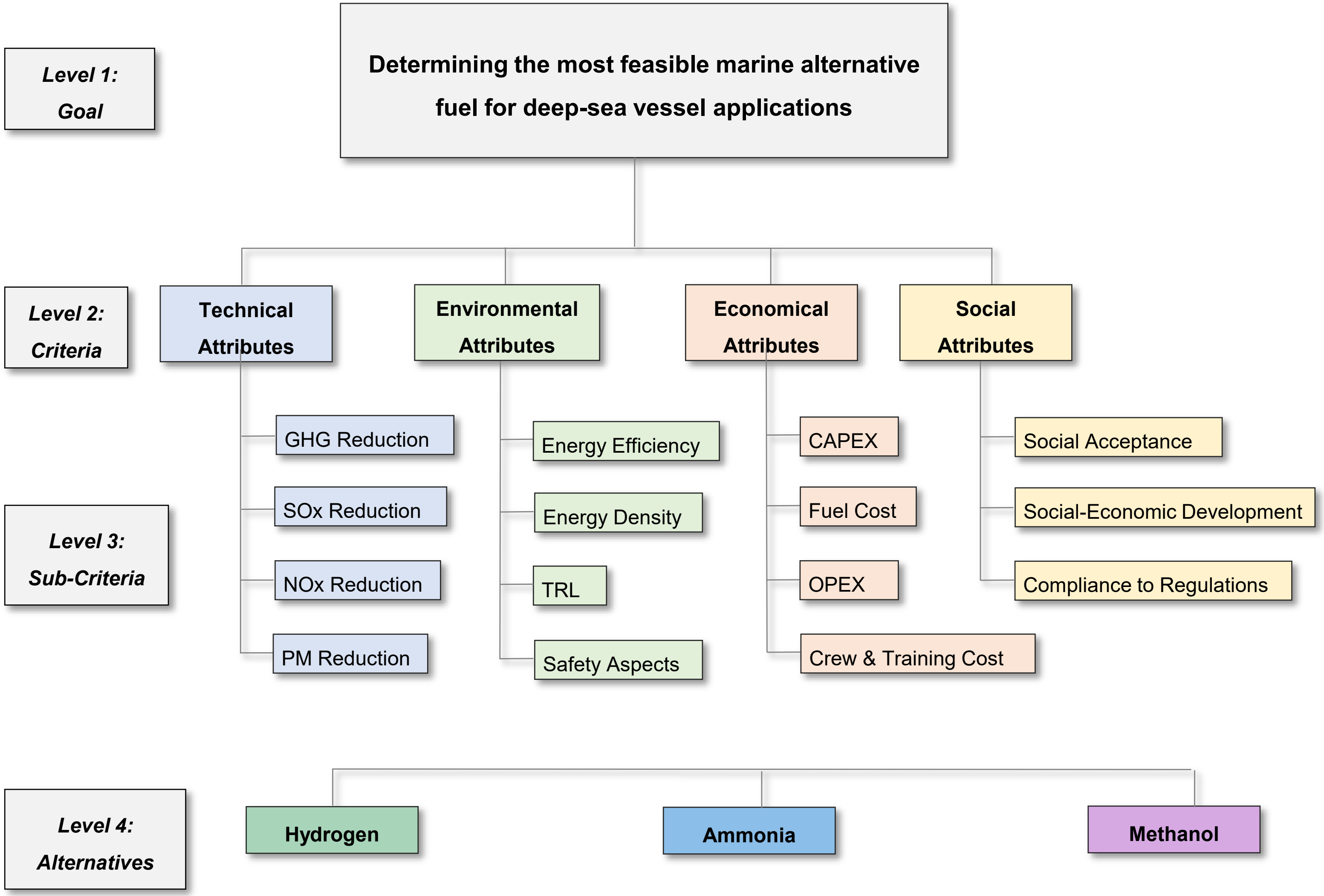
- Secondary Data:
  Performance values of each alternative fuel

Subjective analysis:
- Analytical Hierarchy Process (AHP)

Objective analysis:
- TOPSIS (Technique of Order Preference Similarity to the Ideal Solution)



O1 - Alternative fuels assessment



Main Criteria	Criteria Notation	Criteria Description	Performance Values Data Sources
Technical Attributes	C1	Energy Efficiency	(ABS, 2020b; ABS, 2021c; ABS, 2021b; Ming and Chen, 2021)
	C2	Energy Density	(DNV-GL, 2019b; ABS, 2020b; ABS, 2021a; DNV, 2021; Ming and Chen, 2021; Wan et al., 2021)
	C3	TRL	(DNV-GL, 2019b; Lloyd's Register and UMAS, 2020; DNV, 2021; Ming and Chen, 2021; Mäkitie et al., 2022)
	C4	Safety of Handling, Bunkering & Storage	(Valera-Medina et al., 2018; DNV-GL, 2019b; American Bureau of Shipping, 2021a; Wan et al., 2021; American Bureau of Shipping, 2022)
Environmental Attributes	C5	GHG Emission Factor	(Gilbert et al., 2018; ABS, 2019b; DNV-GL, 2019b; ABS, 2021a; Ming and Chen, 2021; Xing et al., 2021)
	C6	SOx Emission Factor	(Gilbert et al., 2018; ABS, 2019a; ABS, 2019b; Maritime, 2019; Ming and Chen, 2021; Xing et al., 2021; Mäkitie et al., 2022)
	C7	NOx Emission Factor	(Gilbert et al., 2018; ABS, 2019b; DNV-GL, 2019b; ABS, 2020a; Ming and Chen, 2021; Xing et al., 2021; Mäkitie et al., 2022)
	C8	PM Emission Factor	(Brynolf, Fridell and Andersson, 2014; Gilbert et al., 2018; ABS, 2019b; DNV-GL, 2019b; Ming and Chen, 2021; Xing et al., 2021)
Economic Attributes	C9	Capital Expenditure	(Lloyd's Register and UMAS, 2020; DNV, 2021)
	C10	Fuel Cost	(DNV-GL, 2019b; Lloyd's Register and UMAS, 2020; Al-Enazi et al., 2021; DNV, 2021)
	C11	Operational Expenditure	(Deniz and Zincir, 2016; Lloyd's Register and UMAS, 2020; DNV, 2021)
	C12	Crew Training Cost	(Deniz and Zincir, 2016; Al-Enazi et al., 2021)
Social Attributes	C13	Social Acceptance	(Ren and Liang, 2017; Ren and Lützen, 2017; Wan et al., 2021; Ashrafi, Lister and Gillen, 2022)
	C14	Social-Economic Development	(Ren and Liang, 2017; Ren and Lützen, 2017; Ashrafi, Lister and Gillen, 2022)
	C15	Compliance to Regulations	(Ren and Liang, 2017; Ren and Lützen, 2017; DNV-GL, 2019b; DNV, 2021)

O1 - Alternative fuels assessment

Subjective Analysis

Participant Demographics

- Survey was conducted for 4 weeks
- A total of 57 responses were received out of 184 prospective candidates
- 71.9% Respondents were marine engineers, 15.8% marine surveyors, Others 15.8%, 8.8% Academia
- 61.4% were experienced over 15 years

Main Criteria: Assessment Criteria	Main Criteria: Notation	Main Criteria: Weights	Sub-Criteria: Assessment Criteria	Sub-Criteria: Notation	Sub-Criteria: Local Weight	Sub-Criteria: Overall Global Weight (Weight × Local Weight)
Technical Criteria	W	0.283	Energy Efficiency	C1	0.222	0.063
			Energy Density	C2	0.132	0.037
			TRL	C3	0.218	0.062
			Safety	C4	0.428	0.121
Environmental Criteria	X	0.428	GHG Reduction	C5	0.314	0.134
			SO_X Reduction	C6	0.249	0.108
			NO_X Reduction	C7	0.248	0.106
			PM Reduction	C8	0.19	0.081
Economic Criteria	Y	0.176	CAPEX	C9	0.229	0.04
			Fuel Cost	C10	0.308	0.054
			OPEX	C11	0.291	0.051
			Crew & Training Cost	C12	0.172	0.03
Social Criteria	Z	0.113	Social Acceptance	C13	0.376	0.042
			Socio-Econ Development	C14	0.313	0.036
			Compliance to Regulation	C15	0.311	0.035

	Technical Criteria	Environmental Criteria	Economic Criteria	Social Criteria	Overall	Overall Normalized	Ranking
Hydrogen	0.146	0.190	0.138	0.070	0.544	0.349	1
Ammonia	0.159	0.212	0.100	0.062	0.533	0.343	2
Methanol	0.139	0.253	0.031	0.056	0.479	0.308	3

O1 - Alternative fuels assessment

Performance Values for TOPSIS (Objective).

Attributes				Alternatives		
Main Criteria	Sub-Criteria	Criteria Notation	Units	Hydrogen	Ammonia	Methanol
Technical Attributes	Energy Efficiency	C1	g/kW-hr	57	381	381
	Energy Density	C2	MJ/L	9.2	12.7	15.8
	TRL	C3	TRL Scale Rating	4	6	9
	Safety of Bunkering, handling & Storage	C4	Rating Scale	5	3	1
Environmental Attributes	GHG Emission	C5	g/kW-hr	0	102	533
	SO_x Reduction Potential	C6	% Compared to HFO	100	100	92
	NO_x Reduction Potential	C7	% Compared to HFO	100	96	45
	PM Reduction Potential	C8	% Compared to HFO	100	100	56
Economic Attributes	CAPEX	C9	USD/Kg of Fuel	1.5	0.94	0.16
	Fuel Cost	C10	USD/MWh Shaft Output	315	260	105
	OPEX	C11	USD/Kg of Fuel	0.0600	0.0470	0.0064
	Crew & Training Cost	C12	Rating Scale	5	3	2
Economical Attributes	Social Acceptance	C13	Rating Scale	2	4	4
	Social-Economic Development	C14	Rating Scale	5	3	2
	Compliance to Regulations	C15	Rating Scale	5	3	3

O1 - Alternative fuels assessment

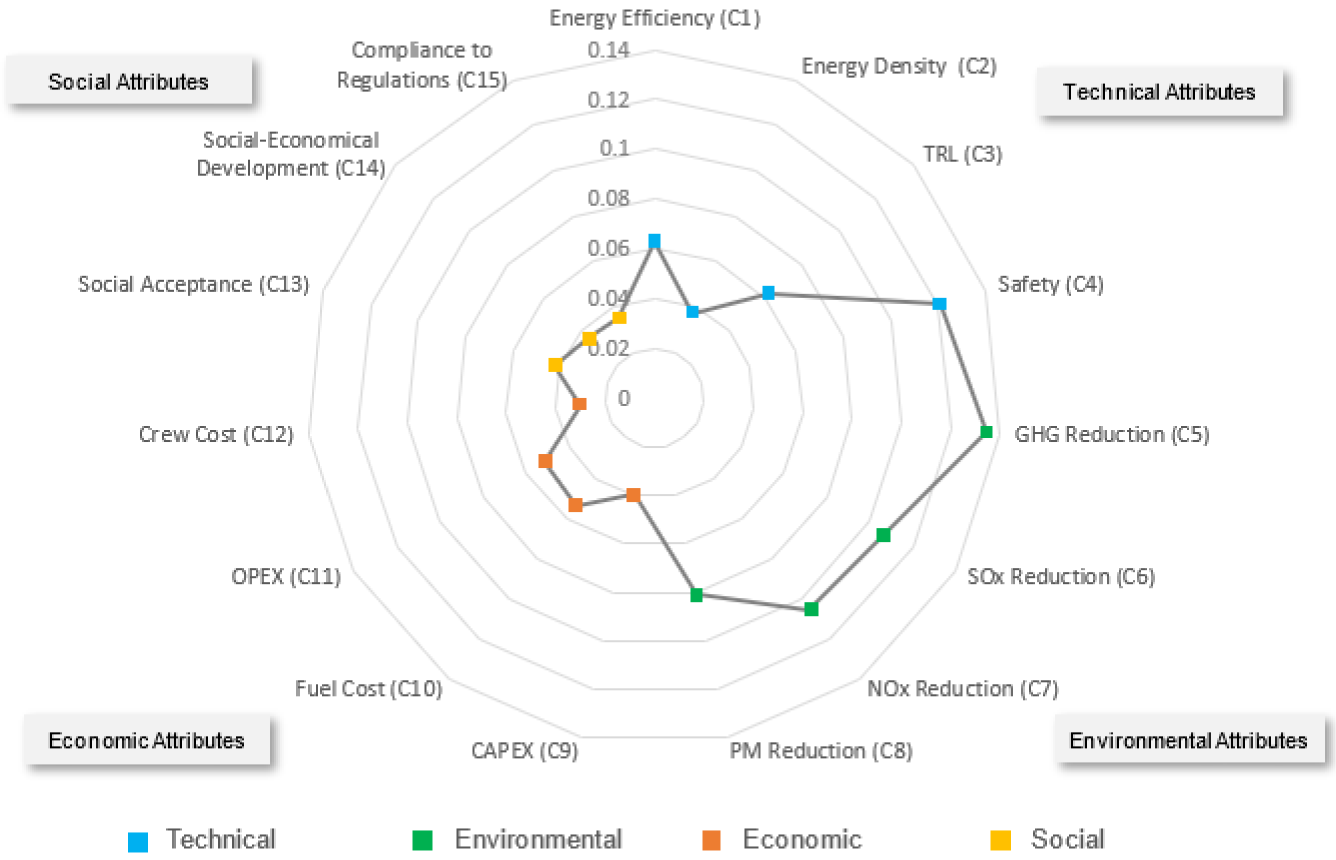
Weighted-Normalized Decision Matrix with Positive & Negative ideals.

Criteria		Technical Attributes				Environmental Attributes				Economic Attributes				Social Attributes		
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Alternatives	**Hydrogen**	0.007	0.015	0.021	0.102	0.000	0.063	0.072	0.053	0.034	0.041	0.040	0.025	0.014	0.029	0.027
	Ammonia	0.044	0.021	0.032	0.061	0.025	0.063	0.070	0.053	0.021	0.033	0.031	0.015	0.028	0.017	0.016
	Methanol	0.044	0.027	0.048	0.020	0.132	0.058	0.033	0.030	0.004	0.014	0.004	0.010	0.028	0.011	0.016
A+		0.007	0.027	0.048	0.020	0.000	0.063	0.072	0.053	0.004	0.014	0.004	0.010	0.028	0.029	0.027
A-		0.044	0.015	0.021	0.102	0.132	0.058	0.033	0.030	0.034	0.041	0.040	0.025	0.014	0.011	0.016

Euclidean Distance from Ideal & Performance Score - Overall.

		S_j^+	S_j^-	P_i	**Rank**
Alternatives	**Hydrogen**	0.1043	0.1465	0.5840	2
	Ammonia	0.0757	0.1257	0.6241	1
	Methanol	0.1465	0.1043	0.4160	3

O1 - Alternative fuels assessment



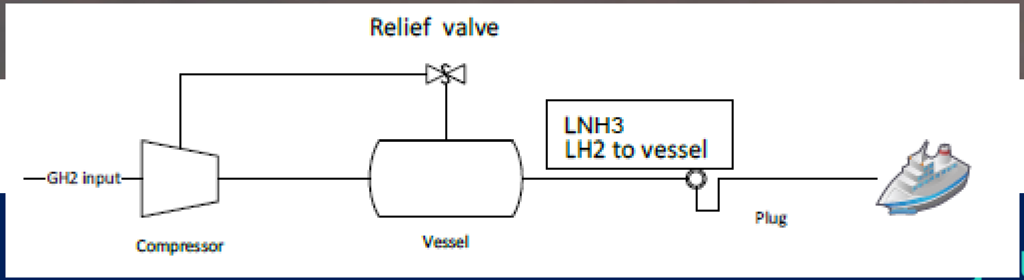
Weights Distribution of Sub-Criteria

- Criteria weights derived in this study can be used as secondary data for new research.
- Finding Ammonia as the most feasible alternative can encourage further research on ammonia, especially to focus resolving the drawbacks of ammonia.
- Clear emphasis is on the GHG reduction and improved safety (71.9% participants Marine Engineers)
- Prompt engine makers and fuel-cell manufactures to improve the efficiency of ammonia related designs, using engineers and operators to address and improve safety concerns.
- Aid the decision-makers and stakeholders of the industry on their preferred choice of fuel for their future vessel designs.
- Can encourage investments and incentives to ammonia pilot projects.

O2 - risks associated with stored alternative fuels

Dispersion analysis

- The Port of Liverpool infrastructure was updated in 2016 with the Liverpool 2 port.
- During berthing and unloading expected to take 94 hours to turnaround a 14,000TEU.
- The location shown is the proposed location of the LH2 vessel.
- The solution could fill the Panamax auxiliary Generator storage tank or run directly from the vessel shown.
- hotel load includes power for lighting, heating, ventilation, air conditioning (HVAC), refrigeration (especially for reefer containers), communications, crew accommodations, cargo handling equipment, and other auxiliary systems



O2 - risks associated with stored alternative fuels

Fuel Comparison

- Under standard conditions, two 5 MW generator sets would consume approximately 2 tons of fuel per hour if operating at full capacity with a specific fuel consumption of around 200 g/kWh.
- To replace the fuel consumption of two 5 MW diesel generator sets operating at full load, approximately 717 kg of liquid hydrogen per hour would be needed.
- This equates to around $10.1m^3$ of liquid hydrogen per hour, considering its lower density compared to traditional marine fuels.

The Control of Major Accident Hazards (COMAH) Limits

- 150 tonnes storage 2 x 100 hr offloads = Tier 2 Upper tier

Notification to the Competent Authority:
Tier 1 sites, operators must notify the CA about the site's details, hazardous substances, and activities carried out.

Tier 2 This notification should include additional information, such as:

- Inventory of dangerous substances.
- A map or layout of the site.
- A description of the installation's environment.
- This notification must also be updated in the event of significant changes or permanent closure.

Dimensions for storage vessel

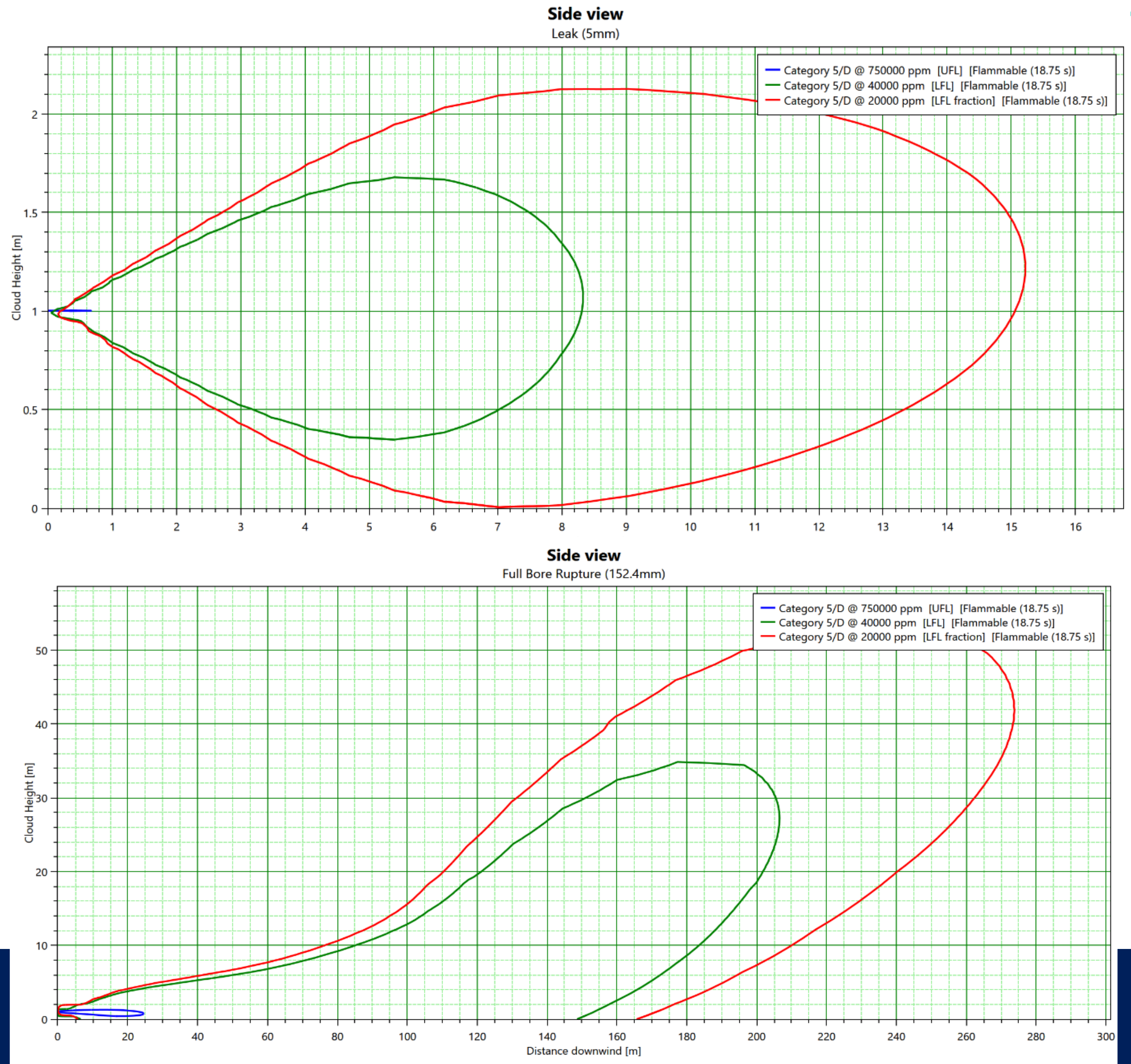
- Mass of hydrogen: 150,000 kg (since 150 tonnes = 150,000 kg).
- Volume = Mass / Density = 150,000 kg / 70.85 $kg/m^3 \approx 2{,}116\ m^3$.
- ***2 bar for leak assumption for 5mm, 25mm and full bore 152.4mm (6 inch)***

O2 - risks associated with stored alternative fuels

Dispersion Patterns:

- *Initial Dispersion:*
  - Upon release, LH2 rapidly vaporizes, forming a dense, cold vapor cloud. The initial dispersion is significantly influenced by the release height and environmental conditions.

- *Downwind Dispersion:*
  - The wind speed (5 m/s) and neutral stability class (Pasquill D) play crucial roles in the downwind dispersion of the hydrogen cloud.
  - Higher wind speeds facilitate faster dilution, while neutral stability conditions result in moderate vertical mixing.
  - The dispersion patterns vary with leak sizes, with larger leaks (full bore) leading to more extensive dispersion areas.



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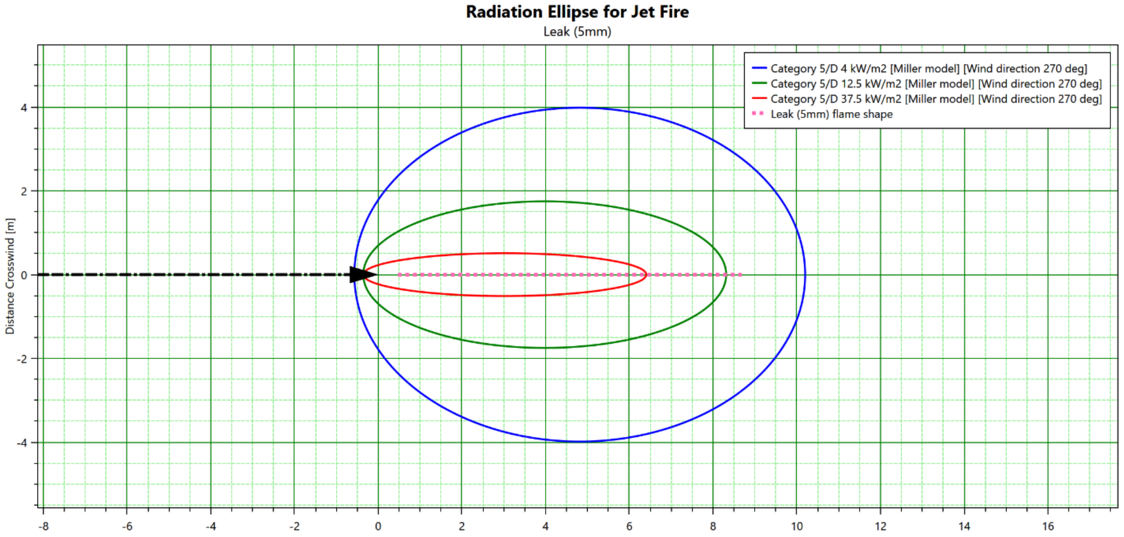
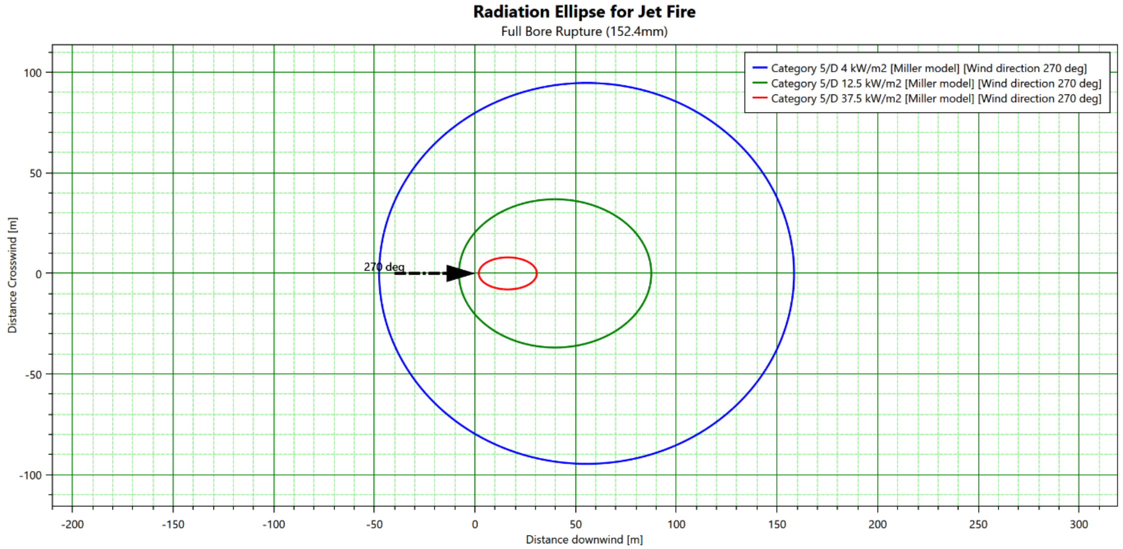
O2 - risks associated with stored alternative fuels

Jet Fire / Immediate Ignition:

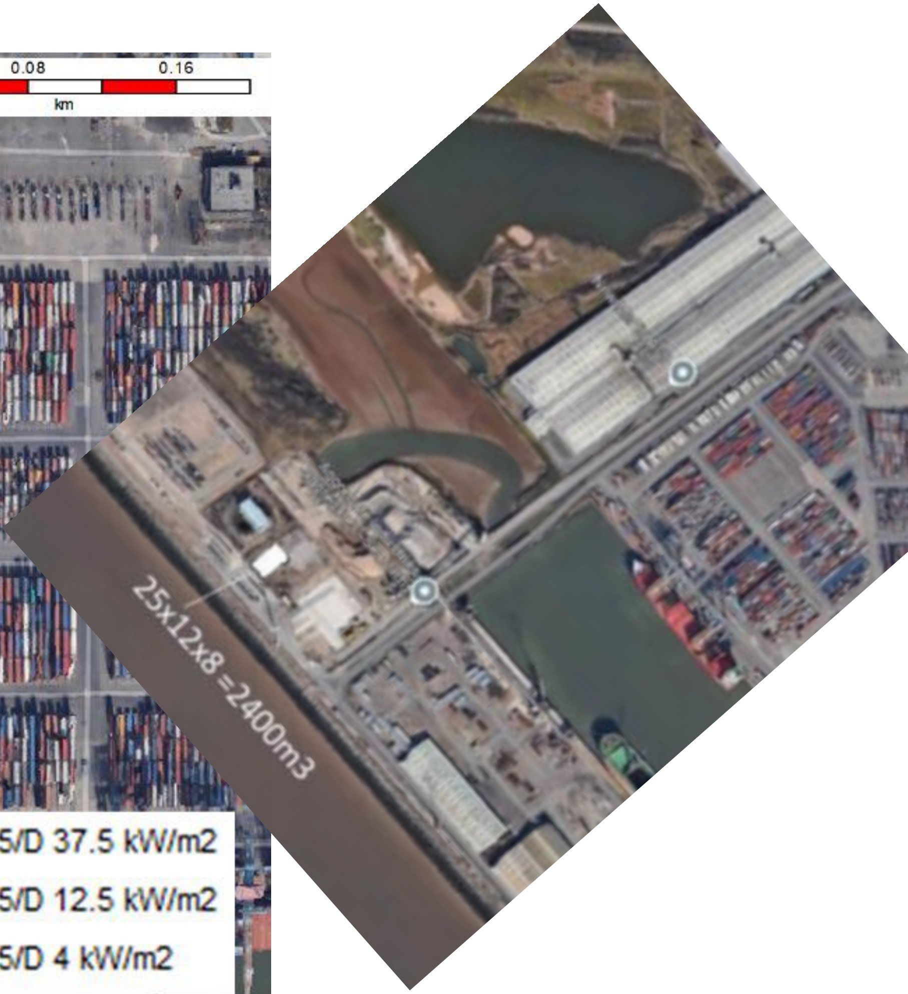
- *Thermal Radiation Effects:*
    - immediate ignition of hydrogen releases can result in jet fires with significant thermal radiation effects.
    - The severity of these effects increases with the size of the leak.
    - full bore releases produce high-velocity flames that can cause severe burns or fatalities
- *Likelihood: Moderate.*
    - Immediate ignition is possible due to the low ignition energy of hydrogen, but it depends on the presence of an ignition source at the time of release.
    - Severity: High. Jet fires can cause severe thermal radiation injuries or fatalities and significant property damage.





