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Power Plants Design – Energy efficiency, safety and sustainability interplay

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Europe-Korea Conference on Science & Technology (EKS2021)

EKC 2021
Europe-Korea Conference on Science and Technology

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Maritime Safety Research Centre

Established in 2016

DNV · Royal Caribbean International · University of Strathclyde Glasgow

Ongoing projects

- ❖ **SEAMAN** – Safety EnhAncing Monitoring ApplicatioNs (Norwegian Research Council)
- ❖ **FLARE** – Flooding Accident Response (H2020)
- ❖ **SafePASS** – Next generation of life Saving appliances and systems for saFE and swift evacuation operations on high capacity PASSenger ships (H2020)
- ➢ **IN 4.0** – Adaptation of Industry 4.0 Model to the Naval Sector (Interreg)
- ➢ **AUTOSHIP** – Autonomous Shipping Initiative for European Waters (H2020)
- ➢ **i-HEATS** – Marine engines intelligent health assessment system based on digital twins (Innovate UK)
- ❑ **TrAM** – Electrically-powered vessels operating in protected waters with zero emissions (H2020)
- ❑ **ShipFC** – Piloting Multi MW Ammonia Ship Fuel Cells (H2020)
- ❑ **LNGBOG** – LNG fuelled tanker boil off formation analysis (Industry)
- ❑ **LNG FEEDSAFE** – Model based safety analysis of LNG fuel feeding system (Industry)
- ❑ **HyShip** – Fuel Cells and Hydrogen Joint Undertaking (FCH) (H2020)
- ❑ **Carnot** Marine Vessel APUs – Feasibility Study, CMDC – Strad I (Innovate UK)
- ❑ **NEPTUNE** CMDC – Strad I (Innovate UK)

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Aim and Objectives

- Present a holistic methodology to identify optimal power plant solutions
- Consider metrics on emissions, lifecycle cost, safety and reliability
- Case study of a modern cruise ship



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Background

Shipping industry challenges

- Energy Efficiency
- Environmental Protection
  - Zero emissions
  - Climate change
  - Cleaner oceans
- Safety−Security−Cyber-Security
  - Zero accidents
- Sustainability
- Resilience
- Cost-effectiveness
- Regulatory Framework

A Virtuous Cycle







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Rationale

Cruise ship industry

- **Growing** sector, one of the fastest rising of tourism
- Very **energy intense** ships due to hotel load demand
- High **emissions** and **fuel** consumption
- **Complex** energy systems

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Current design practice

- Single design point
- Design by experience – Shipyards evolve designs
- Conservatism – Redundancy
- Focus on low capital cost
- Retrofit technologies driven by regulations (BWT systems, scrubbers)