- Below 4 kW/m2 – No effect on outdoor personnel, assuming that an escape route is available without passing through a zone of higher radiation.
- Between 4 and 12.5 kW/m2 – Personnel within this zone can use escape routes, assuming that they are able to exit the affected area within 30 seconds. Personnel may not enter this area. Indoors personnel are subject to 0.3 lethality probability.
- Between 12.5 and 37.5 kW/m2 – Outdoor personnel may take escape action lasting a few seconds but are likely to suffer second degree burns. Indoors personnel are subject to 0.3 probability of lethality.
- Above 37.5 kW/m2 – Instantaneous death for indoor and outdoor personnel.

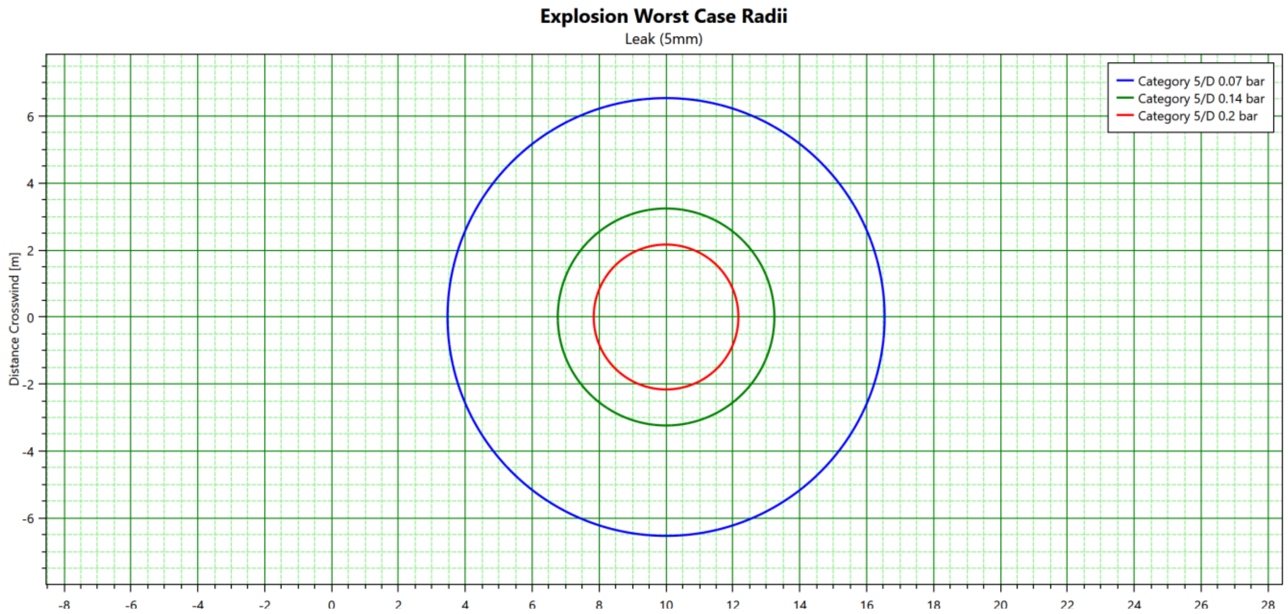
O2 - risks associated with stored alternative fuels

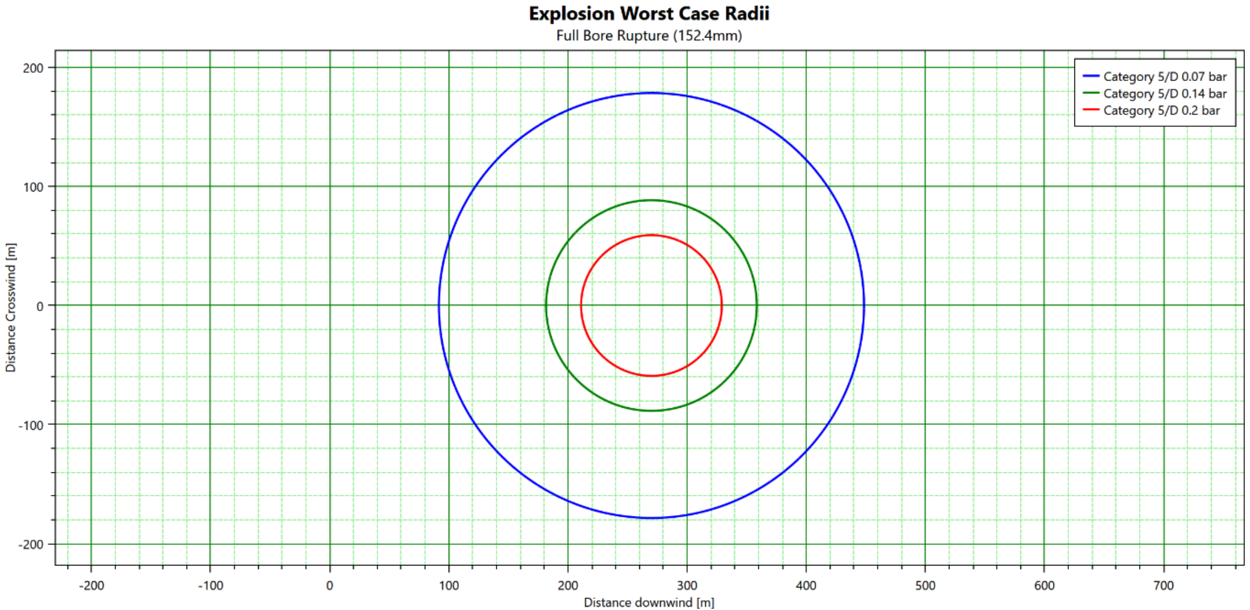


O2 - risks associated with stored alternative fuels

Explosion Overpressure:

- *Overpressure Effects:*
  - analysis shows that small leaks can generate overpressure levels to cause structural damage and injuries.
  - Larger leaks can lead to catastrophic overpressure effects.
- *Likelihood: Low to Moderate.*
  - Explosions require a specific set of conditions, including the right concentration, an ignition source, and a moderate amount of confinement.
- *Severity: Very High.*
  - Explosions can cause extensive structural damage and result in numerous injuries or fatalities.



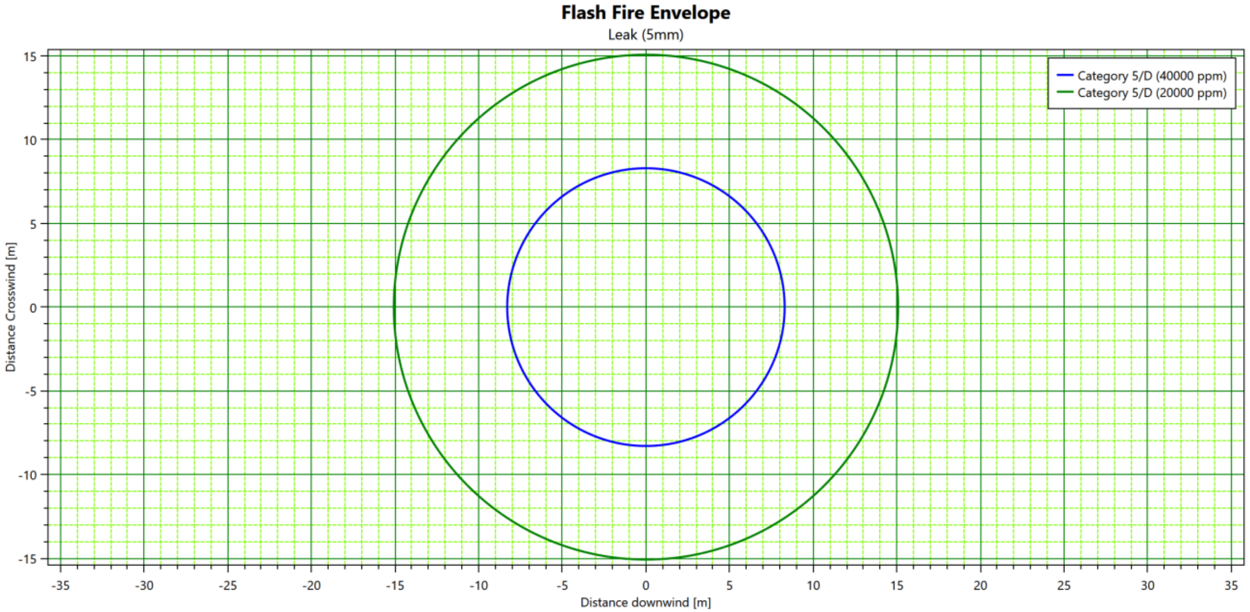


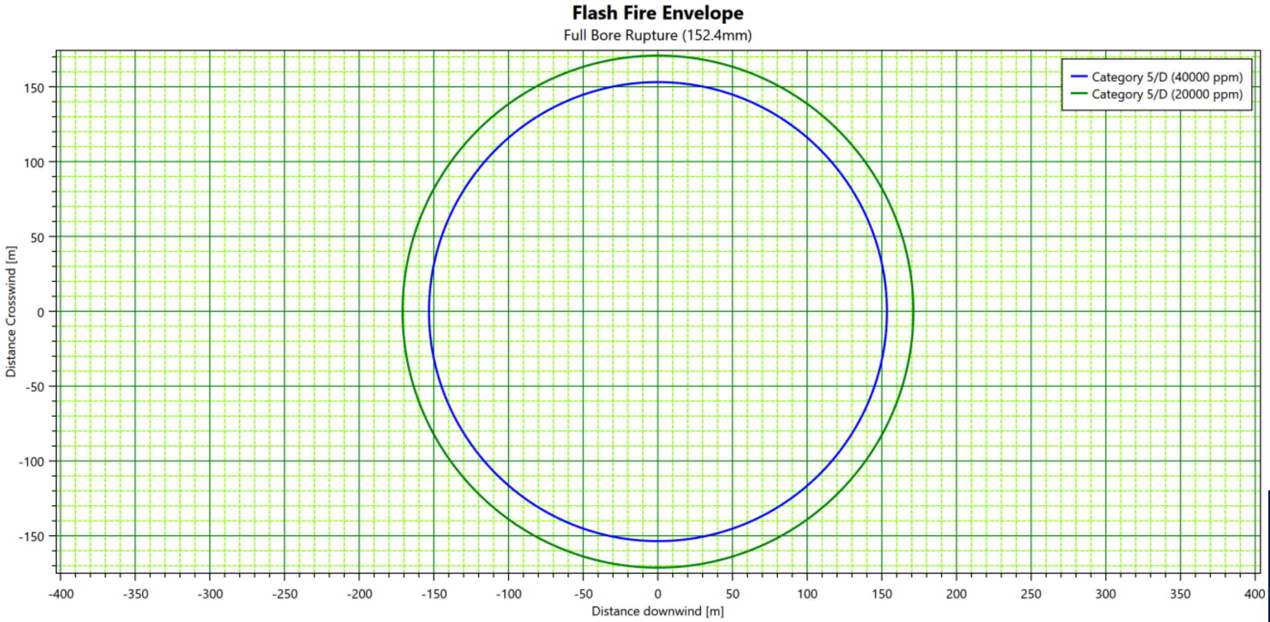
- 0.07 bar – Window glass on structures shatters and light injuries are caused to humans due the fragments.
- 0.14 bar – Moderate damage to houses (windows and doors blown out and severe damage to roofs). People injured by flying glass and debris.
- 0.2 bar – Residential structures collapse. Serious injuries to people are common and fatalities may occur.

O2 - risks associated with stored alternative fuels

Flash Fire / Unignited Dispersion Analysis:

- *Flash Fire Risks:*
  - The delayed ignition of dispersed hydrogen clouds can result in flash fires.
- *Burn-Back Potential:*
  - In the event of a flash fire, there is a risk of burn-back to the release location.
- *Likelihood: Moderate.*
  - Flash fires are a significant risk if the dispersed H2 cloud encounters an ignition source.
  - requires a delayed ignition which is less likely than immediate ignition.
- *Severity: High.*
  - Flash fires can cause rapid and widespread flame propagation, leading to severe injuries or fatalities





O2 - risks associated with stored alternative fuels

Overall Implications of Dispersion analysis:

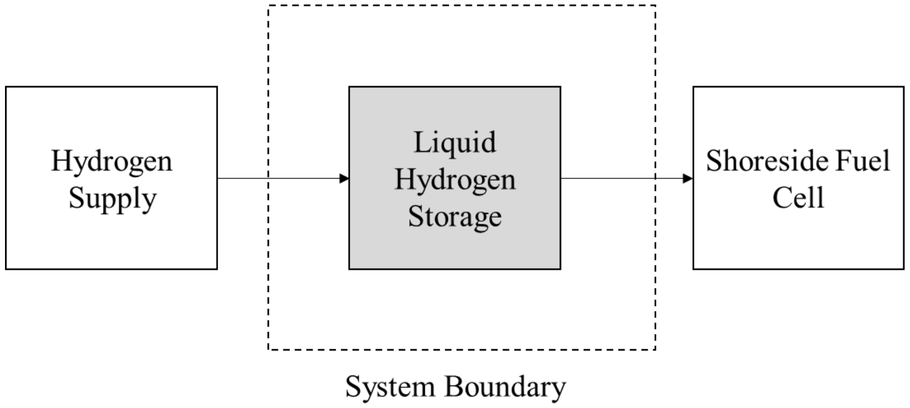
- *Most Likely Consequence:*
  - A jet fire is the most likely consequence as it is the result of immediate ignition which is probable due to the low ignition energy of hydrogen.
  - A jet fire could also be the result of a delayed ignition due to the burn back of a flash fire.
- *Worst Consequence:*
  - Although an explosion represents the worst-case scenario, it is less likely than a jet fire due to need of a delayed ignition source and a moderate level of confinement.
  - Therefore, a jet fire is taken to be the worst consequence due to its high likelihood and severity.

Safety Measures:

- *Leak Detection:*
  - Implementing robust leak detection systems to identify and respond to hydrogen releases promptly.
- *Ignition Prevention:*
  - Ensuring that potential ignition sources are minimized or eliminated in areas where hydrogen is stored or used.
- *Emergency Response:*
  - Developing comprehensive emergency response plans, including evacuation procedures and training for personnel.

O3 & O4 – Dynamic risk model and framework

Dynamic Risk Model:



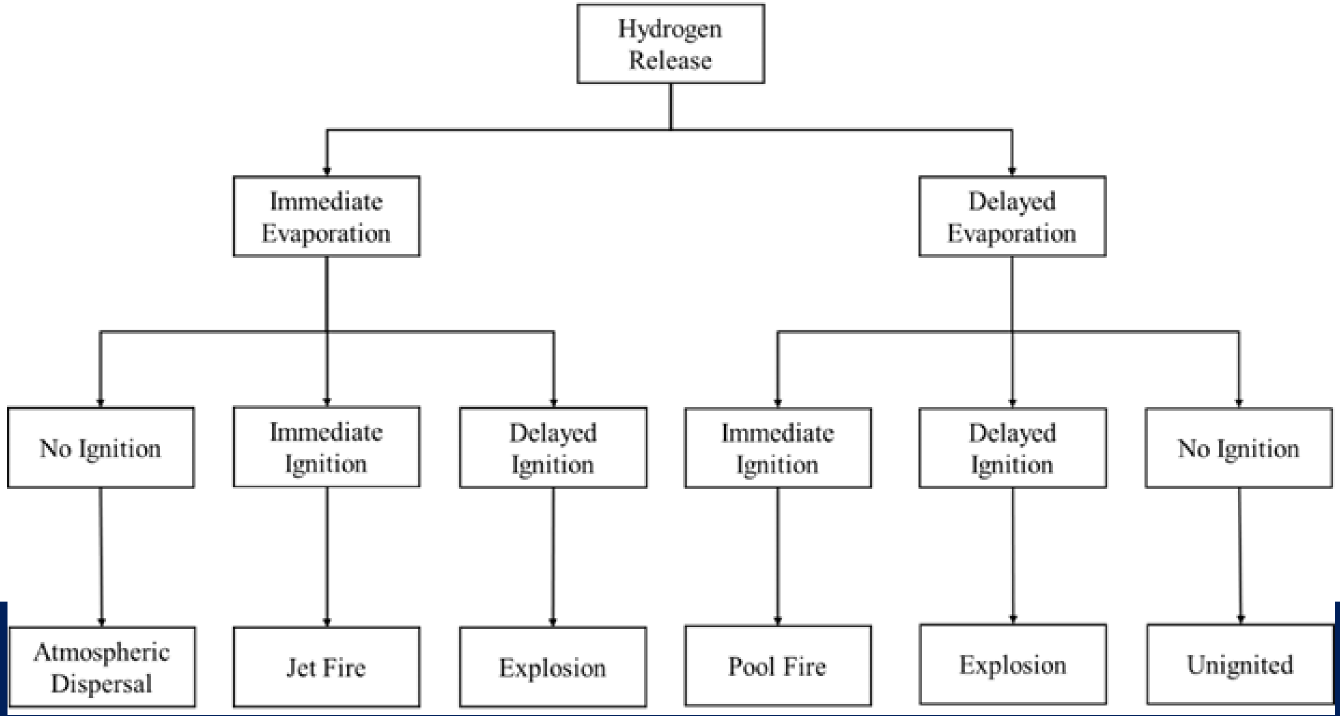
- A dynamic risk assessment model was developed following from results outlined in the fuel studies completed by BB with LJMU (decision-making), and LR & SES (dispersion analysis).
- The model considers the potential hazards and consequences of stored fuels on port structures, the environmental, and human health to fully evaluate from a risk control and management perspective.
- Bayesian networks (BN) are used in dynamic risk assessments due to their ability to integrate both qualitative and quantitative data.
- This allows for the network to be updated and adapted as new information becomes available.
- The system boundary will be limited to the LH2 storage system, as shown.

O3 & O4 – Dynamic risk model and framework

Dynamic Risk Model:

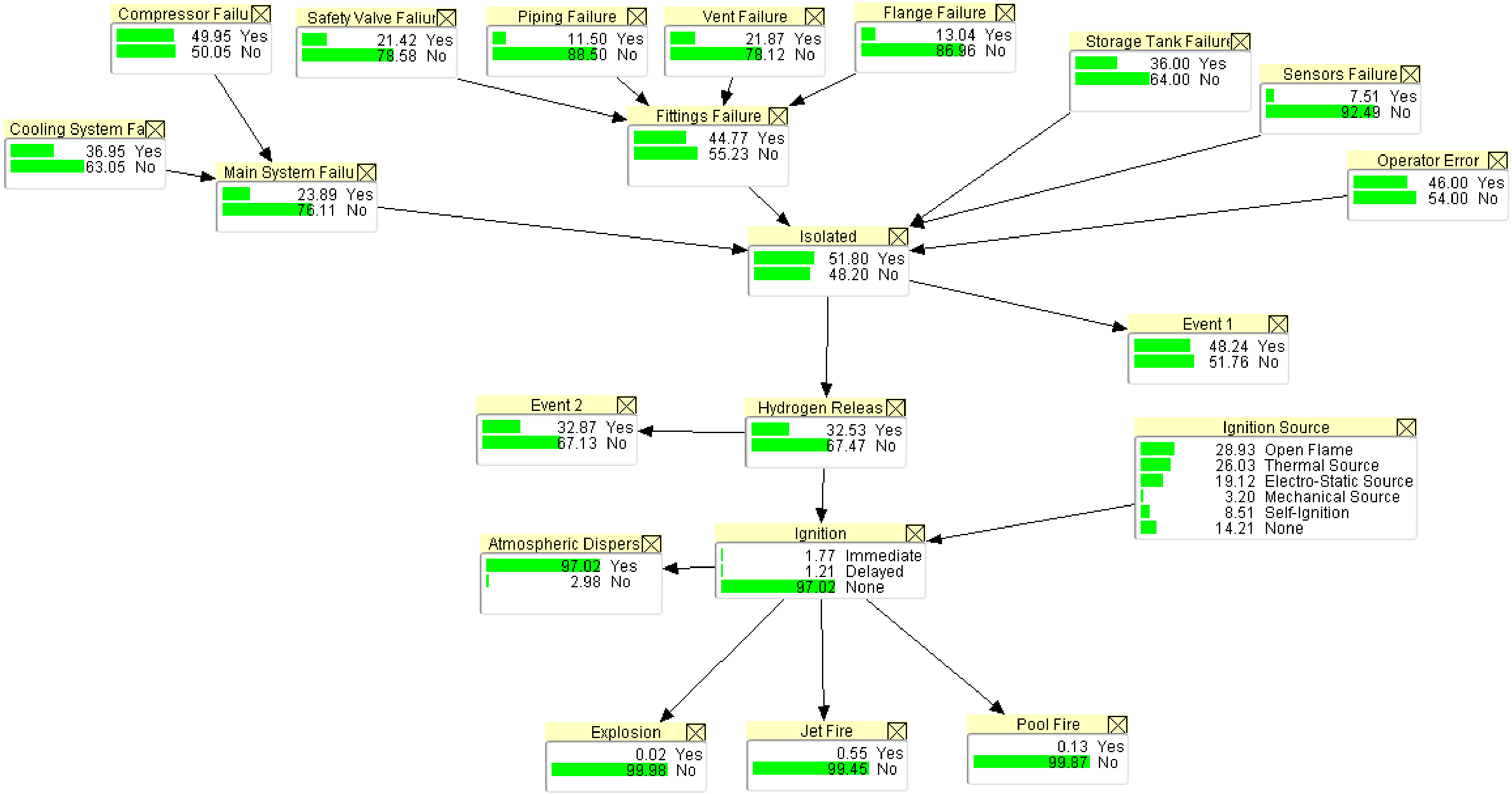
- To determine the variables that would form the Bayesian Network, a sequence of events is created that indicates the causes of the LH2 release and the potential consequences of the release with the presence of an ignition source.

- This was expanded to include the possibility of a delay in the evaporation and the ignition of the release. This would affect the consequence of the release of LH2.



O3 & O4 – Dynamic risk model and framework

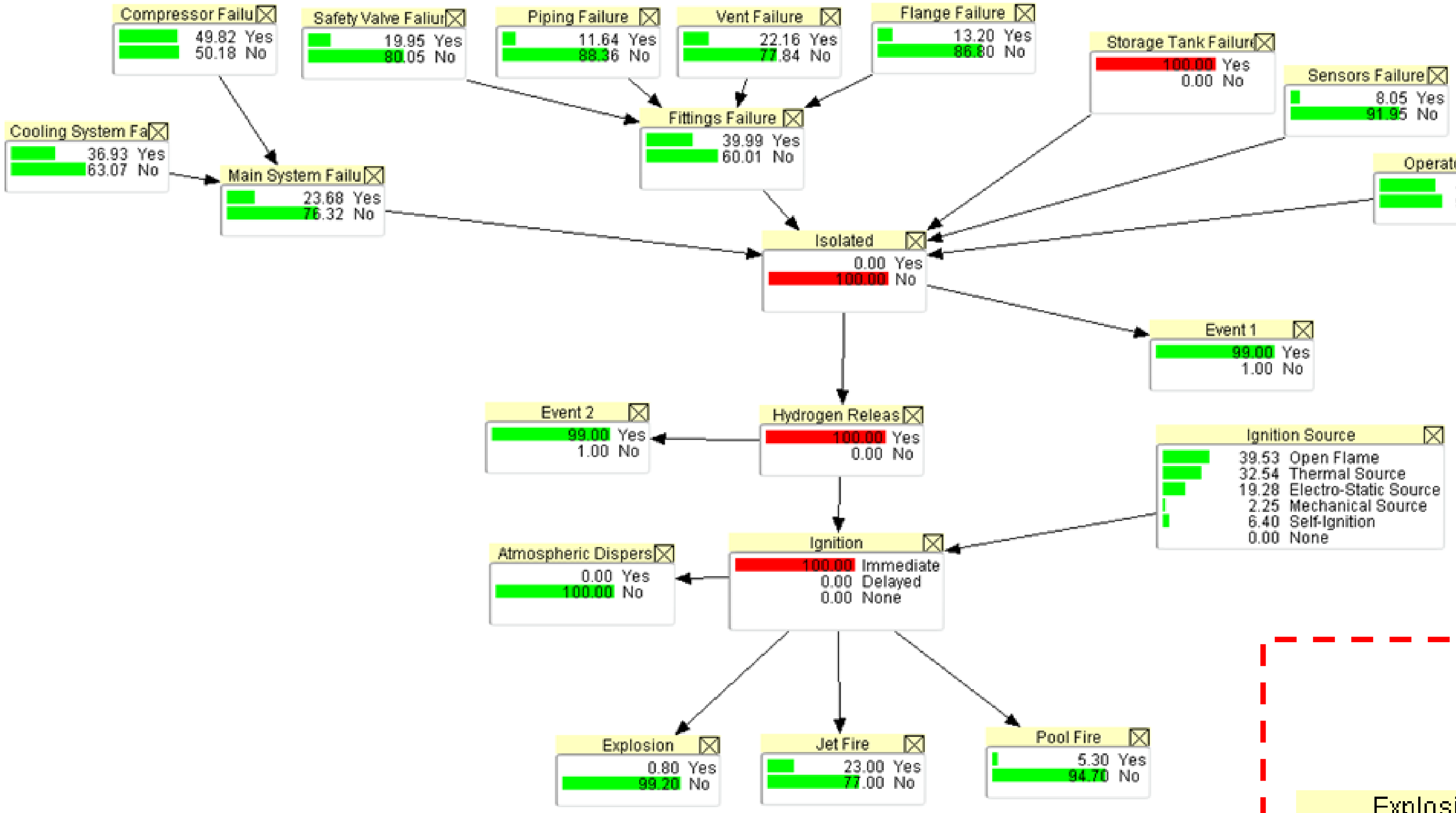
Dynamic Risk Model:



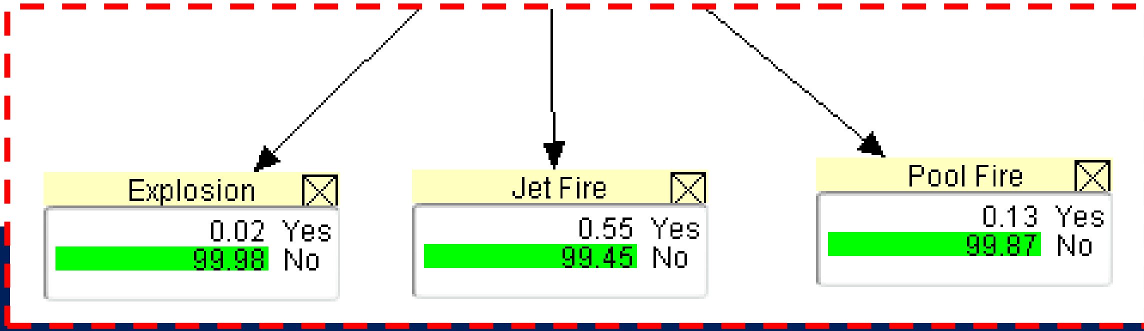
O3 & O4 – Dynamic risk model and framework

Dynamic Risk Model:

Test Case – Assessment of Storage Tank Failure, with Hydrogen release and ignition



probability of a jet fire occurring increases from 0.55% to 23%.



O3 & O4 – Dynamic risk model and framework

Asset Integrity Management (AIM) Framework:

What makes asset integrity management so important?

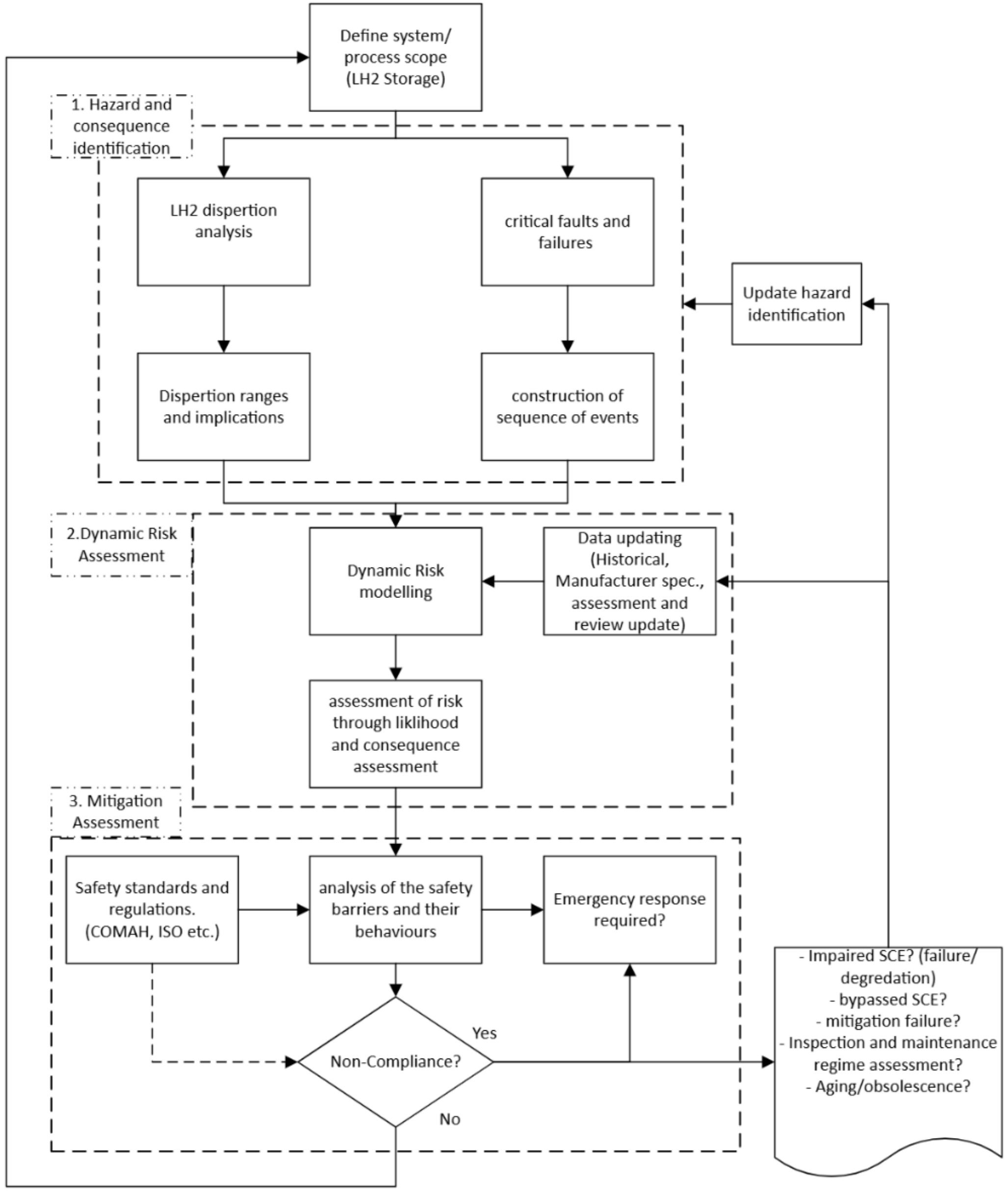
- ability to protect and extend an asset's operational life expectancy,
- increasing the return on capital investment,
- helping to reduce costs,
- increase safety
- enhance performance

should define the people, process and equipment/system integrity requirements to avoid a potential major accident hazard by evaluating following basic aspects

- Do we understand what can go wrong?
- Do we know what systems are in place to prevent this from happening?
- Do we have assurance and verification functions that these systems will work?

O3 & O4 – Dynamic risk model and framework

Asset Integrity Management (AIM) Framework:



Conclusions and further research

- Traditionally ship to shore power or cold-ironing involves a vessel being connected to a shore side power supply.
- The vessel would use this connection to power the onboard services required whilst berthed, allowing the vessel to shut down its main engines and generators reducing the noise and emissions.
- there would still be emissions associated with the generation of the shore side power supply.
- Hydrogen could be used in conjunction with local, shore side generators or fuel cells.
- Hydrogen can be stored as either a gas or a cryogenic liquid. The decision as to the storage method depends ultimately on its end use but is heavily influenced by storage location and the volume of hydrogen required.
- The results of this research demonstrate the potential applicability of LH2 inventories for ports to power vessels at berth.
- These are the initial assessments of the system and can be further refined through the development of a design for a LH2 system.
- This would enable the model to be refined with specific component specifications to further enhance the dispersion analysis and dynamic risk modelling.

Project Deliverables

Reports:

- ✓ Interim Report – October 2024
- ✓ Final Report – January 2025
- ✓ Clean Maritime Assembly – June 2025 (you have just witnessed it!)

Publications:

Conference (Presented at ESREL 2025 15^{th} – 19^{th} June 2025):

- ✓ Rasheed, R., Loughney, S. & Blanco-Davis, E. 2025. An Assessment of Alternative Fuels for Oceangoing Vessels. *Proceedings of the 35th European Safety and Reliability Conference (ESREL2025) and the 33rd Society for Risk Analysis Europe Conference (SRA-E 2025) 15 – 19 June 2025, Stavanger, Norway*

Papers - at least 2 are in progress

- Determining the most feasible alternate fuel option capable of meeting the IMO's 2050 emission targets and subsequent decarbonization towards the end of this century. *Ocean Engineering*
- Dispersion analysis of LH2 inventories and development of a dynamic risk model for integrity management of port infrastructure. *Accident Analysis and Prevention*

Thank You!

HYDRO-Port: Safety Management and Risk Assessment of Liquid Hydrogen Bunkering and Storage in Ports

Dr. Sean Loughney
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The Dolphin - A New Wave Energy Conversion Device for Sustainable Ports

Szymon Szatkowski (Project Associate)

Dr Pablo Jaen-Sola, Prof. Erkan Oterkus, Prof. John Currie (Project Supervisors)

Dolphin Energy Systems, Pentland Materials Supply Ltd. &

Edinburgh Napier University (School of Computing, Engineering and the Built Environment)

Agenda

- Project Background
- Dolphin Device Overview
- Current Findings
  - Control System
  - Turbine System
- Reference Study Location
- Prototype Testing
- Computational Fluid Dynamics
- Design Qualities
- Conclusions

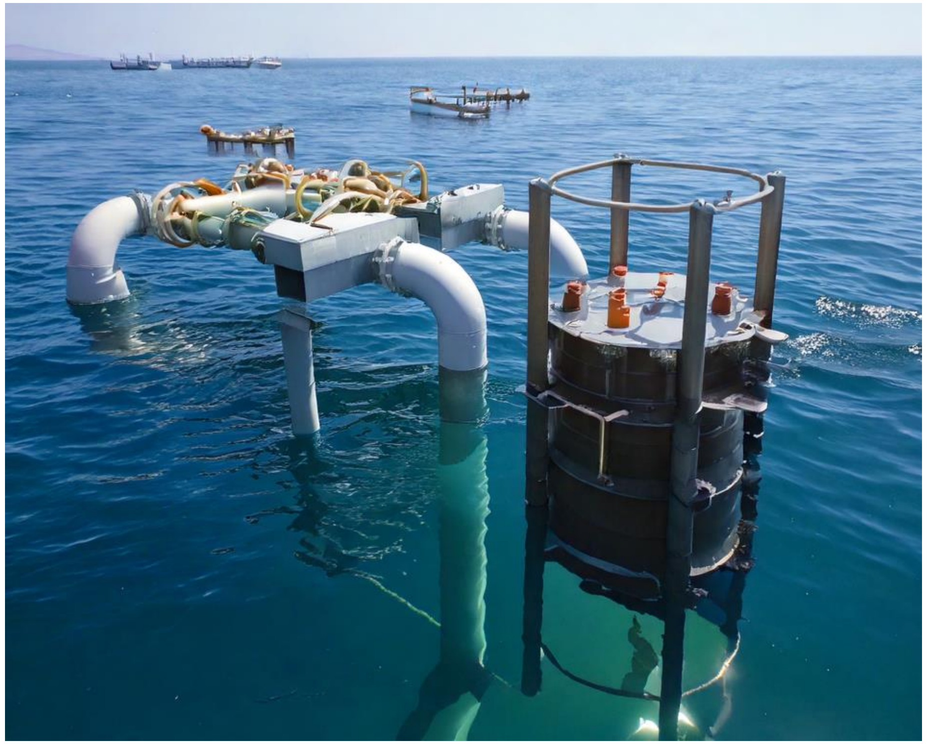

Figure 1. Rendered Dolphin Device Concept [1].

Dolphin Device Overview

- Patented design for a Wave Energy Converter [1].
- Float mounted on top of a pumping chamber.
- Fluid drawn into to the system by negative pressure, system under hydraulic lock.
- Pressurized fluid spins the turbine generating electrical Energy.
- Sets of shutter valves and check valves controlling the water flow in the system.

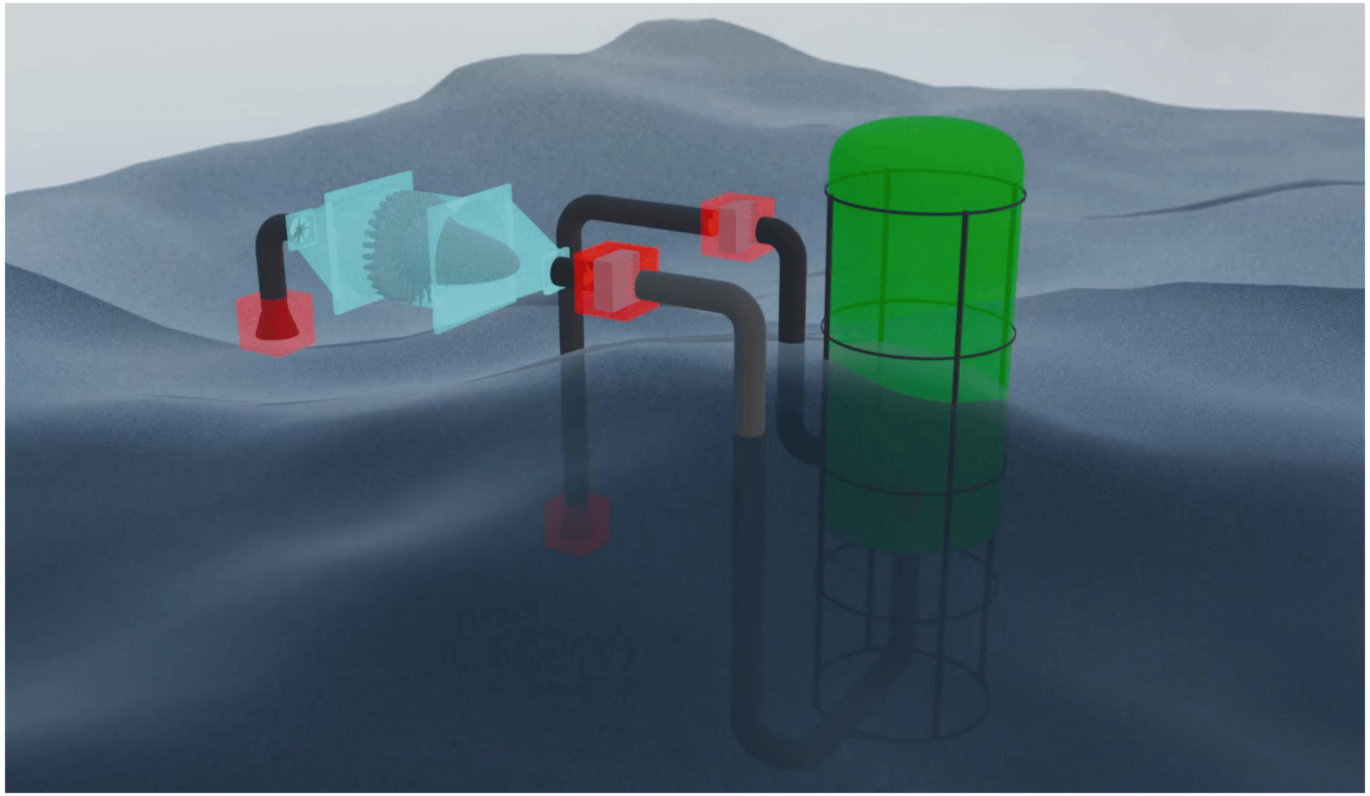

Figure 2. Dolphin Wave Energy Converter in operation [1].

Control System Development

- Arduino uno MPU6050 equipped with an accelerometer and gyroscope sensor.
- Monitoring and filtering vertical movements, detecting peaks and troughs.
- Allows for accurate opening and closing times with variable conditions.
- The control system set-up passed dry in-lab testing.
- Water experimental set-up validated the use of the control system under variable wave conditions.

Figure 3. Schematic of Shutter Valve in Closed Position.

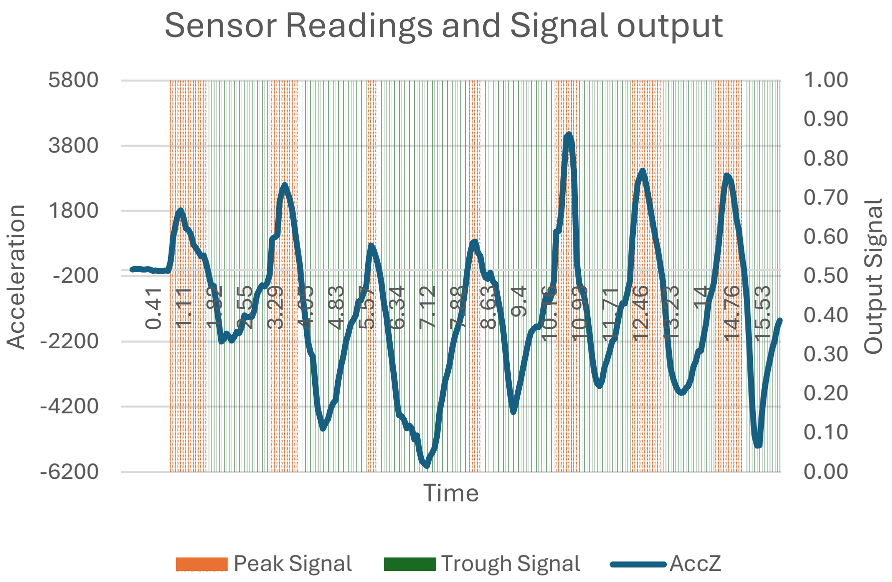

Figure 4. Sensor Readings.

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Turbine Concept Design

- The concept design of the turbine assembly implemented a horizontal flooded turbine.
- Initial testing showed pump to power efficiency of 76.47%, subject to further improvements.
- The very much needed flooded nature of the turbine limited its performance.
- Trapped water in turbine housing provided resistance.

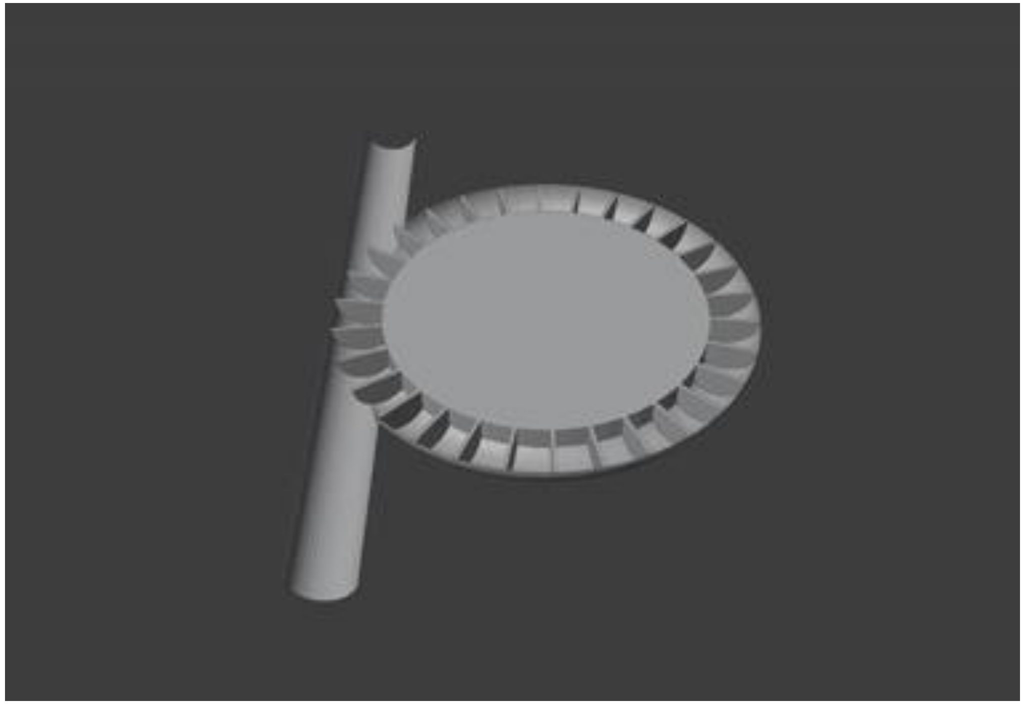

Figure 5. Section View of Horizontal Turbine, Initial Design.

Revised Turbine System

- The presented problems, contributed towards the redesign process of the turbine assembly.
- A flow-through impulse turbine design was implemented, containing a water divider, guide vanes and the turbine.
- Parameters to be defined: number of blades, shape of the blades, inlet diameter, etc.
- Improved water extraction capabilities.
- Velocity of the working fluid increased at the turbine.
- The turbine design also facilitates powertrain accommodation in parallel with the sealine which means that operations and maintenance can be done out of the water.

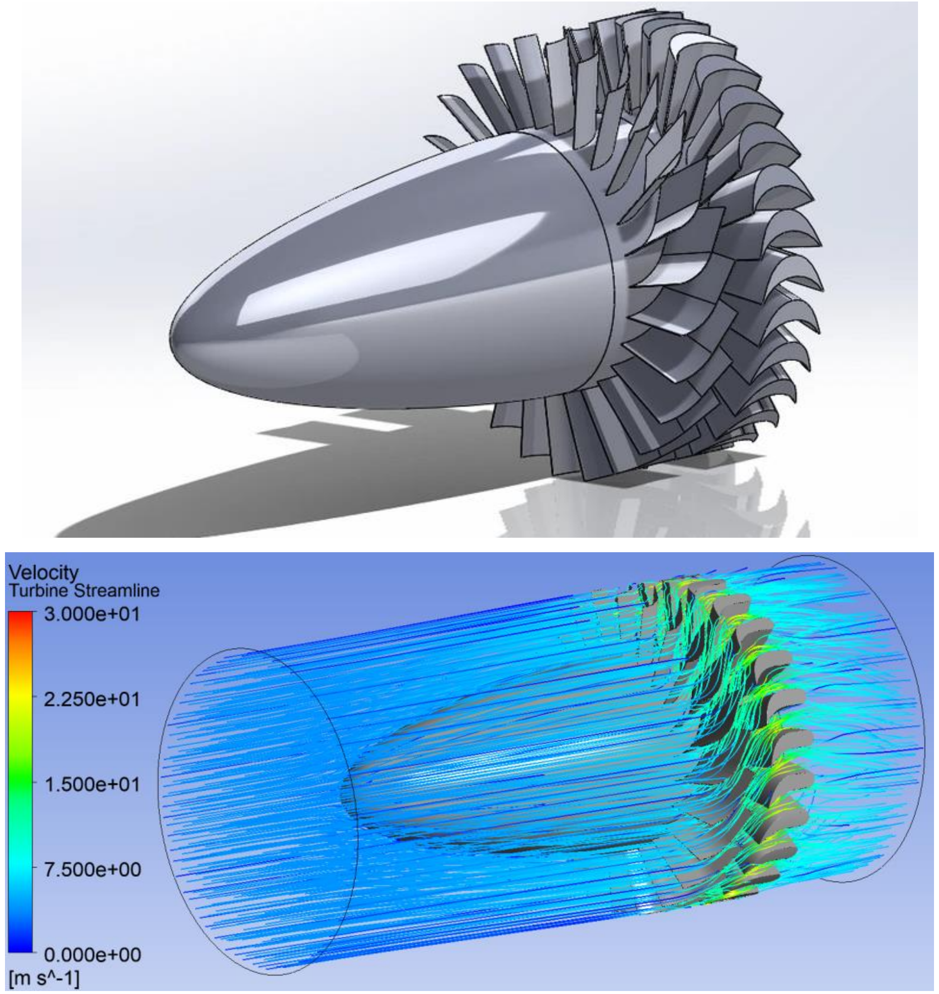

Figure 6A & 6B. New 0.6m Impulse Turbine Assembly & View of CFD Simulation Model with Streamlines.

Reference Study Location

- Montrose Port is the planned test site for the Dolphin Wave Energy Converter (DWEC).
- It offers moderate, predictable wave conditions ideal for early-stage testing.
- The port's infrastructure supports easy access, monitoring, and maintenance.
- Figures 7 and 8 validate local wave data and confirm site suitability through correlation with national climatological datasets [2].
- Testing here will guide design improvements before larger-scale deployment.

Figure 7. Overview of the Montrose Study Location; a) model mesh; b) Montrose plan view; c) River South Esk outlet [2].

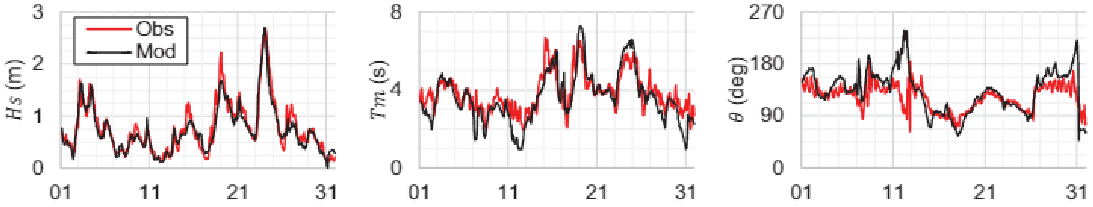

Figure 8. Wave (HS, TM and θ) model validation and prediction [2].

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Prototype Testing

- The Dolphin device concept design was scaled down in order to conduct physical testing.
- The device will be tested in terms of the control system and pumping chamber performance.
- In order to simplify the model, a damping plate was introduced in place of turbine system.
- The damping plate simulates the pressure losses across the turbine system.

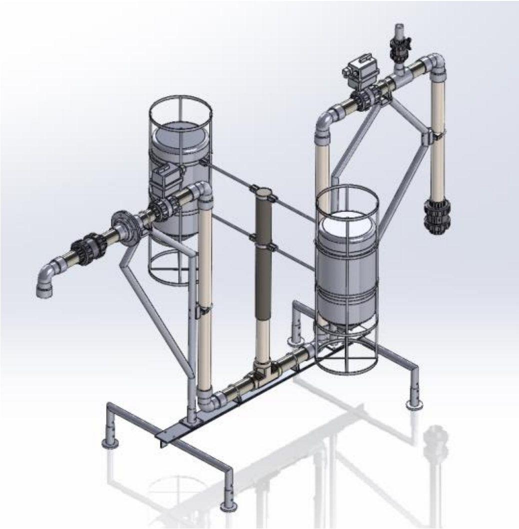

Figure 9. Dolphin Device Prototype Model.

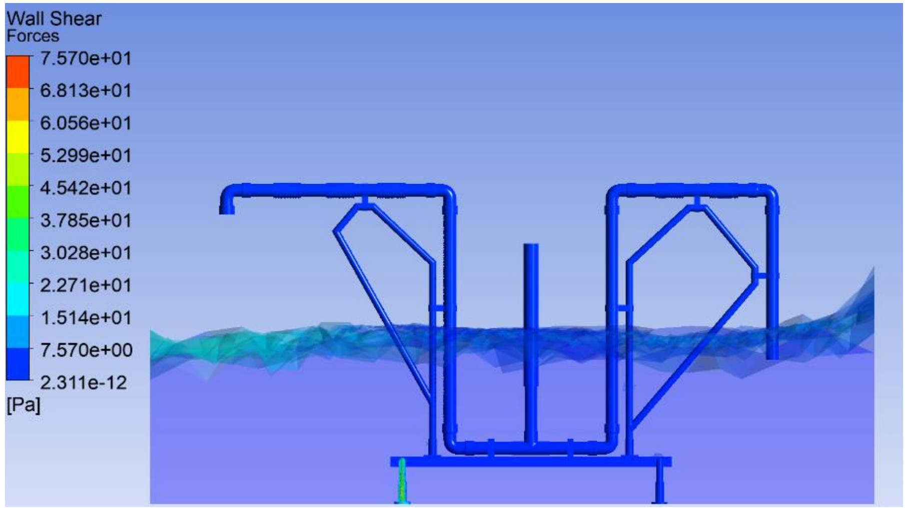

Figure 10. Wave CFD Simulation.

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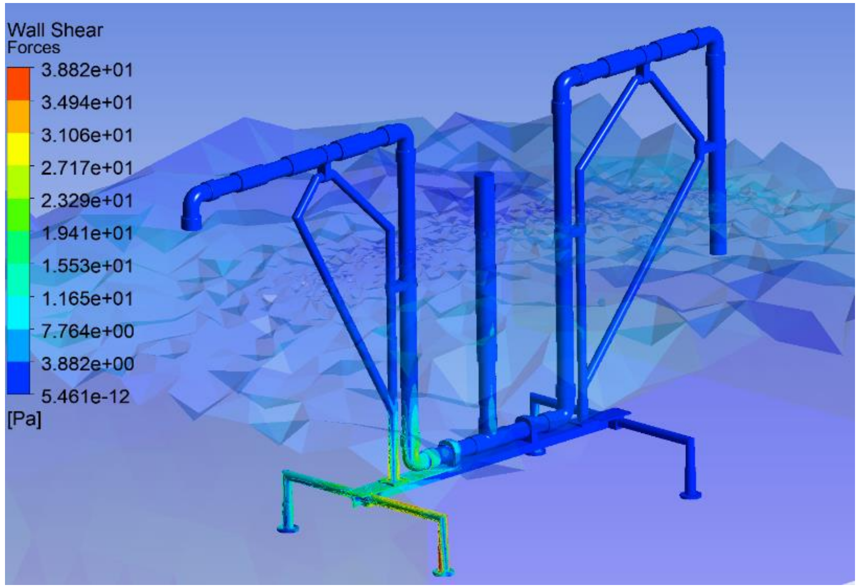
Fluid-Structure Interaction

- FSI simulation was performed using ANSYS Fluent with a multiphase wave model.
- A simplified structural model was used to reduce computation while preserving key load paths.
- Second-order Stokes wave theory simulated realistic wave behavior at Montrose Port.
- Figure 11B shows stress concentrations at support legs during peak wave impact.
- Identifying high-stress zones helps guide sensor placement and improve structural design.



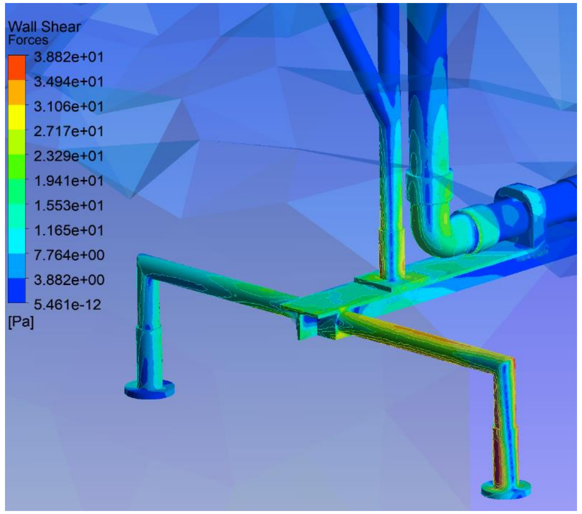


Figure 11A & 11B. A) CFD Simulation - Wave at Midspan; B) Zoomed in Leg View.

Testing Facilities

Figure 12. Kelvin Hydrodynamics Laboratory [3].

Figure 13. The FloWave Ocean Energy Research Facility [4].

Design Qualities

- Simple and robust design.
- Easily customizable device, fit to work in any suitable location.
- Novel design of shutter valves that promote long operation periods without maintenance.
- Adaptation of proven solutions for power gathering equipment.

“**they** (wave energy devices) **need to be cheaper, produce more Energy and brave the ocean’s brawn better and for longer**”. Wave Energy devices are outfitted with heavy and expensive hulls that make the technology too expensive to make it viable. “**About 35% - 50% of wave energy costs are spent on structural enhancements**” – Prof. Krish Sharman [5].

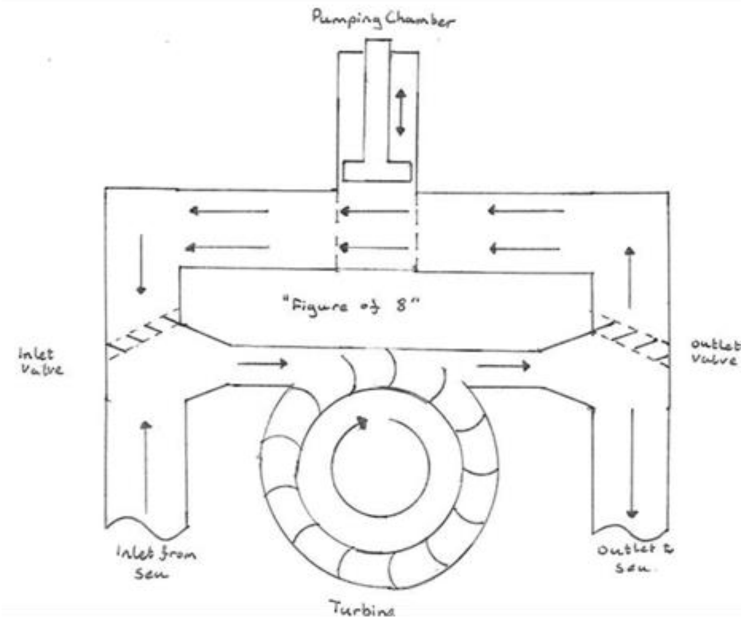
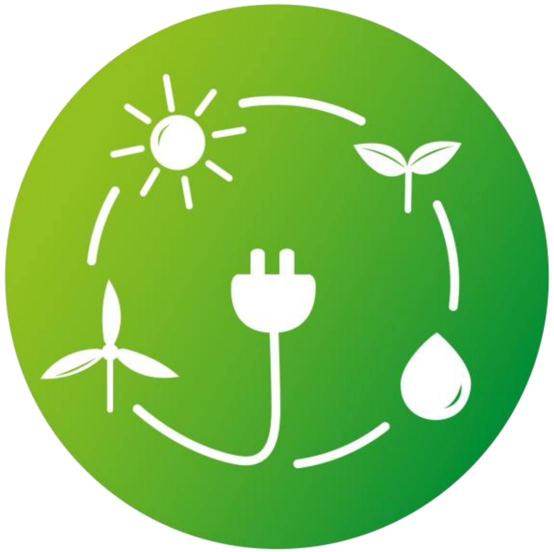


Figure 14. Schematic of the Dolphin Wave Energy Converter power extraction system.

Conclusions

- The DWEC prototype shows promise as a modular, near-shore wave energy solution.
- FSI simulations confirmed structural resilience under typical wave loading at the chosen reference study location.
- Key stress zones were identified to guide sensor placement and design refinement.
- The Arduino-based control system reliably detected wave motion and actuated valves.
- Montrose Port was validated as an ideal site for field testing and future deployment.
- Future work is going to be based on in-lab prototype testing and development, as well as full-scale field testing.



Thank You!

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2. Pratame, M.; Venugopal, V.; Poleykett, J. Wave and Tidal Hydrodynamics Characterization of Montrose Bay: A severely-Eroding Coast in East Scotland. 2013. pp. 546-553

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Sustainable WAterborne Transportation (SWAT):

Enhancing Sustainable Freight Transport Through Swarming of Zero-emission Fleet for UK Waterways

Funded by:

UK National Clean Maritime Research Hub

Prof. Evangelos Boulougouris

Dr Amin Nazemian

DEPARTMENT of NAVAL ARCHITECTURE, OCEAN & MARINE ENGINEERING

UNIVERSITY of STRATHCLYDE MARITIME SAFETY RESEARCH CENTRE

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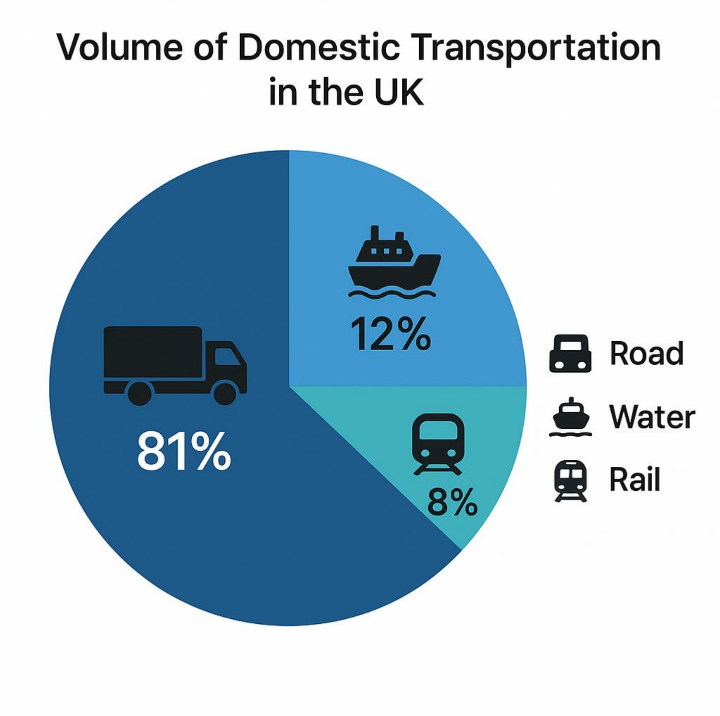
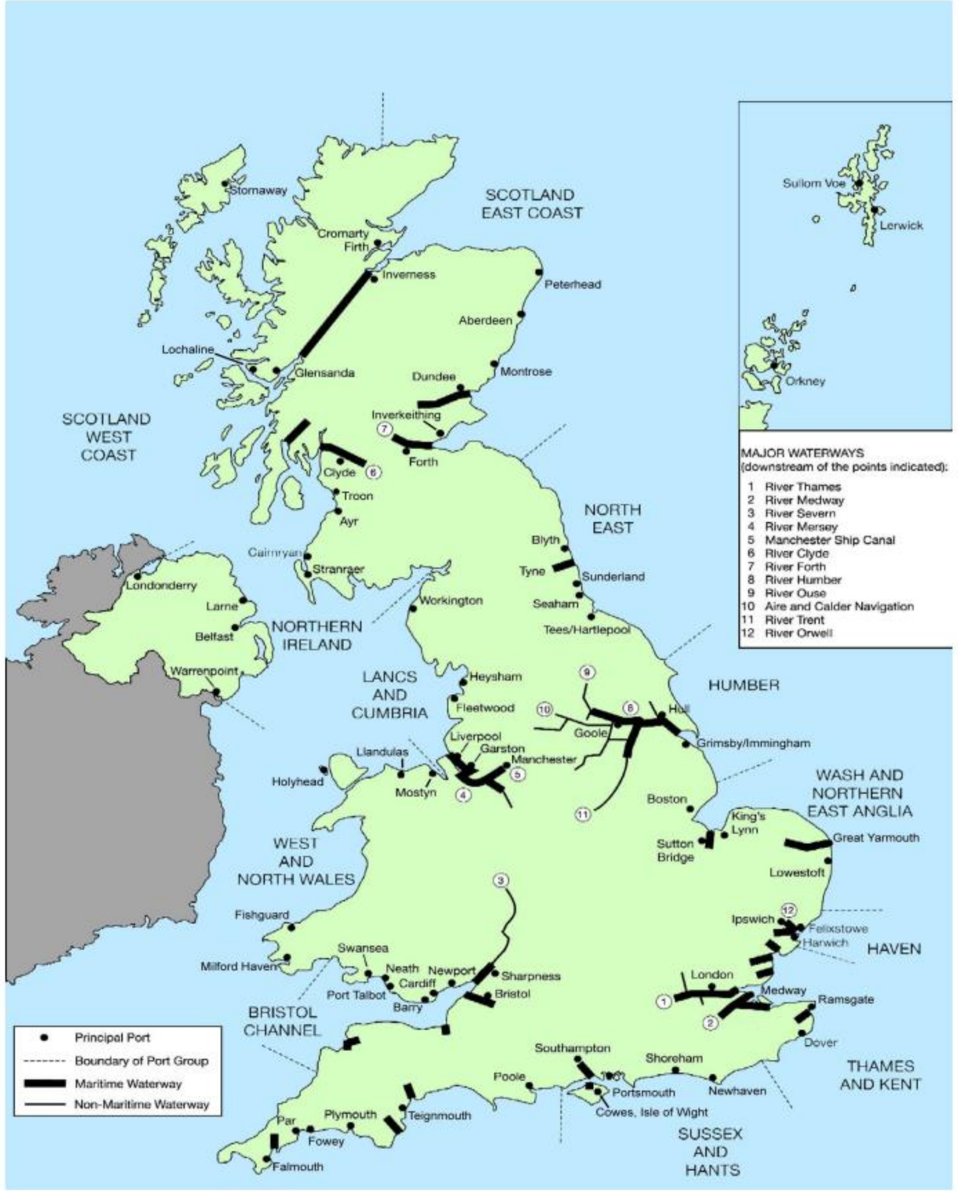
Current Statement

Ref: Dft Maritime Statistics; port-freight-statistics-2023



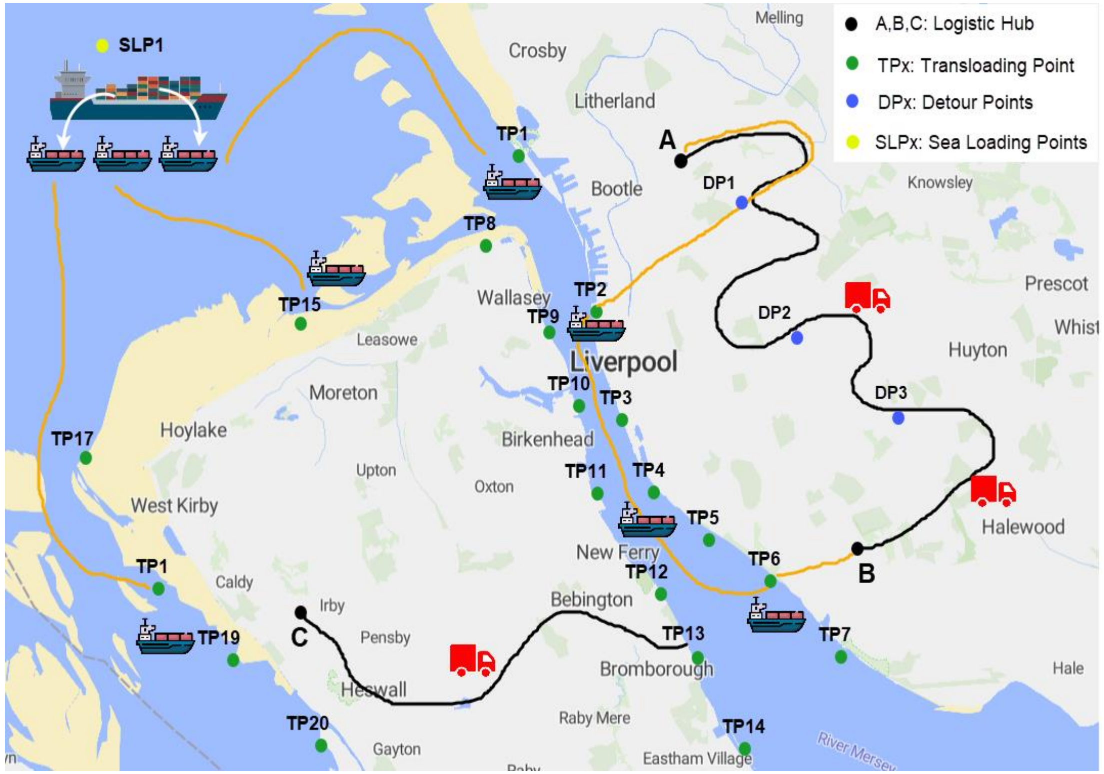
UK Waterways

- **Extensive Inland Waterway Network:** The UK has over 5,000 miles of rivers and canals, representing a significant asset for transportation.
- **Untapped Freight Capacity:** Enhancing waterway infrastructure and integrating multi-modal logistics could increase inland freight capacity, offering a viable alternative to road freight.
- **Cost-Effectiveness:** Utilizing waterways for freight transport can be a more economical option compared to road freight, especially for unitized or bulk goods.
- **Environmental Sustainability:** Shifting freight from road to waterways reduces carbon emissions, supporting environmental sustainability goals. Reduce road congestion.
- **Economic Impact:** Inland waterways contribute to local economies through transportation, tourism, and related industries



Ref: DfT, Domestic Waterborne Freight Technical Notes

Vision



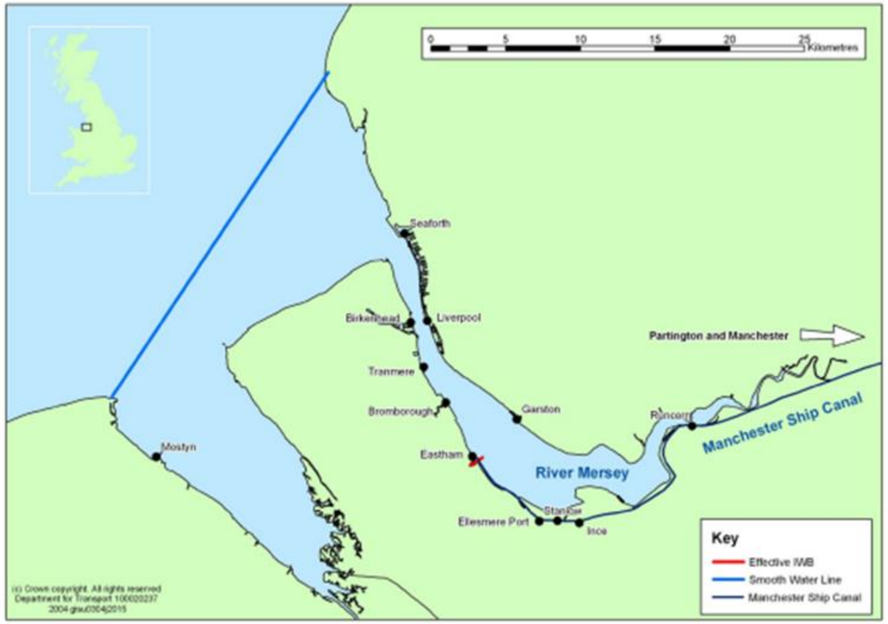
Liverpool-Manchester Ship Canal as a Case study

1- Development of zero-emission, small, vessels with flexibility of landing and cargo handling in different coastal/shore areas and poorly accessible regions to support the shift of freight transport from road to sustainable waterways transport.

2- Feasibility study of modal shift form road to water transport.

3- UK-wide and local area logistic plan and freight highway.

4- Provide the stakeholder with a comprehensive insight to support UK and international stakeholders take their next steps to coastal and inland waterways transport.



Benefits and Impacts

1- Waterborne transport can transfer large freight volumes from roads and as a result reduce emissions and decongest road infrastructure.

2- Energy-efficient, zero-emission and automation technology can help fully exploit the potential of small-sized waterborne transport.

3- Lower costs of small waterborne transport revolutionise transportation system compared to road transport.

4- Flexible, fully automated transport chain is expected to facilitate waterborne services to new and previously poorly accessible regions.

5- Swarming barges operating not just individually, but in a coordinated fleet.
6- Less noise, Hybrid electrified ship, access to shallower waters or smaller ports that bigger ships can not, which could reduce the need for constant expensive dredging.

Autonomous battery electric-driven barge (Designed by Kongsberg Maritime)

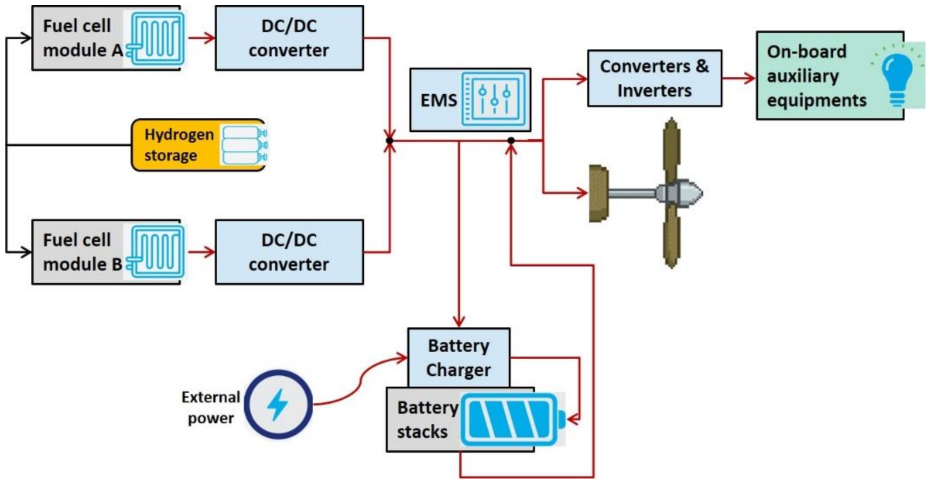
Work progress I

Ambition	Measures
(1) **“Waterborne transport can transfer large freight volumes from road and as a result reduce emissions and decongest road infrastructure.”**	**Python GIS code:** To address this ambition, a Python code integrated with GIS mapping capabilities will be developed to simulate the logistics dynamics of the Liverpool-Manchester area. The simulation will focus on the movement of goods between key logistics points, such as port terminals and warehouses. By incorporating real-world geographical data, the GIS map will visualize the flow of goods, optimize routing, and offer insights into spatial relationships that affect logistics efficiency. The Python code will compare two primary modes of transportation—maritime and road—evaluating factors such as travel time, distance, cost, and environmental impact.
(2) **“Emerging energy efficient, zero-emission and automation technology can help fully exploit the potential of small-sized waterborne transport. ”**	**Barge Train Concept Design:** By assuring the flexibility of the applied design of the zero-emissions power train concept, through the application and validation of a power-plant and electrical propulsion system engineering tool, the zero-emissions concept is explored across the whole range of competitive designs of small-size cargo vessels. These vessels are able to approach some areas which were inaccessible in the past for larger vessels, with the potential of revolutionizing small-sized waterborne transport. The implemented energy-efficient technologies drive the reduction of energy consumption and operating costs, while at the same time reducing or eliminating greenhouse gas emissions and other pollutants.

Barge Train Concept Design I

1) Propelled battery-powered barge

2) Propelled Hybrid FC/Battery-powered barge



Hybrid FC/Battery-powered CTV (HySHIP project Nazemian et al.)

Autonomous battery electric-driven barge (Designed by Kongsberg Maritime)

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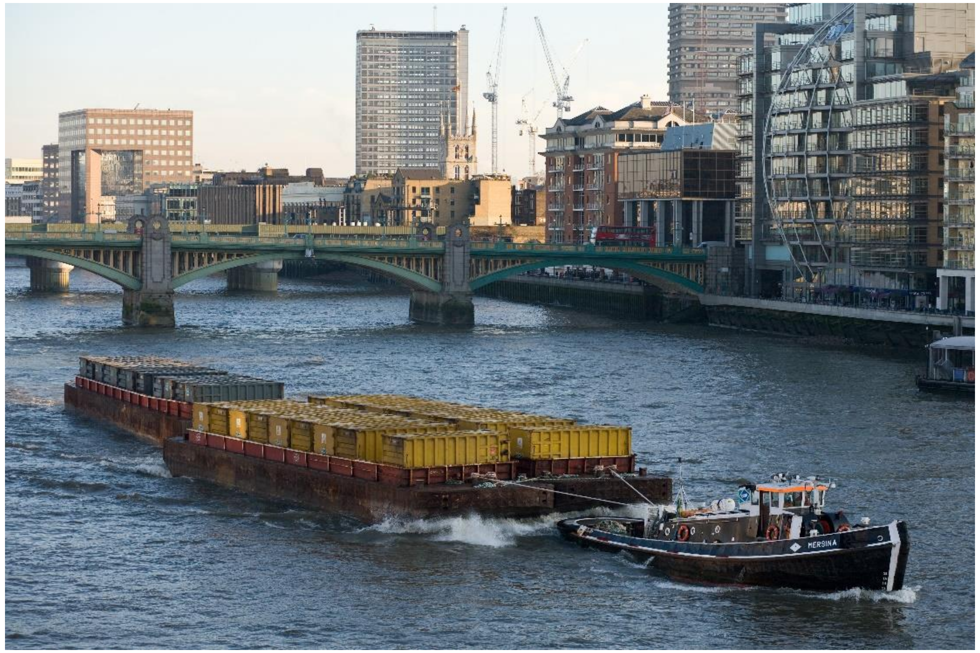
Barge Train Concept Design II

3) Articulation barge train with pusher/tower tug

Articulation barge with pusher tug (Robert Allan Ltd.)



4) Multiple barge towing with tower tug

Work progress II

Ambition	Measures
(3) **"A comprehensive solution for whole UK logistics based on cargo type and demand"**	**ARENA logistics Simulation:** To achieve an appropriate barge design, it is necessary to develop a Discrete Event Simulation (DES) that models key logistical operations across the UK. This simulation will capture the dynamic processes involved in the transportation of goods, focusing on specific logistics scenarios that reflect typical supply chain challenges within the UK. By simulating real-life logistics activities such as loading, unloading, transit times, and handling operations at ports and warehouses, the DES will help identify inefficiencies, bottlenecks, and areas for improvement. The barge design will then be optimized based on the data generated from this simulation, ensuring that it meets UK-wide logistical requirements. These requirements may include factors such as load capacity, fuel efficiency, speed, and maneuverability in different waterways. Additionally, the barge design will be tailored to fit UK-specific regulations, infrastructure constraints, and environmental considerations. The combination of simulation data and optimization techniques will guide the development of a barge that is not only efficient for current logistics demands but also flexible enough to adapt to future changes in the UK's transportation network.

Discrete Events Simulation (ARENA)

- Multi-objective simulation using Python & ARENA
- Scenarios modelled: at-sea transloading, port distribution
- Optimization of barge capacity (best at 110 TEUs)
- Metrics: Cost, Time, Emissions

Scenario 1: Port Glasgow to Port Liverpool

Scenario 2: At Sea Transloading and distribute to local port

Scenario 3: Deliver TEUs to Liverpool port and Liverpool port transfer by Barge

Scenario 4: Deliver TEUs to Liverpool port and Liverpool port to Terminals and Terminals to Truck

Discrete Events Simulation (ARENA)

Scenario 1: Port Glasgow to Port Liverpool

Scenario 2: At Sea Transloading and distribute to local port

Scenario 3: Deliver TEUs to Liverpool port and Liverpool port transfer by Barge

Scenario 4: Deliver TEUs to Liverpool port and Liverpool port to Terminals and Terminals to Truck

	Value	Type
Capital Cost of each Barge (£)	17,600,000	Fixed
Capital Cost of each Truck (£)	185,000	Fixed
Hourly Operational Cost of Trailer Truck (£)	35.24	Fixed
Daily non-Operational Cost of Trailer Truck (£)	39.09	Fixed
Hourly Operational Cost of River Barge (£)	176.22	Fixed
Daily non-Operational Cost of River Barge (£)	195.49	Fixed
Handling Cost at port per TEU (£)	37	Fixed
Storage Cost per TEU per Day (£)	3	Fixed
	Capacity	
Maximum number of containers for each barge (TEU)	120	Variable [Integer]
Crane Throughput rate at a port (TEU/hr)	30	Fixed [Integer]
Crane Throughput rate at sea transloading (Ship to Barge) (TEU/hr)	30	Fixed [Integer]
Sorting and transfering Time per TEU at port (hr)	0.45	Fixed
Average Traveling speed of Barge (knot)	15	Fixed
Average Traveling speed of Trucks (mph)	54	Fixed
Liverpool Port Daily Container Demand (TEU)	3000	Fixed [Integer]
Liverpool Port annual trade (TEU/Year)	250,000	Fixed [Integer]
Maritime Transport Emission (Emission Factor)	0.040	kg CO2e/TEU-km
Road Transport Emission (Emission Factor)	0.140	kg CO2e/TEU-km
Number of Operational days per year	365	Fixed

$$\textbf{Objective Function} = \frac{1}{3}(\textbf{Time} + \textbf{Cost} + \textbf{Emission})$$

$$\text{Total Cost} = \sum \left(C_{trans(i)} + C_{handling(i)} + C_{storage(i)}\right)$$

$$C_{trans(i)} = D_i \times c_{per\,TEU-km} \times d_i$$

$$\text{Total Time to Arrival} = T_{transport} + T_{Transshipment} + T_{port\ handling}$$

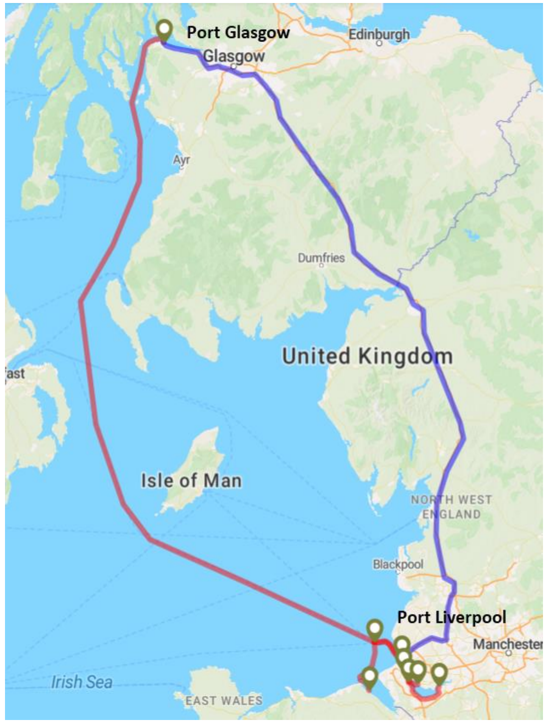
$$T_{port\ handling} = \sum \left(t_{sorting(j)} + t_{transfer(j)}\right)$$

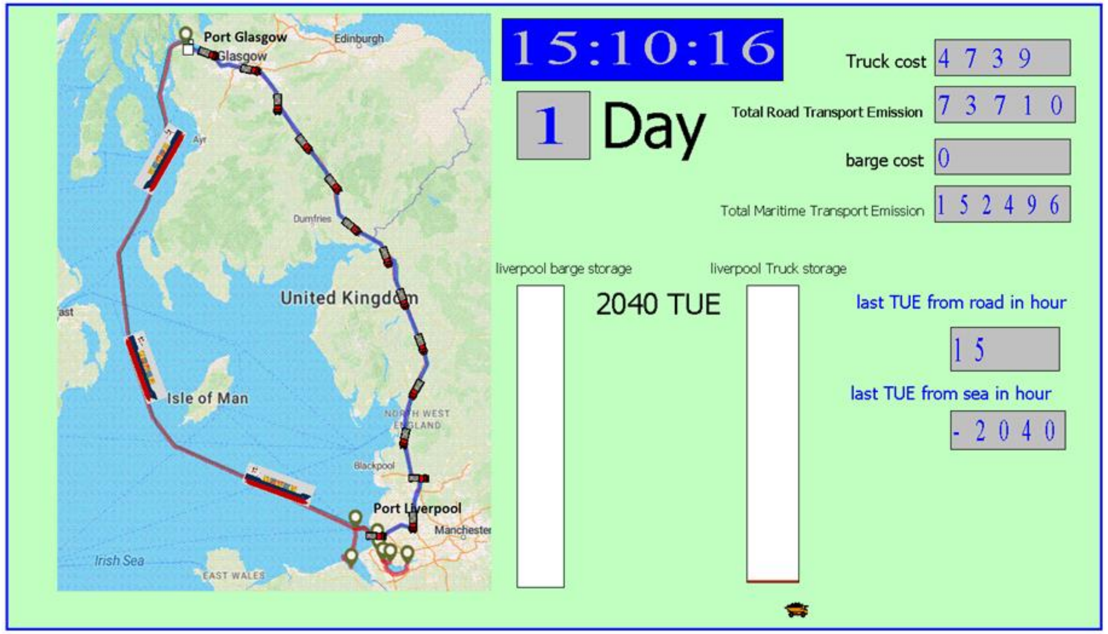
$$\text{Total } CO_2e \text{ emissions } (kgCO_2e) = \sum (\text{ mass of goods (ton)} \times \text{ distance travelled (km)} \times \text{ emission factor of transport mode } (kgCO_2e/\text{ton} - \text{km}))$$

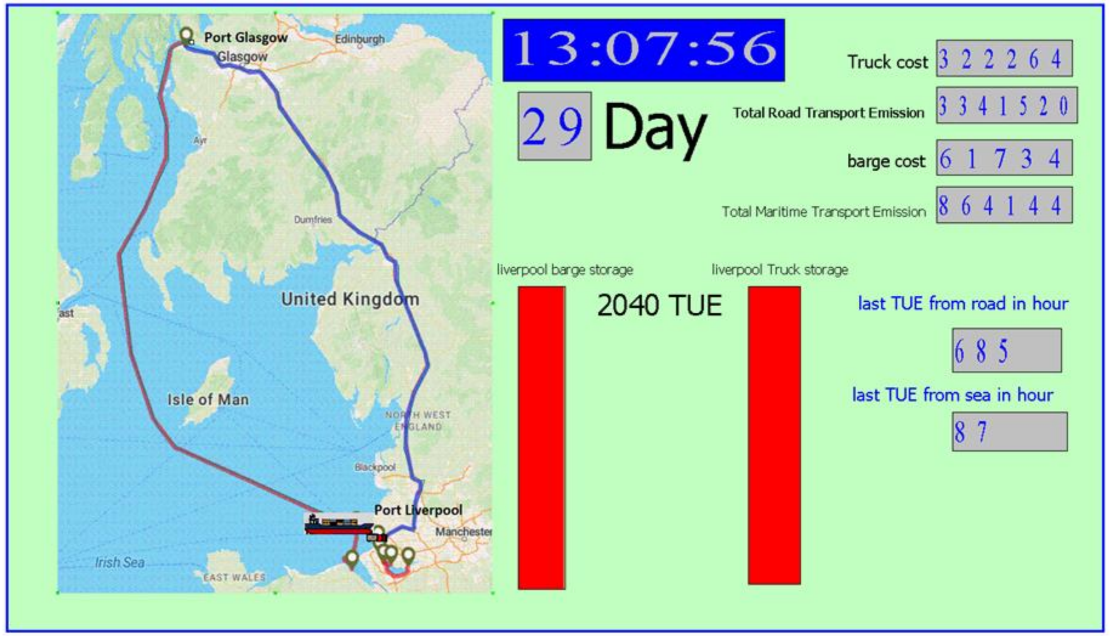
Scenario 1: Port Glasgow to Port Liverpool

Aim:

From Port Glasgow to Port Liverpool by barge ship and compare it with road transportation by truck



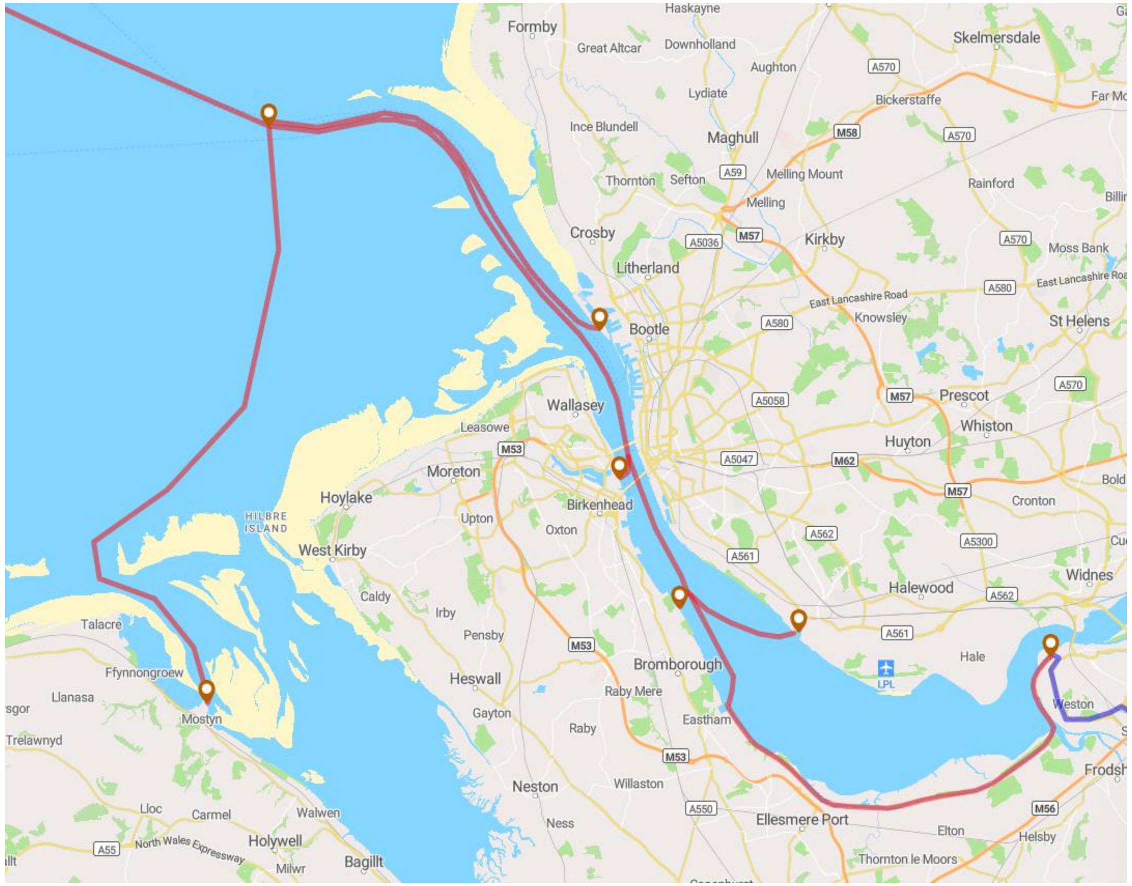




Conclusion:

Reduced emissions by 25% and halved costs despite longer transit times.

Scenario 2: At Sea Transloading and distribute to local port



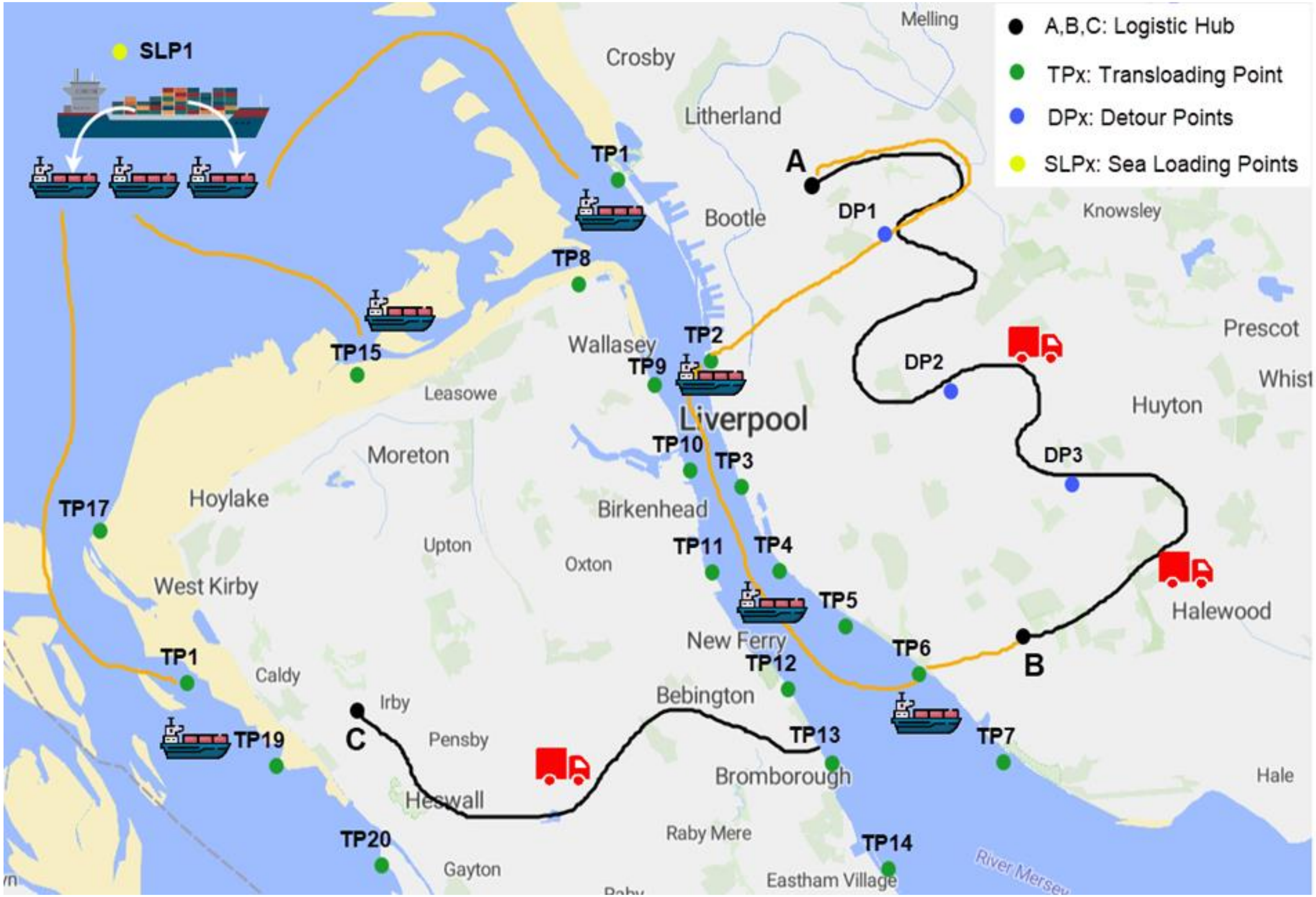
Aim:

TEU containers transfer from Big ship to smaller barges at sea and barges swarm to local ports

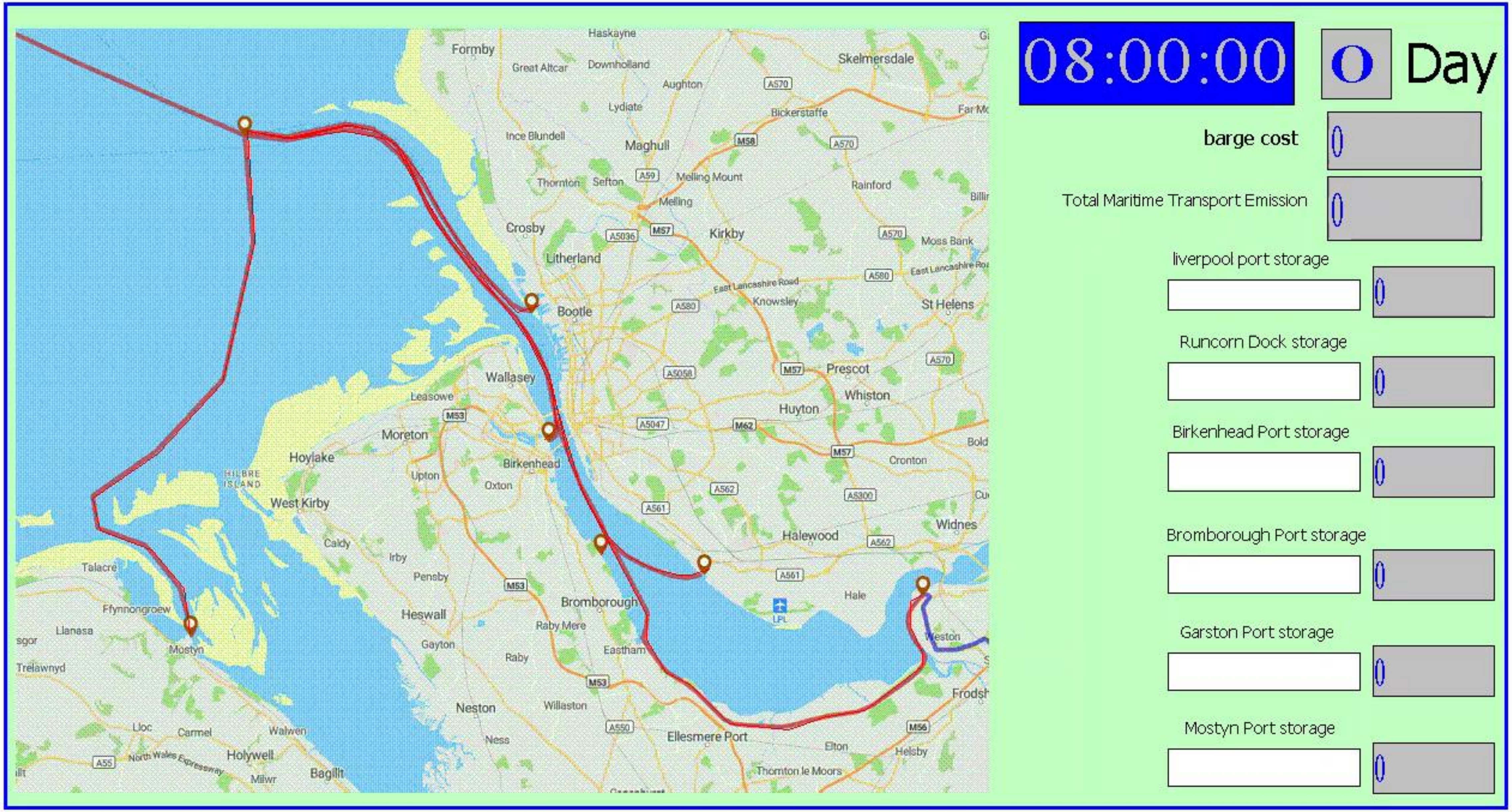
Location	Latitude	Longitude	Num
Port Glasgow	55.95632	-4.76343	1
Port Liverpool	53.45549	-3.02187	2
Runcorn Dock	53.33914	-2.74942	3
Birkenhead Port	53.40023	-3.02435	4
Bromborough Port	53.35661	-2.97757	5
Garston Port	53.35057	-2.90869	6
Mostyn Port	53.3232	-3.26402	7
Big Container Ship	53.45849	-3.05141	8

Conclusion:

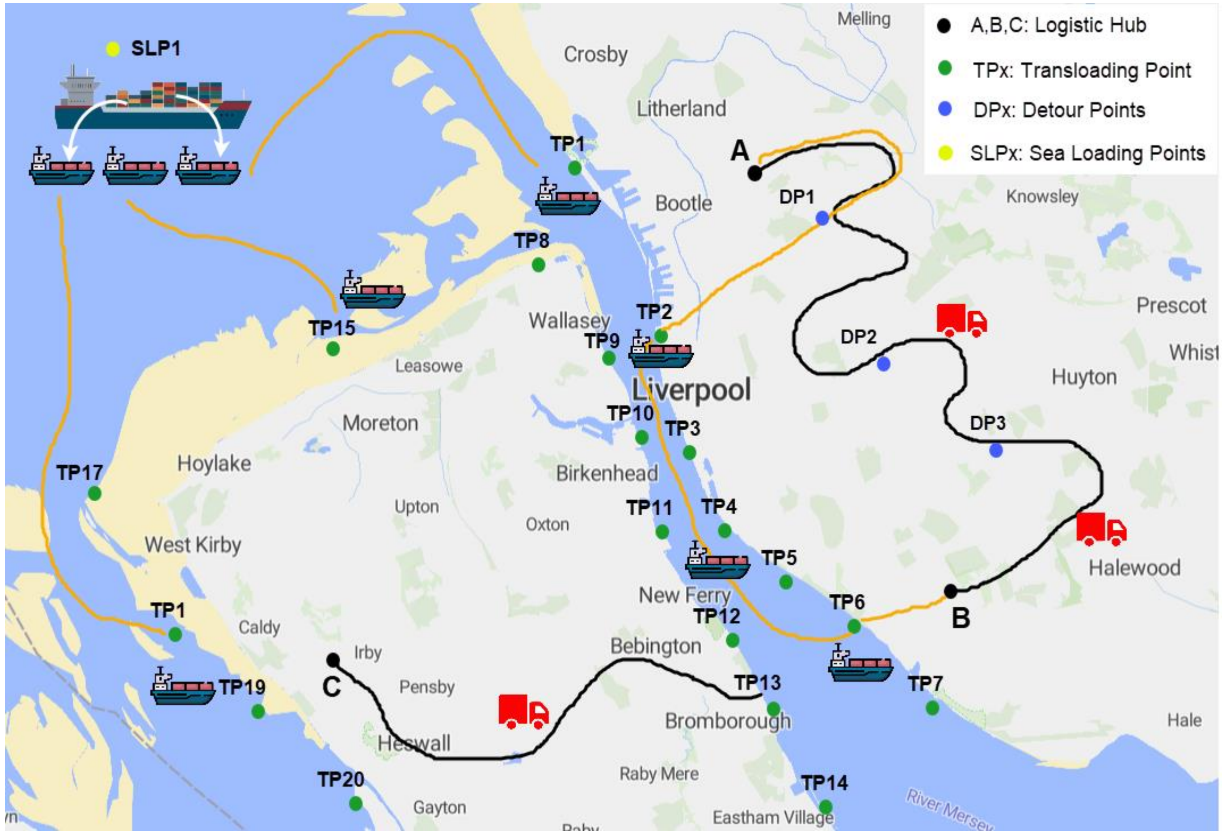
achieved significant emissions reductions (38,195 kg CO2e) through at-sea transloading and a consistent, flexible cargo distribution, but required specialised coordination.


A,B,C: Logistic Hub
TPx: Transloading Point
DPx: Detour Points
SLPx: Sea Loading Points
SLP1
TP1
TP2
TP3
TP4
TP5
TP6
TP7
TP8
TP9
TP10
TP11
TP12
TP13
TP14
TP15
TP17
TP19
TP20
DP1
DP2
DP3
A
B
C
Melling
Crosby
Litherland
Bootle
Knowsley
Prescot
Whist
Huyton
Halewood
Hale
Wallasey
Leasowe
Liverpool
Moreton
Hoylake
Birkenhead
Upton
Oxton
West Kirby
New Ferry
Caldy
Irby
Pensby
Heswall
Bebington
Bromborough
Raby Mere
Gayton
Eastham Village
River Mersey

Scenario 2 Animation



Scenario 3: Deliver TEUs to Liverpool port and Liverpool port transfer by Barge



Aim:

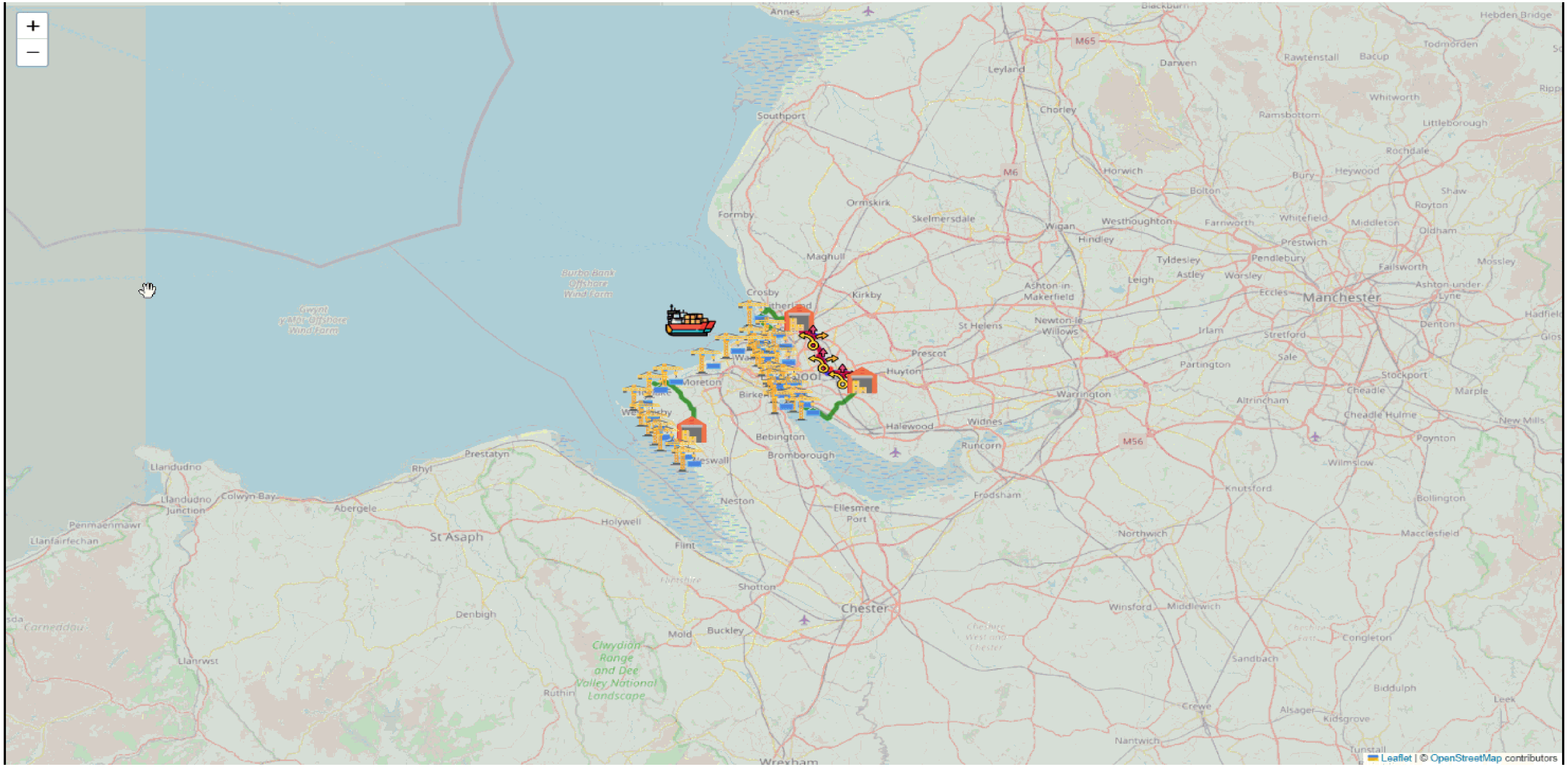
TEU containers transfer from Big ship to Liverpool Port and these TEUs transfer from port to smaller barges and barges swarm to local ports

Location	Latitude	Longitude	Num
Port Glasgow	55.95632	-4.76343	1
Port Liverpool	53.45549	-3.02187	2
Runcorn Dock	53.33914	-2.74942	3
Birkenhead Port	53.40023	-3.02435	4
Bromborough Port	53.35661	-2.97757	5
Garston Port	53.35057	-2.90869	6
Mostyn Port	53.3232	-3.26402	7
Big Container Ship	53.45849	-3.05141	8

Conclusion:

Cost savings (£1,275.18 per barge) but increased emissions and delivery time due to port handling.

In-house code development of maritime logistics



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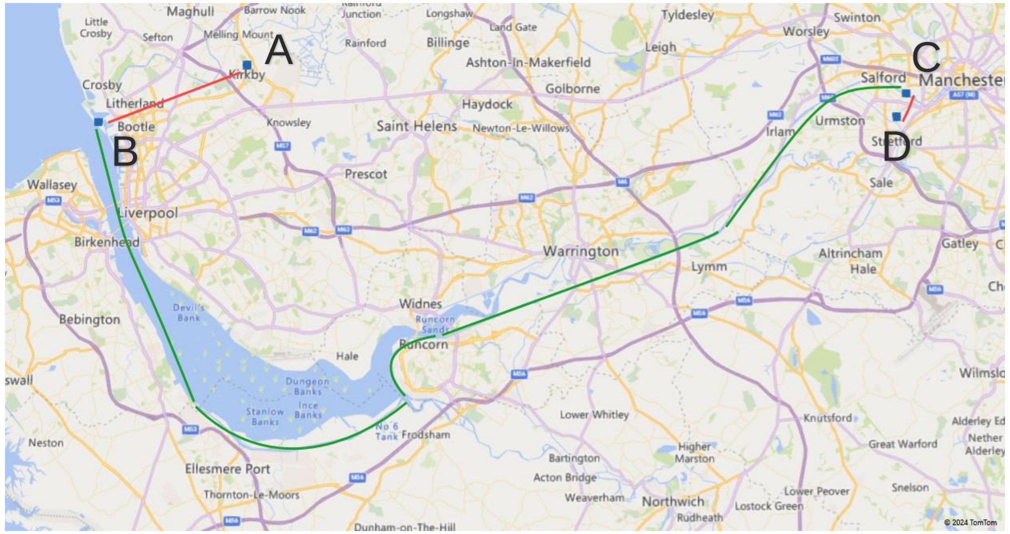
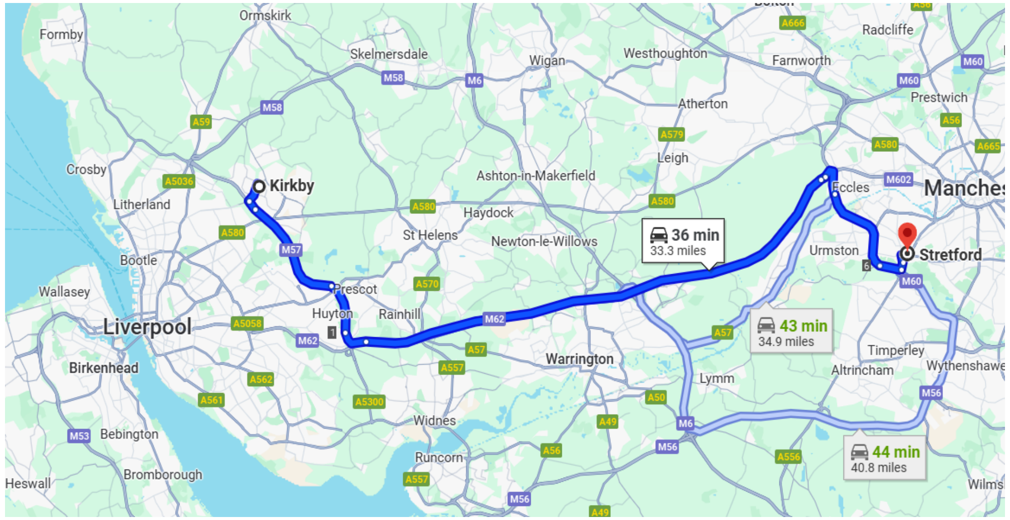
Scenario 4: Deliver TEUs to Liverpool port and Liverpool port to Terminals and Terminals to Truck





Aim:

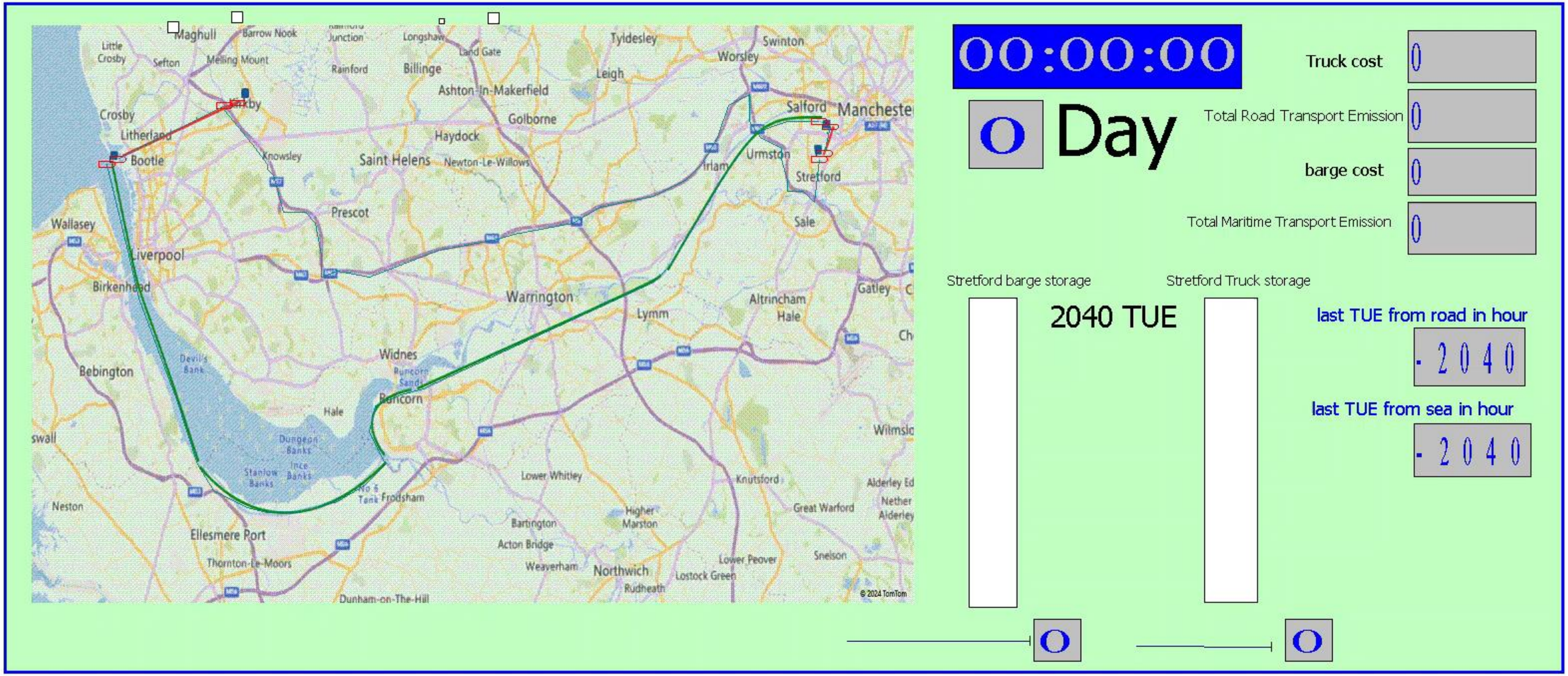
TEU containers transfer from Big ship to Liverpool Port and these TEUs transfer from port terminals and terminals to Truck

Location	Latitude	Longitude	Num
Liverpool City	53.4857771	-2.88998	A
Liverpool port	53.4554931	-3.02187	B
Salford Quay	53.470524	-2.30179	C
Manchester City	53.4454523	-2.31079	D

Conclusion:

reduced emissions by 75% along the Manchester Ship Canal, balancing cost and environmental goals.

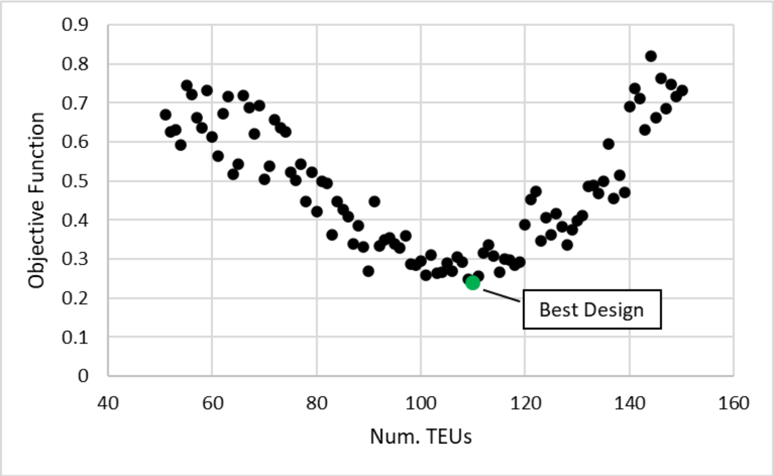
Scenario 4 Animation



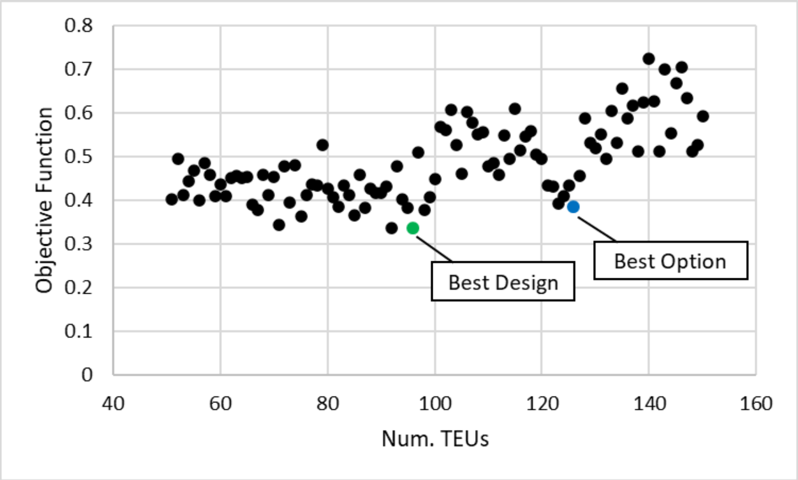
Work progress III

Ambition	Measures
(4) **“Lower costs/emission/time are needed for waterborne transport to become more competitive with road transport. ”**	**Optimization Algorithm:** Consequently, the SWAT project will contribute to making small waterborne transport a more attractive option compared to road transport and therefore contribute to greater utilization of this sustainable and efficient mode of transport (modal shift). Finally, an optimization algorithm will be integrated into the logistics simulation to determine the optimal barge capacity for efficient transport operations. This algorithm will systematically analyze various factors that influence barge performance, including cargo load, fuel consumption, travel time, and operational costs. By simulating different scenarios with varying barge capacities, the algorithm will assess how each capacity impacts the overall efficiency and cost-effectiveness of the logistics system.
(5) **“Uncover stakeholder insights to guide future initiatives that address barriers and promote a shift from road to waterway transportation for more sustainable logistics.”**	**Survey Conduction by Qualtrics:** This study contributes to a better understanding of the perspectives of the maritime/transport/logistic stakeholders, whereas the results can support the prioritization of future initiatives towards addressing existing barriers and overcoming misconceptions for coastal/waterway transportation and shifting from road to water transportation

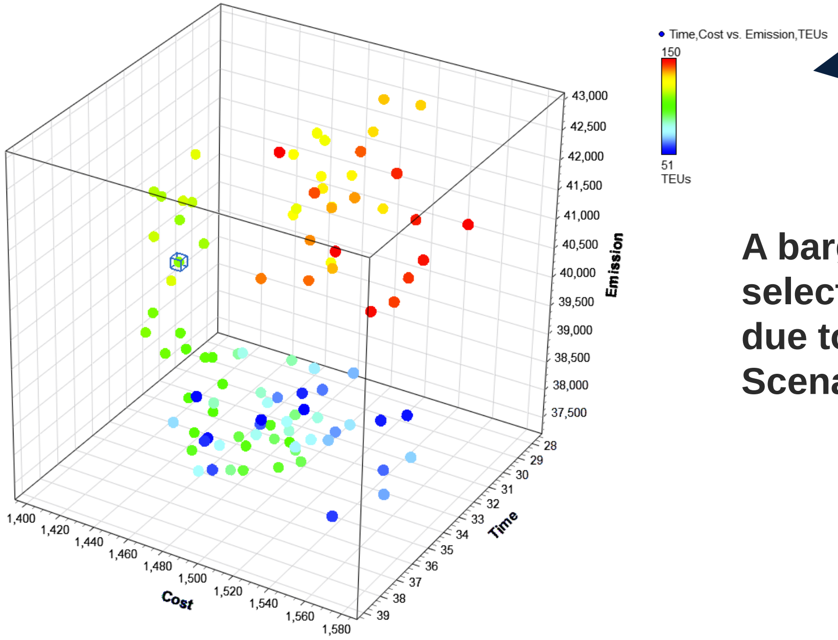
Barge Capacity Optimisation



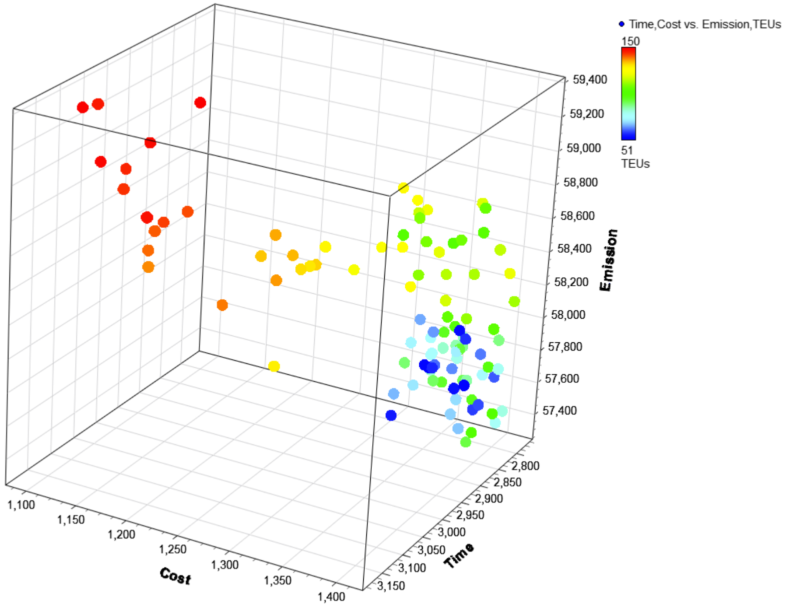
110 TEUs via barge sea transport provides the best balance between cost, emissions, and time



A barge with 126 TEUs is selected as the best option due to its proximity to Scenario 2 (110 TEUs)

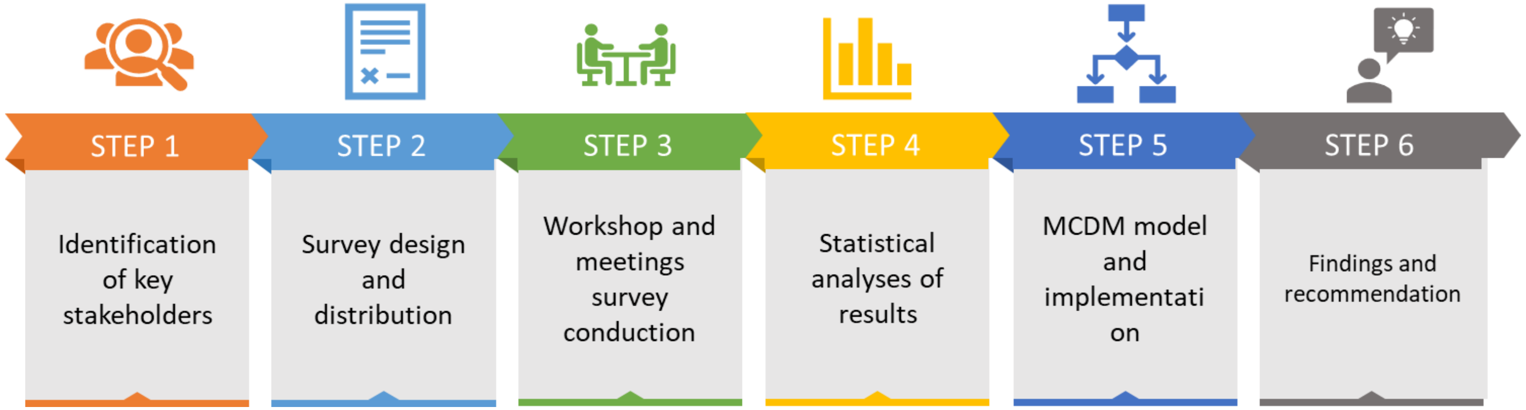


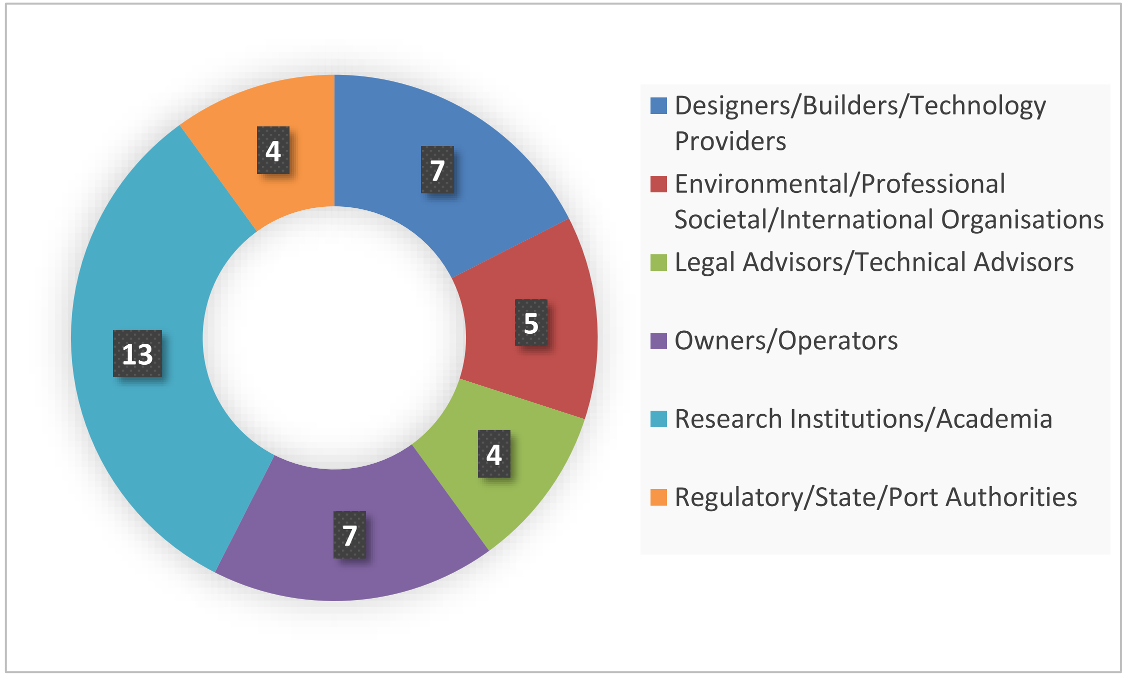
3D plot of three objectives Time, Cost, and Emission for different number of TEUs [51 to 150] for **scenario 2** simulation



3D plot of three objectives Time, Cost, and Emission for different number of TEUs [51 to 150] for **scenario 3** simulation

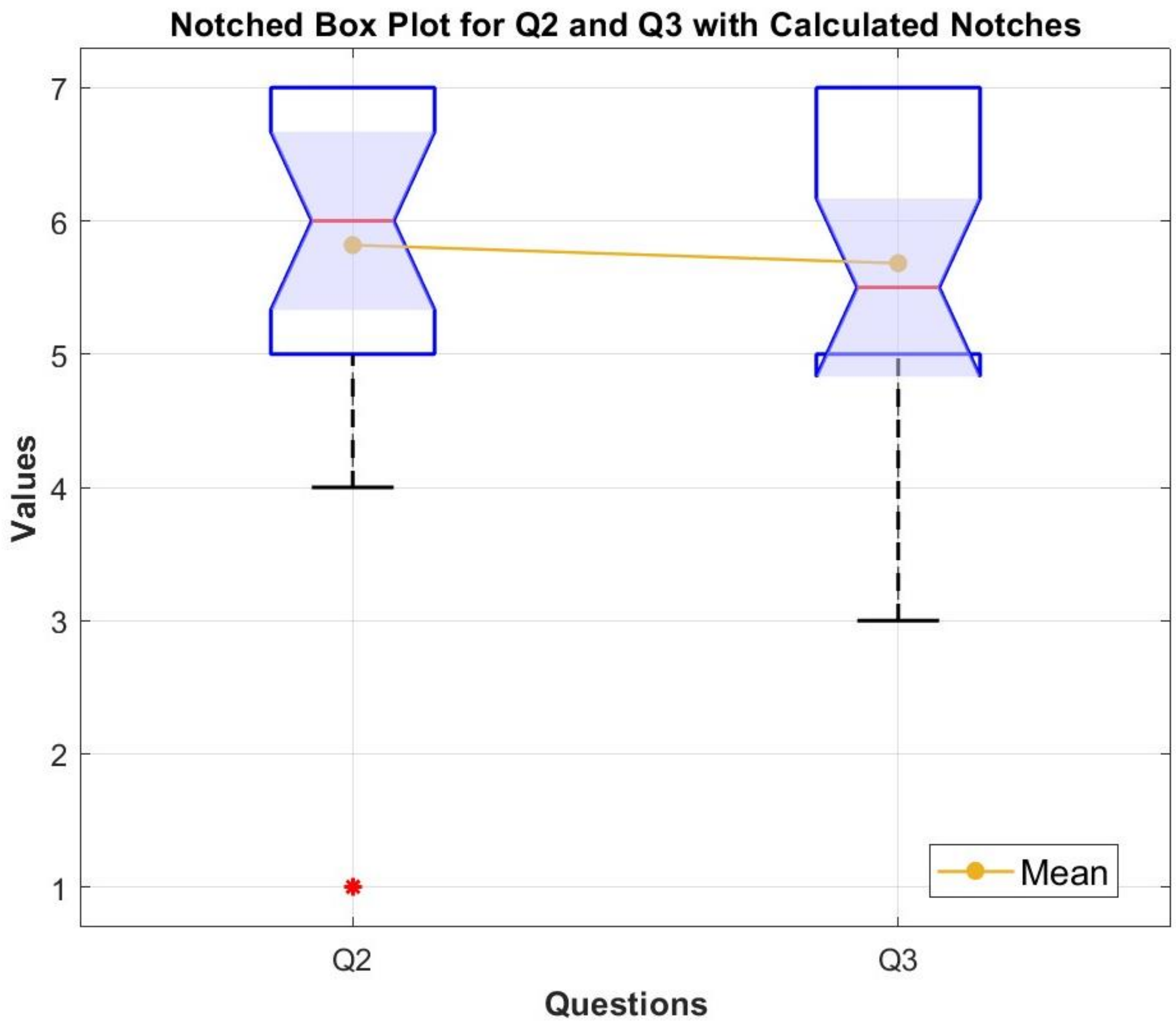
Survey conduction





Likert scales:

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Somewhat disagree
- ☐ Neither agree nor disagree
- ☐ Somewhat agree
- ☐ Agree
- ☐ Strongly agree

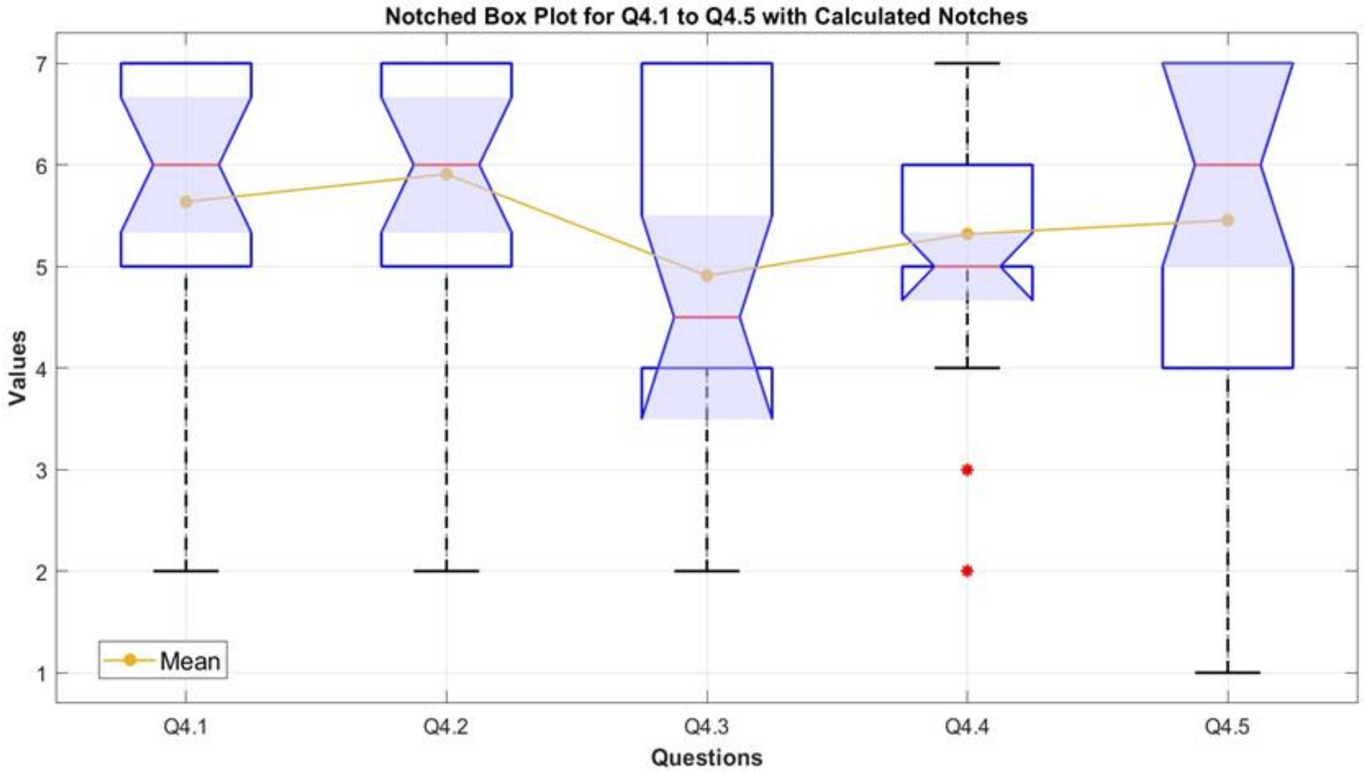


Q2. Is there a need for transition from single-mode transportation to multi-modal transportation?

Q3. Is there a need for transition from road transportation to maritime transportation?

! General agreement of stakeholders for implementing multi-modal transportation and shifting from road to waterway transportation.

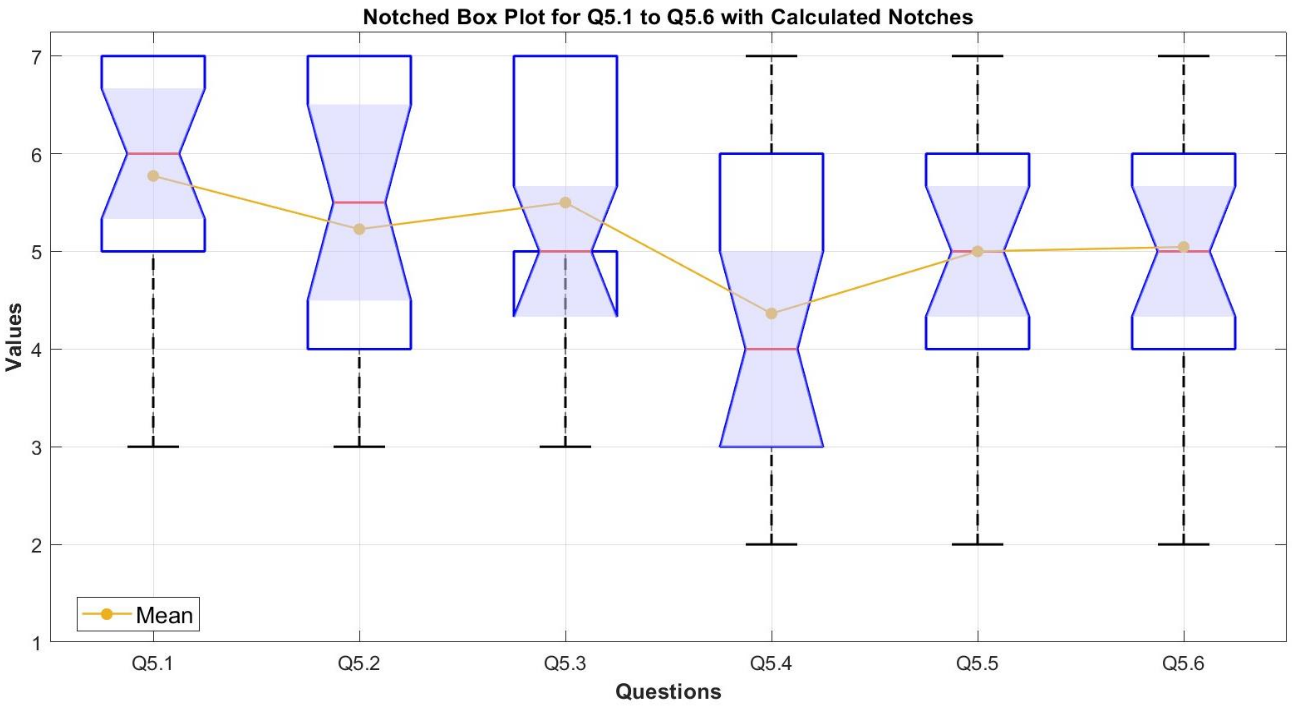
Q4. Which would be the benefits from the transition to multi-modal maritime transportation?



Q4.1- Financial benefits (reduced fuel consumption, optimized routing, reduced manning cost and etc.)
Q4.2- Environmental benefits (reduced environmental footprint)
Q4.3- Social benefits (increased job opportunities, better working conditions)
Q4.4- Increased safety (comparing water transportation to road transportation and their accidents)
Q4.5- Added resilience in case of major worldwide/national disruptions (recession, diseases, wars, piracy)

- The environmental benefits, the financial benefits, and added resilience received the highest levels of agreement.
- For each aspect, industry responses consistently reflected one level higher agreement than academia

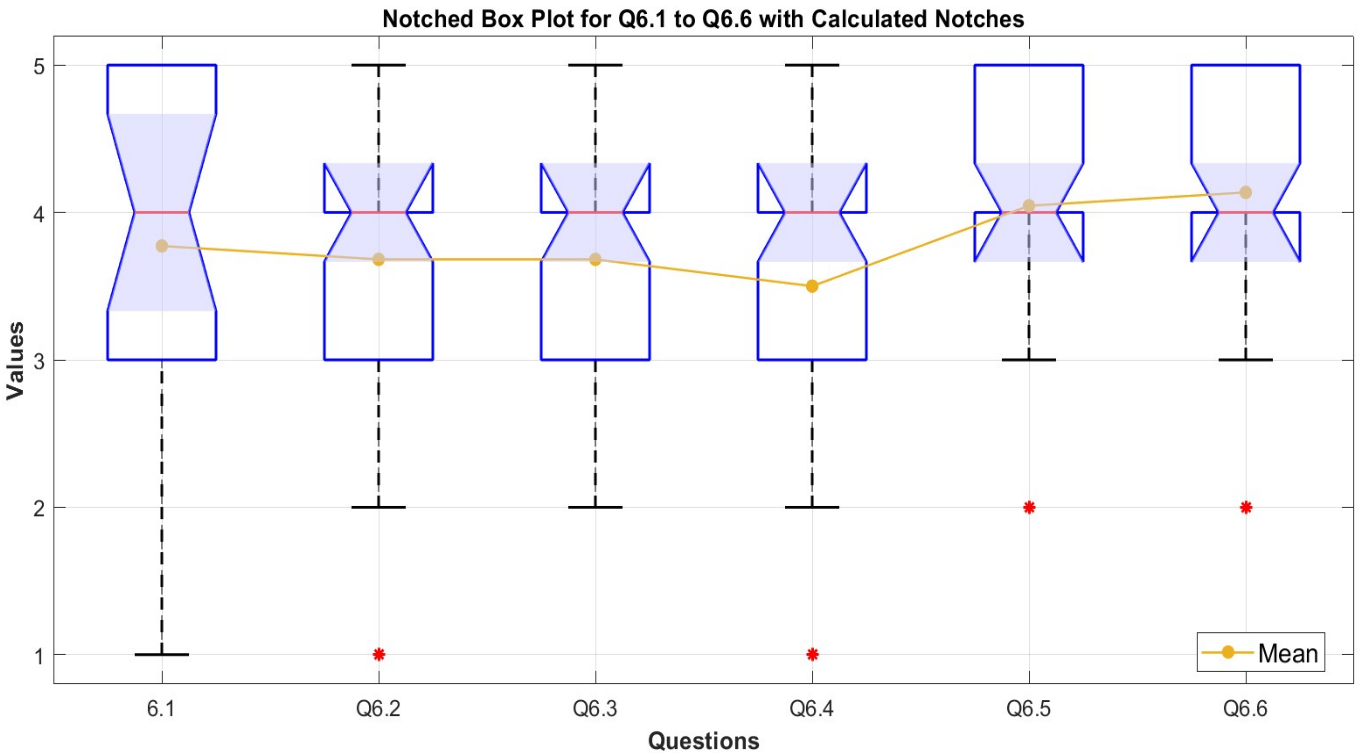
Q5. Which are the biggest challenges for shifting from road transportation to coastal/waterway shipping?



Q5.1- A guarantee from government to cover infrastructure cost of ports, inland waterways, swarming barges.
Q5.2- coastal/waterway shipping needs a procedure for testing, validation, verification, and refinement.
Q5.3- coastal/waterway shipping has more investment/operation cost to develop.
Q5.4- It is more difficult that coastal/waterway shipping adopt new technologies like Autonomy, Decarbonization, Digitalization.
Q5.5- coastal/waterway shipping has more regulatory/controversial obstacles compared to road transportation.
Q5.6- coastal/waterway shipping needs upskilling and modification of the current training framework.

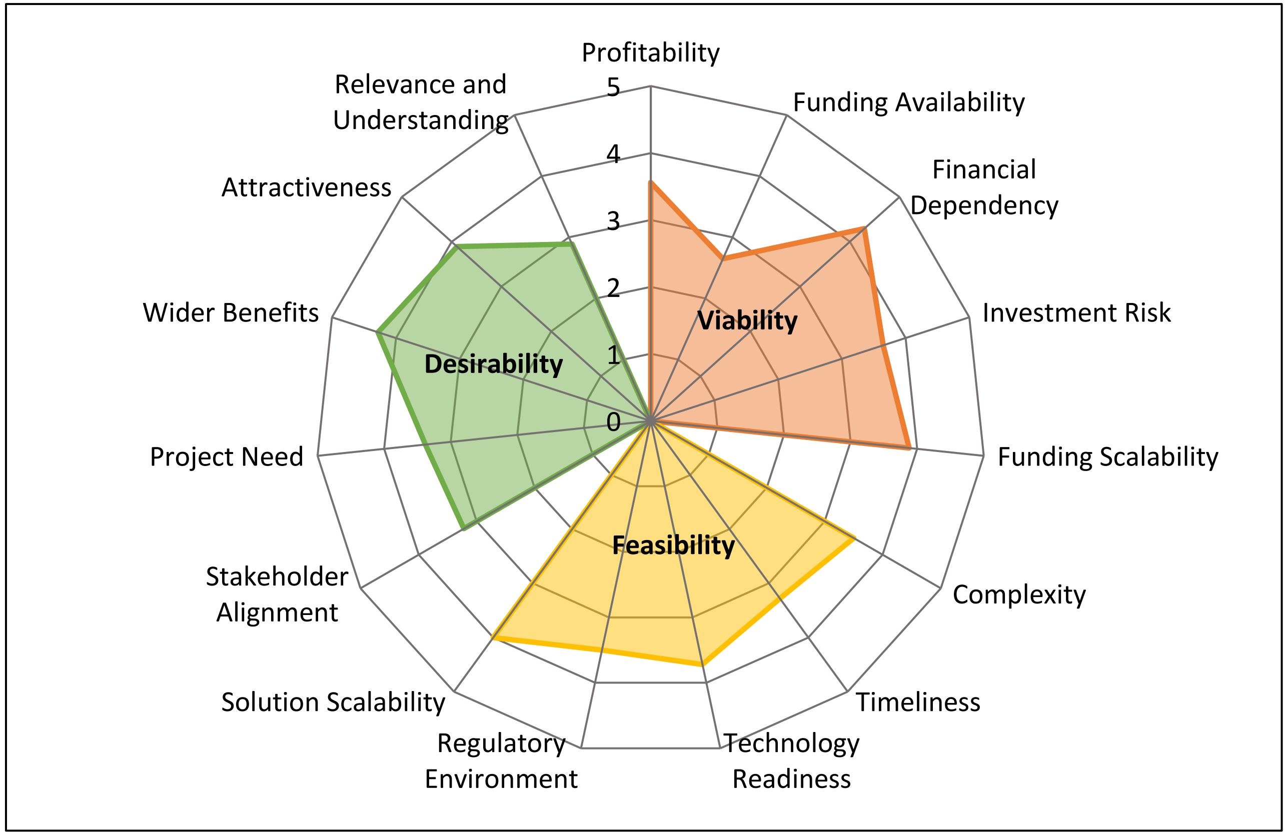
- Almost stakeholders agreed Q5.1 is the most important challenge of modal shifting to maritime transportation.
- Coastal/waterway shipping can employ emerging technologies like autonomy, decarbonisation, and digitalisation.

Q6. Please assess the impact of the following barriers to the transition to multi-modal transportation and shifting to waterway shipping:



Q6.1- Regulatory barriers (ships will not be allowed to sail until new regulations have been implemented)	
Q6.2- Technological limitations (technology not mature)	
Q6.3- Social limitations (lack of expert skills)	
Q6.4- Safety and security issues	
Q6.5- Economical barriers (question of profitability)	
Q6.6- Lack of a sustainable and resilient maritime freight model from government	

- Economic barriers and lack of a sustainable and resilient maritime freight model for transition to coastal/waterway shipping from government are perceived as the significant barriers to this modal transition in the UK



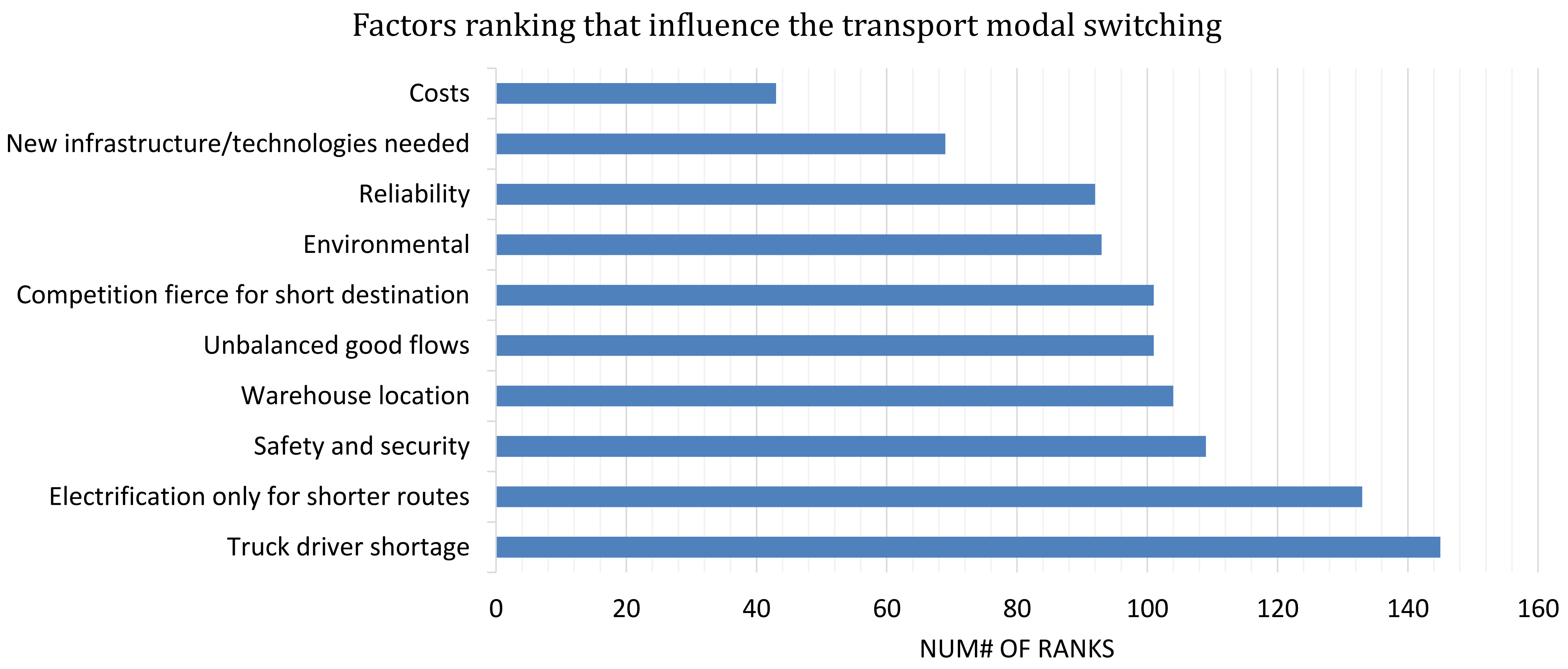
Q7. Viability (Financially sustainable and capable of growing over time)

Q8. Feasibility (They can be achieved from technical and regulatory perspectives)

Q9. Please rate the Desirability (Stakeholders see value in the transition, whether it's needed, and whether it's attractive and there is a demand for them)

- **Viability Insights:** Stakeholders recognise financial potential in transitioning to waterborne transportation, but it is seen as highly reliant on external funding with moderate investment risks. Ensuring sustainable funding pathways and reducing risks could improve its viability.
- **Feasibility Challenges:** High complexity and moderate regulatory and technological readiness pose barriers to implementation.
- **Desirability Overview:** While wider benefits (e.g., environmental impact) are strongly recognised, mixed views on stakeholder alignment and process understanding highlight the need for better communication and engagement.

Q10. Please rank the factors from most to least in terms of their influence on the potential for switching modes. (1 to 10)



Vision & Evidence

- The UK maritime sector is critical to freight movement.
- Ambitious vision: coastal & inland waterway “freight highway” using zero-emission vessels.
- Simulations show strong environmental and cost benefits.
- Real-world challenges remain: funding, regulations, operational complexity.

The Opportunity

- Coastal shipping is a viable, underutilized option to boost resilience & efficiency.
- Port-centric logistics and regional distribution hubs can strengthen the network.
- UK can become a key sustainable freight hub with coordinated action.

The Challenge & Questions Ahead

- What combination of innovation, policy, and investment is needed to overcome barriers?
- How quickly can the UK unlock its waterways’ full potential for freight?

Thank You

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Digital Decision-Support Tools for Ferry Port Decarbonisation: Energy-Aware Scheduling with Landside Traffic Simulation

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26 June 2025

Agenda

Agenda

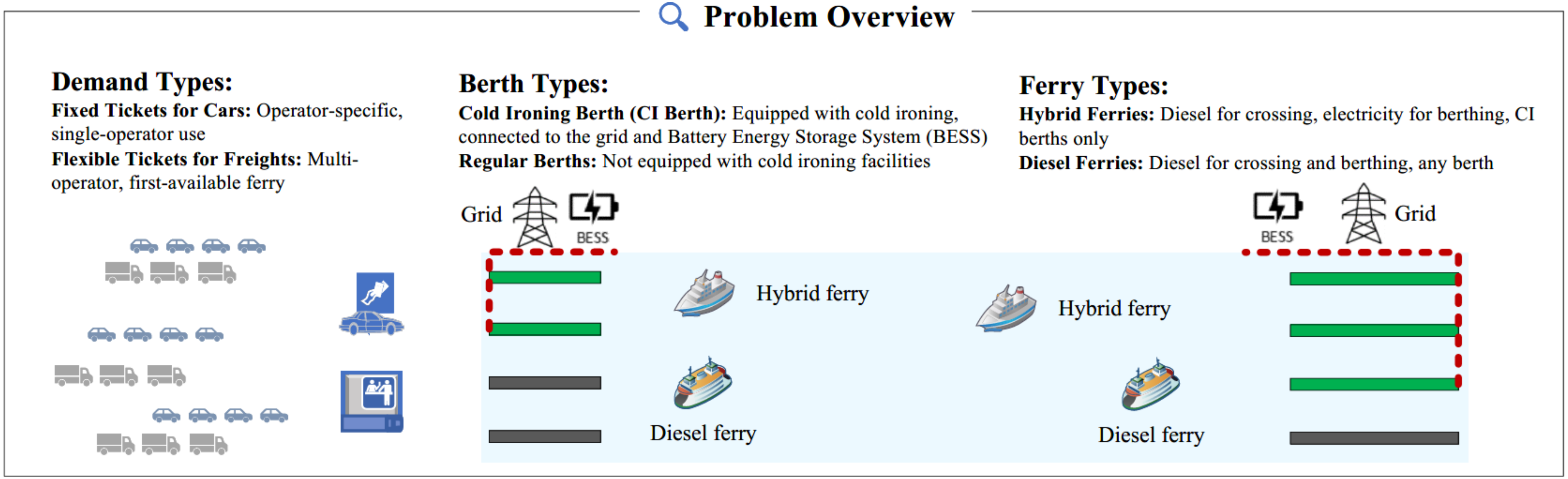
Problem Description

Optimal Berth Allocation and Scheduling for Hybrid and Diesel Ferries

Demand Types:
- **Fixed Tickets:** Operator-specific.
- **Flexible Tickets:** Multi-operator, first-available ferry.

Berth Types:
- **CI Berths:** Equipped with cold ironing, connected to grid and BESS.
- **Standard Berths:** No cold ironing facilities.

Ferry Types:
- **Hybrid:** Diesel for crossing, electricity for berthing, CI berths only.
- **Diesel:** Diesel for both crossing and berthing, any berth.



Problem Description

Scenarios for Diesel-to-Hybrid Ferry Replacement

Phase 1: All Diesel

- **Operator 1**
  Diesel ferries: 3
  Regular berths: 3
  Hybrid Ferries: 0
  Cold Ironing berths: 0
- **Operator 2**
  Diesel ferries: 3
  Regular berths: 3
  Hybrid Ferries: 0
  Cold Ironing berths: 0
- **Operator 3**
  Diesel ferries: 3
  Regular berths: 3
  Hybrid Ferries: 0
  Cold Ironing berths: 0
- **Grid/BESS Capacity**
  0 MVA / 0 MW

Phase 2: Hybrid Start

- **Operator 1**
  Diesel ferries: 1
  Regular berths: 1
  Hybrid Ferries: 2
  Cold Ironing berths: 2
- **Operator 2**
  Diesel ferries: 3
  Regular berths: 3
  Hybrid Ferries: 0
  Cold Ironing berths: 0
- **Operator 3**
  Diesel ferries: 3
  Regular berths: 3
  Hybrid Ferries: 0
  Cold Ironing berths: 0
- **Grid/BESS Capacity**
  5 MVA / 0 MW

Phase 3: Hybrid Shift

- **Operator 1**
  Diesel ferries: 0
  Regular berths: 0
  Hybrid Ferries: 3
  Cold Ironing berths: 3
- **Operator 2**
  Diesel ferries: 1
  Regular berths: 1
  Hybrid Ferries: 2
  Cold Ironing berths: 2
- **Operator 3**
  Diesel ferries: 3
  Regular berths: 3
  Hybrid Ferries: 0
  Cold Ironing berths: 0
- **Grid/BESS Capacity**
  5 MVA / 5 MW

Phase 4: Full Hybrid

- **Operator 1**
  Diesel ferries: 0
  Regular berths: 0
  Hybrid Ferries: 3
  Cold Ironing berths: 3
- **Operator 2**
  Diesel ferries: 0
  Regular berths: 0
  Hybrid Ferries: 3
  Cold Ironing berths: 3
- **Operator 3**
  Diesel ferries: 0
  Regular berths: 0
  Hybrid Ferries: 3
  Cold Ironing berths: 3
- **Grid/BESS Capacity**
  7 MVA / 8 MW

Methodology

Iterative Optimisation–Simulation Loop

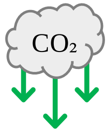
- Run the **Energy-Aware Scheduling (EAS) model** to generate initial berth and ferry schedules.
- Use **Discrete-Event Simulation (DES)** to evaluate landside traffic flow and identify bottlenecks.
- If **mean queue time** at key bottlenecks (e.g. passport control or weighbridge) exceeds the acceptable threshold:
  - Adjust the **vehicle arrival profiles** (especially for shiftable demand) by rescheduling them to less congested periods.
  - Update the **demand input matrix** for the EAS model to reflect the revised arrival times.
  - Re-run the **EAS model** with the updated demand profile.
- Repeat the optimisation–simulation loop until:
  - Mean queue times at critical nodes fall within the acceptable range.
  - Operational, environmental, and traffic service-level targets are all satisfied.

Methodology

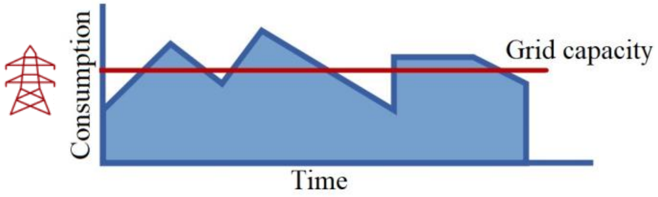
Energy-Aware Scheduling (EAS) model

Tri-Objective Optimisation

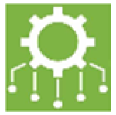
1. Environmentally Friendly: Minimise CO_2 emissions during berthing



2. Energy Reliability: Avoid grid exceedance to enhance system reliability and prolong battery life



3. Cost Efficiency: Reduce excessive berth usage to lower operational and maintenance costs

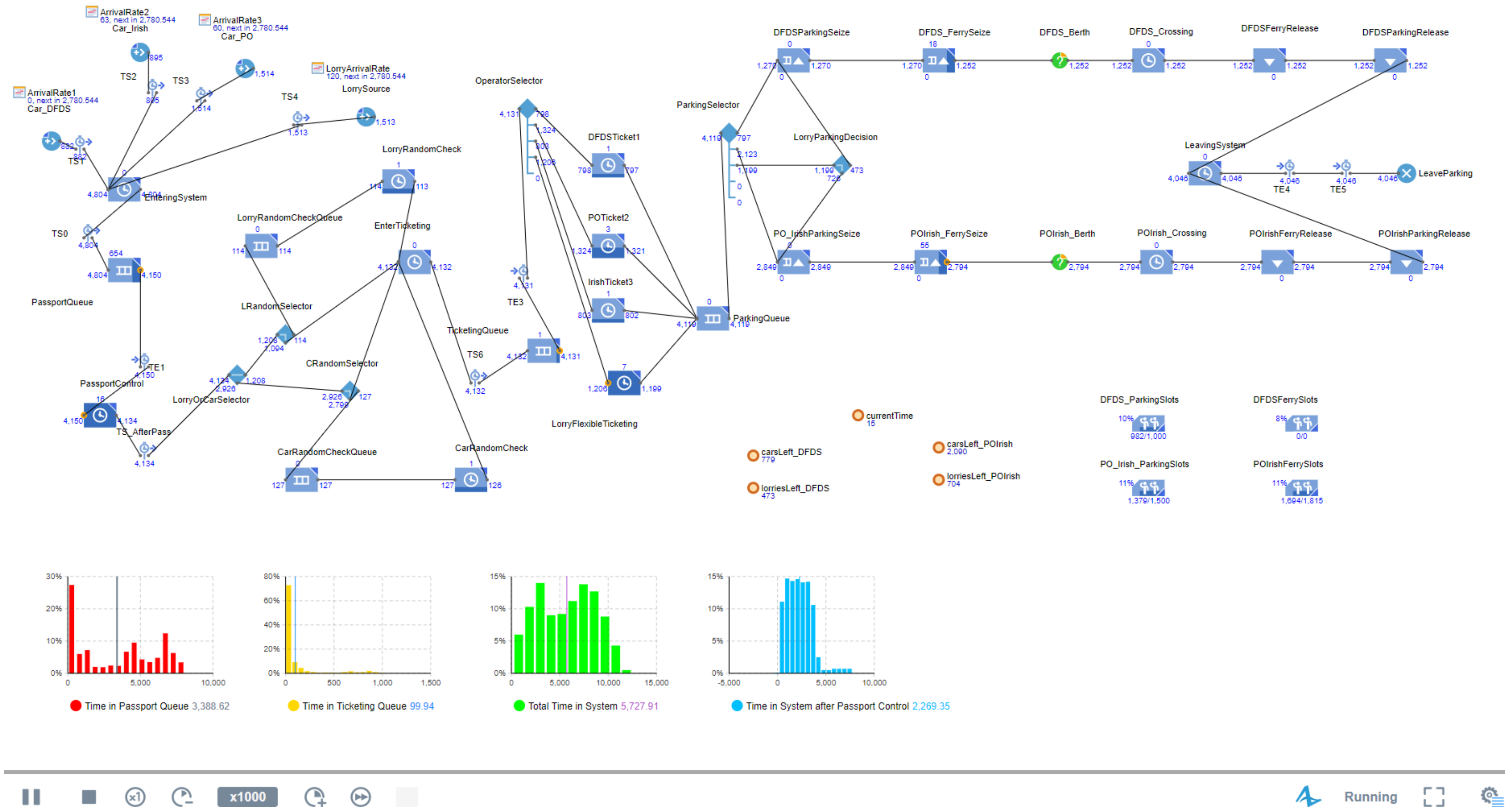


Three key operational decisions that form the backbone of the proposed optimisation framework are as follows:

- the initial berthing time of each ferry within a defined flexibility window,
- the assignment of berths to ferries during each time period, and
- the termination time of each ferry's service.

Methodology

Discrete-Event Simulation to Assess Scheduling Impact on Port Traffic

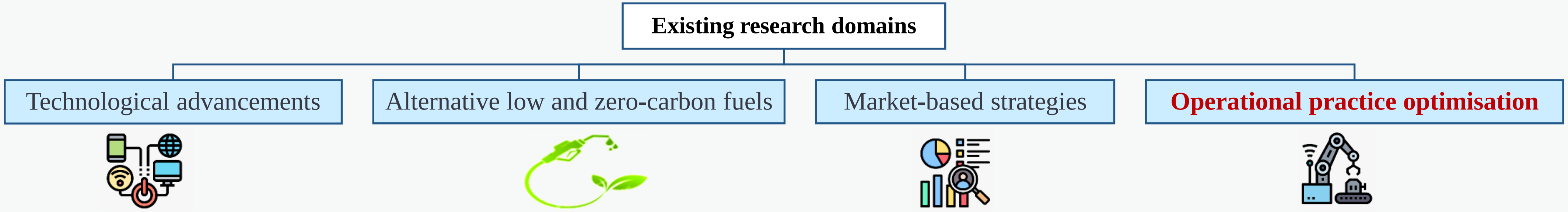


Agenda

1	Problem Description and Methodology
2	Research Questions
3	Preliminary Results of the Analytical Model
4	Preliminary Results of the Simulation Model

Approaches for decarbonising maritime operations

1 Categorisation of existing research efforts in decarbonising maritime shipping:



2 Research questions:

- What is the impact of replacing diesel ferries with hybrid ferries under four different scenarios on CO_2 emissions reduction?
- Under each scenario, how many times does grid capacity exceed demand, requiring reliance on the Battery Energy Storage System (BESS)?
- What is the minimum number of cold ironing-equipped berths needed to enable feasible scheduling under each scenario?
- How does the scheduling obtained through the proposed mathematical model affect traffic at the Port of Dover?

Agenda

1	Problem Description and Methodology
2	Research Questions
3	Results of the Analytical Model
4	Preliminary Results of the Simulation Model

CO_2 Emissions (kg) During Berthing Under Different Scenarios

- Implemented in Python using Gurobi 12.0.0
- Comparison of BAU and EAS Across Hybridisation Phases for Busy and Non-Busy Days:

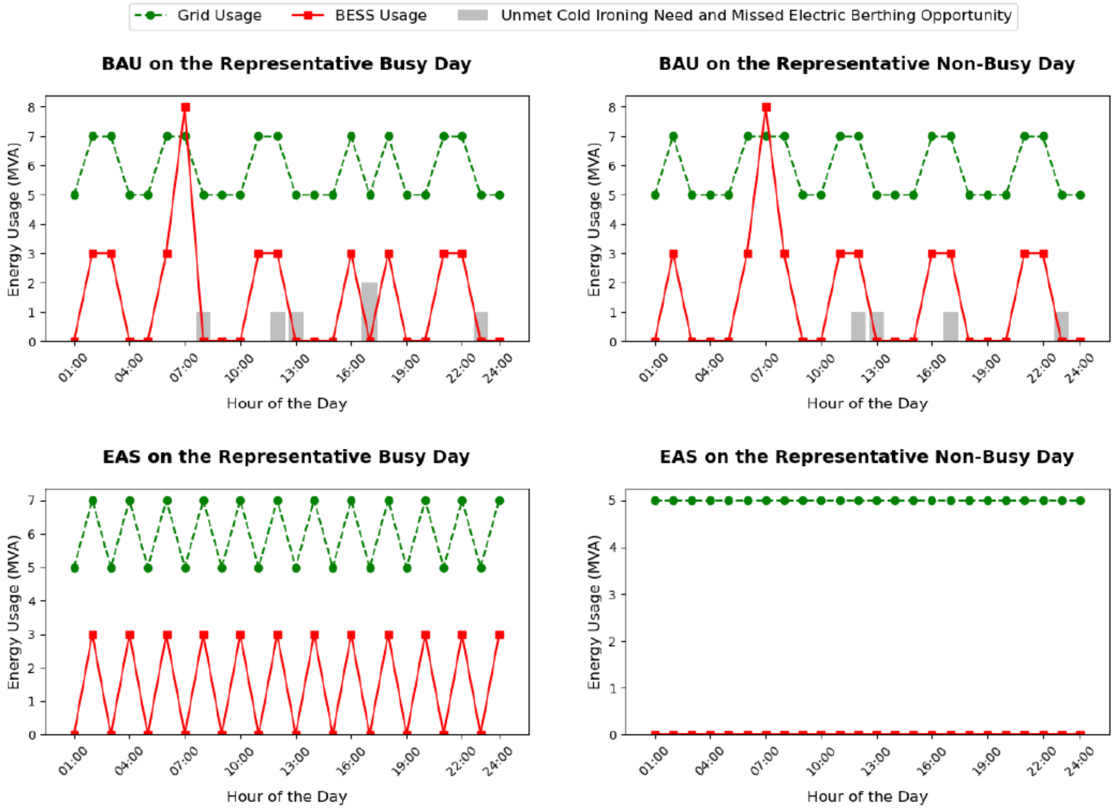
Busy Days					
Phase	**Crossings**	**Grid Exc.**	**Missed Elec.**	**CO_2 Red.**	**Cap. Eff.**
1. All Diesel	41 / 36*	0 / 0*	0 / 0*	**12%**	**12%**
2. Hybrid Start	41 / 36*	0 / 0*	0 / 0*	**14%**	**12%**
3. Hybrid Shift	41 / 36*	5 / 0*	0 / 0*	**19%**	**12%**
4. Full Hybrid	41 / 36*	10 / 12*	6 / 0*	**35%**	**12%**
Non-Busy Days					
Phase	**Crossings**	**Grid Exc.**	**Missed Elec.**	**CO_2 Red.**	**Cap. Eff.**
1. All Diesel	40 / 24*	0 / 0*	0 / 0*	**40%**	**40%**
2. Hybrid Start	40 / 24*	0 / 0*	0 / 0*	**42%**	**40%**
3. Hybrid Shift	40 / 24*	5 / 0*	0 / 0*	**48%**	**40%**
4. Full Hybrid	40 / 24*	10 / 0*	4 / 0*	**51%**	**40%**

Legend: Asterisks (*) indicate EAS values.
Crossings = Total crossings (BAU/EAS); Grid Exc. = Grid exceedance events (BAU/EAS);
Missed Elec. = Missed electric berthing; CO_2 Red. = CO_2 reduction with EAS;
Cap. Eff. = Capacity usage efficiency improvement with EAS.

Results of the Analytical Model

CO_2 Emissions (kg) During Berthing Under Different Scenarios

- Berthing schedules under the BAU and EAS approaches during Phase 4 (Full Hybrid)



BAU

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Operator 1	1	2	3			4	5	6			7	8	9			10	11	12			13	14	15	
Operator 2		1	2	3			4	5	6			7	8	9			10	11	12			13	14	15
Operator 3					1	2	3			4	5	6			7	8	9			10	11			

EAS

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Operator 1		1		2		3		4		5		6		7		8		9		10		11		12
Operator 2		1		2		3		4		5		6		7		8		9		10		11		12
Operator 3	1		2		3		4		5		6		7		8		9		10		11		12	

(a) On the representative busy day

BAU

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Operator 1	1	2				3	4	5			6	7	8			9	10	11			12	13	14	
Operator 2		1	2	3			4	5	6			7	8	9			10	11	12			13	14	15
Operator 3					1	2	3			4	5	6			7	8	9			10	11			

EAS

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Operator 1			1			2			3			4			5			6			7			8
Operator 2		1			2			3			4			5			6			7			8	
Operator 3	1			2			3			4			5			6			7			8		

(b) On the representative non-busy day

CO_2 Emissions (kg) During Berthing Under Different Scenarios

- Aggregate Performance Results Across Diesel-to-Hybrid Transition Phases:

Phase	P/P (Peak Car/Peak Freight)				P/O (Peak Car/Off-Peak Freight)			
	CO_2%	Grid Exc.	Elec. Berth%	Crossings	CO_2%	Grid Exc.	Elec. Berth%	Crossings
1. All Diesel	–	0	**0%**	36	–	0	**0%**	36
2. Hybrid Start	**16%**	0	**22%**	36	**16%**	0	**22%**	36
3. Hybrid Shift	**39%**	0	**56%**	36	**39%**	0	**56%**	36
4. Full Hybrid	**70%**	12	**100%**	36	**70%**	12	**100%**	36
Phase	**O/P (Off-Peak Car/Peak Freight)**				**O/O (Off-Peak Car/Off-Peak Freight)**			
	CO_2%	Grid Exc.	Elec. Berth%	Crossings	CO_2%	Grid Exc.	Elec. Berth%	Crossings
1. All Diesel	–	0	**0%**	24	–	0	**0%**	24
2. Hybrid Start	**20%**	0	**29%**	24	**20%**	0	**29%**	24
3. Hybrid Shift	**44%**	0	**63%**	24	**44%**	0	**63%**	24
4. Full Hybrid	**70%**	0	**100%**	24	**70%**	0	**100%**	24

Legend: CO_2% = Emission improvement (compared to phase 1 (*All Diesel*)), Grid Exc. = Grid capacity exceedances, Elec. Berth% = Percentage of berthing instances powered by electricity, Crossings = Total ferry crossings.

Agenda

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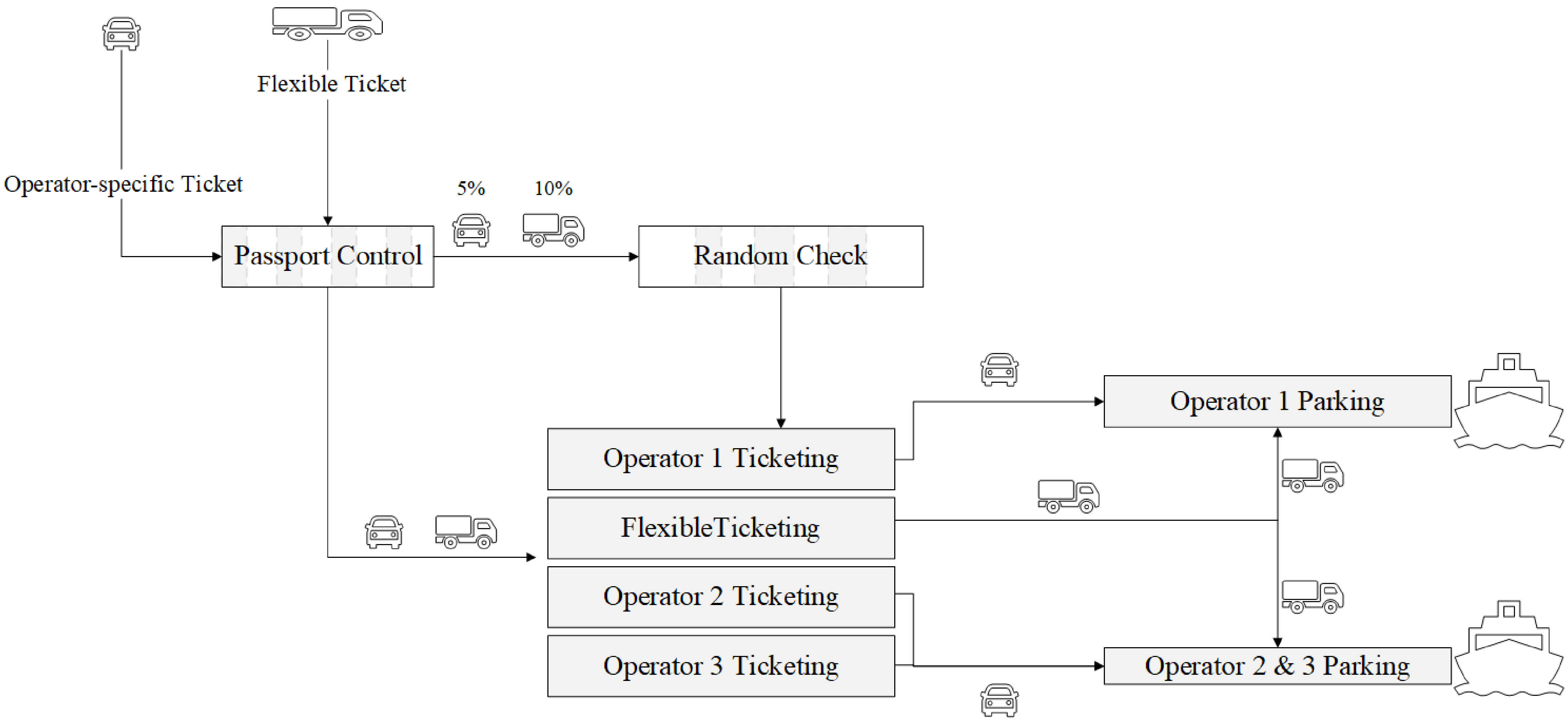
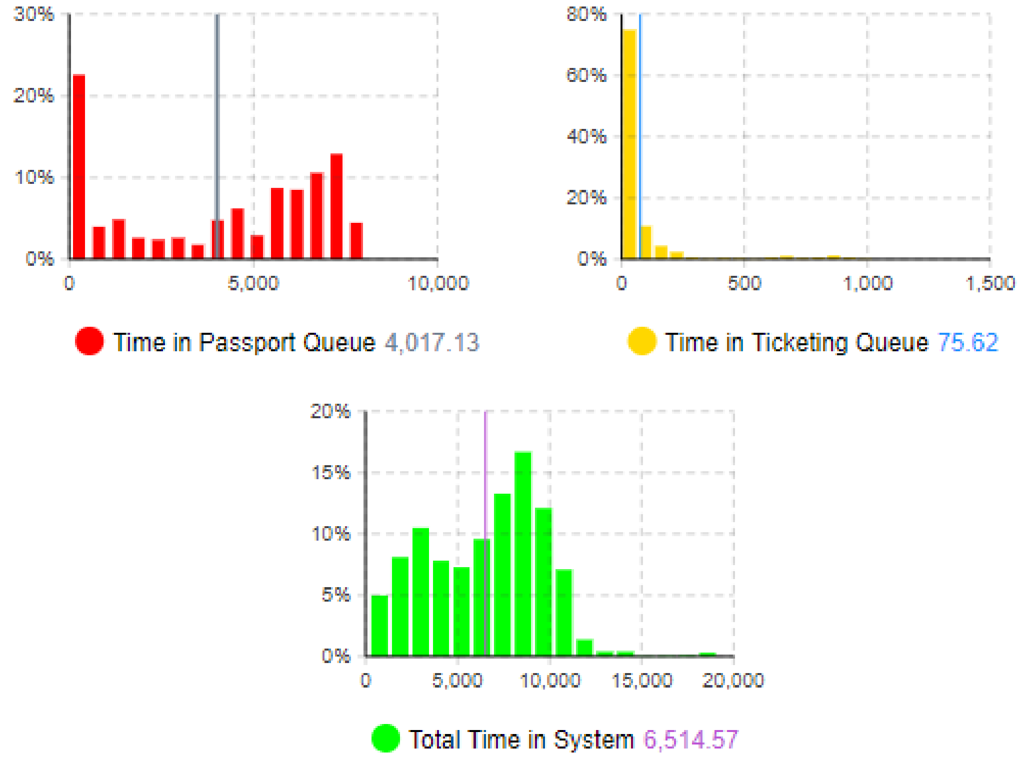
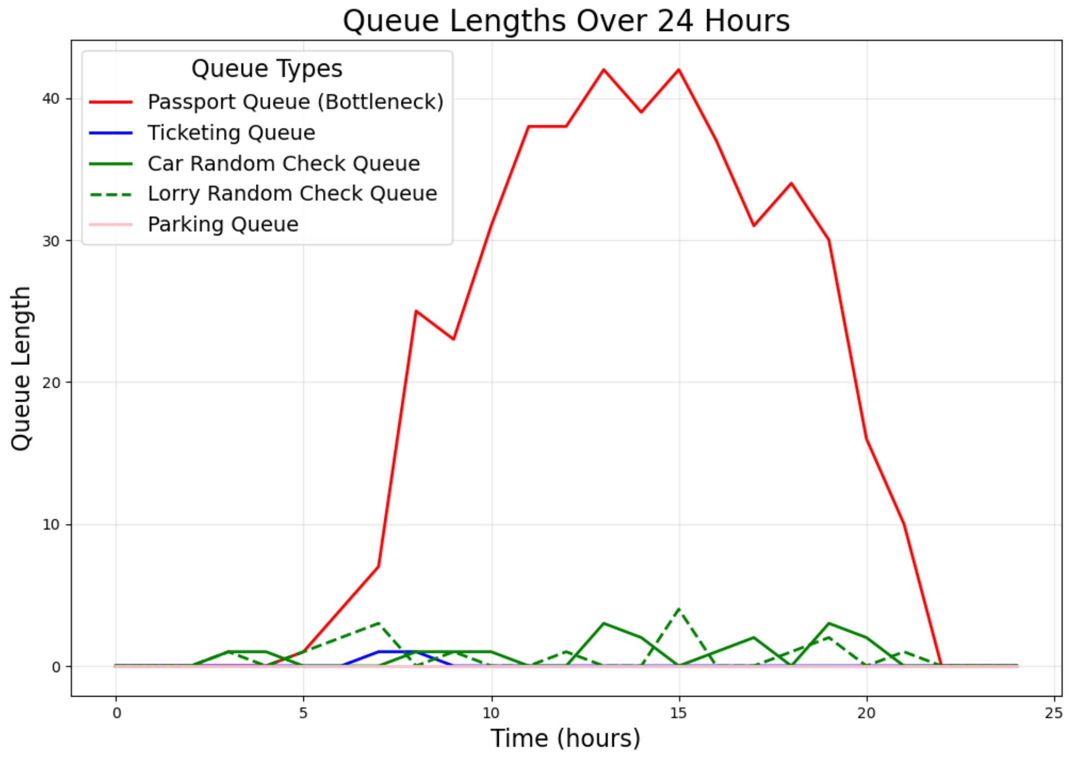
Schematic Representation



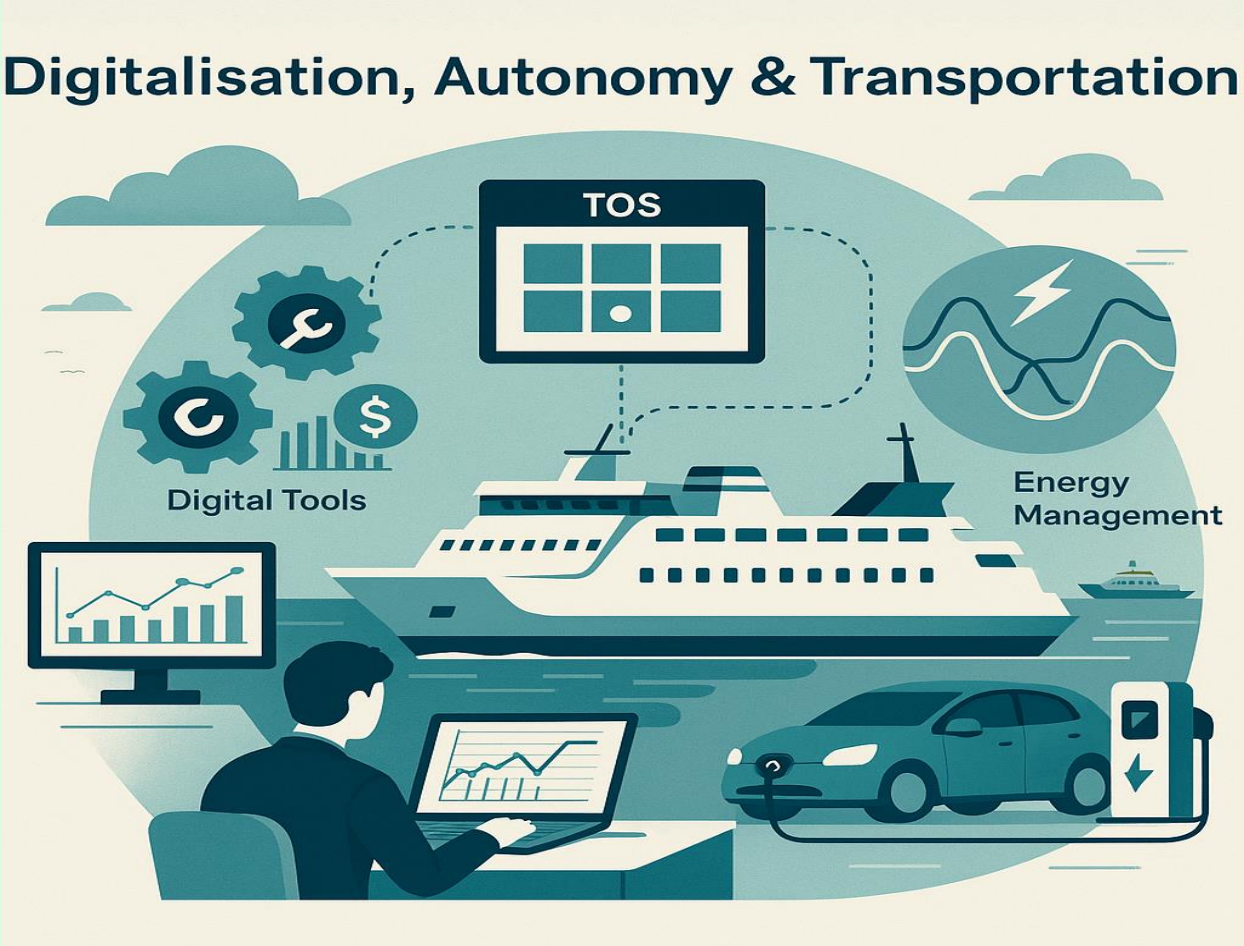
Simulation Results

- Implemented as a Discrete-Event Model in AnyLogic 8.9.1 for 24-Hour Traffic Simulation





- Based on identifying a more than reasonable queue time, the Optimisation-Simulation Approach needs to be done iteratively after modification of scheduling input by affecting the arrival time of vehicles.



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Practical Implications of the Proposed Digital Decision Support Tools for Ferry Ports:

Environmental, Economic, Operational Benefits and Technical Feasibility

Conclusion

Value and Feasibility of the Proposed Decision Support System

Environmental and Operational Impact

- Up to **70% CO_2 reduction** under full-hybrid operations; **12–51% savings** vs BAU
- **Fewer ferry crossings**; improved berth use reduces congestion and maintenance
- **No missed electric berthing** under EAS, compared to **5 (busy)** and **4 (non-busy)** missed under BAU

Economic Value

- **Lower operational costs** through efficient berth and energy use
- Requires **fewer grid and BESS upgrades** compared to Business-As-Usual scenarios
- Enables a **cost-effective, scalable decarbonisation strategy**

System Compatibility and Integration

- Built with **standard tools**: Gurobi (optimisation) and AnyLogic (simulation)
- Functions as a **decision-support layer**, external to the existing Terminal Operating System (TOS)
- **No real-time data required**; uses historical input and forecasting
- Supports **phased deployment**, from diesel-only to fully hybrid fleets

THANK YOU!