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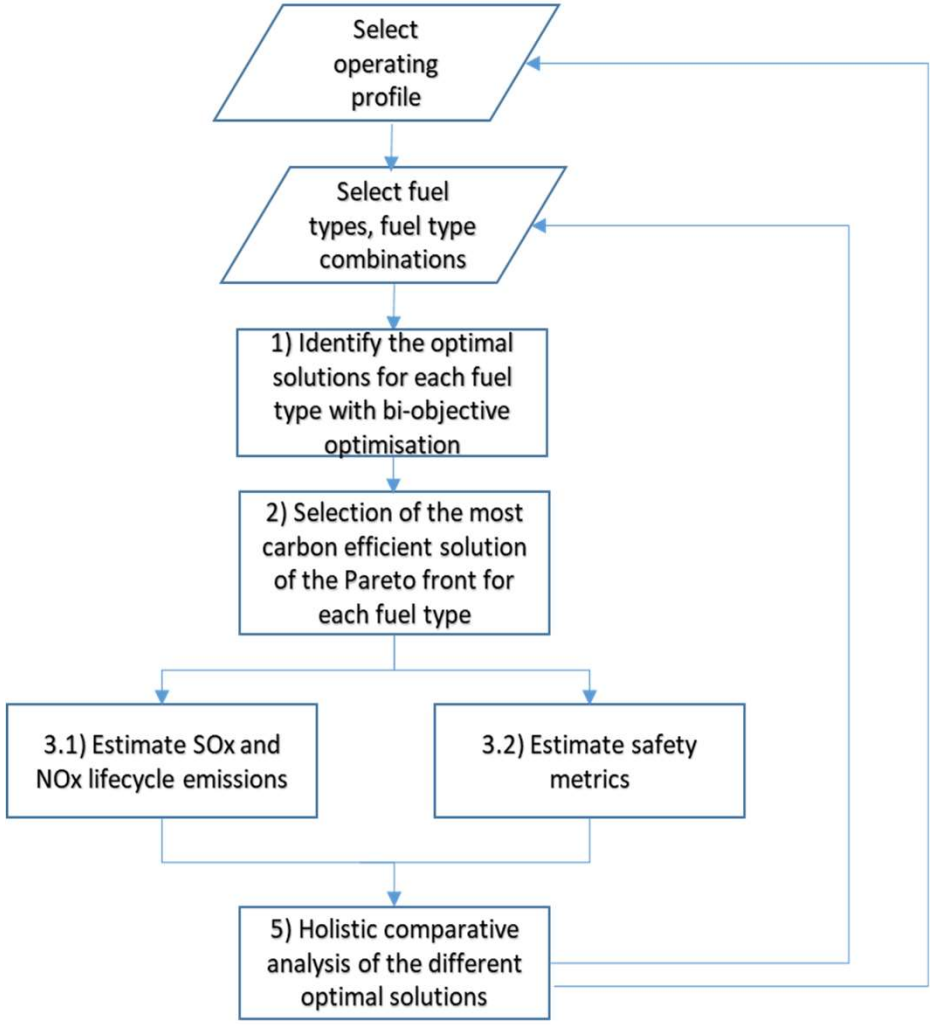
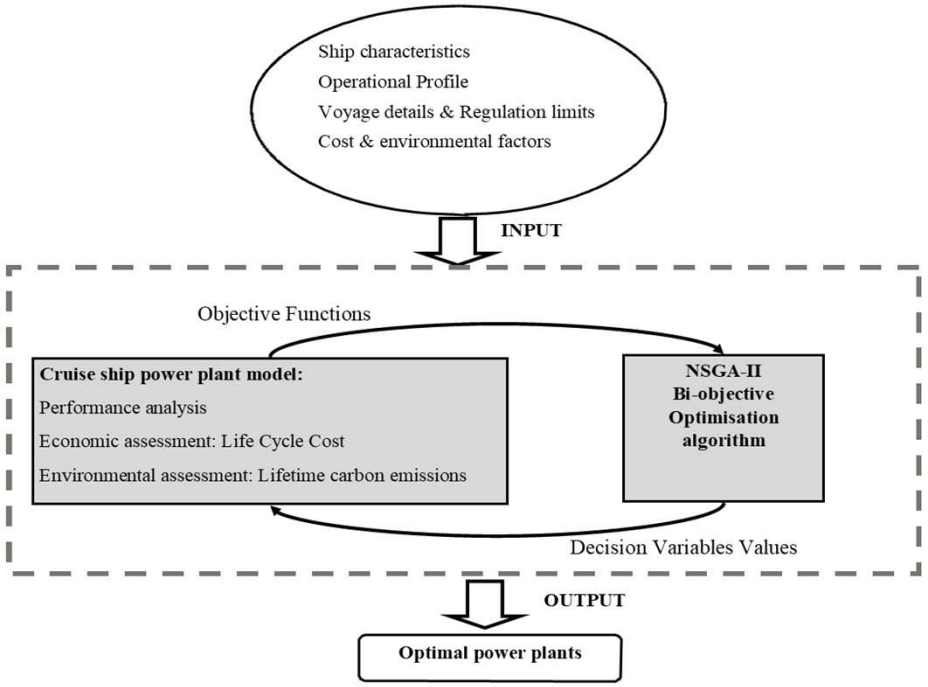
Proposed methodology





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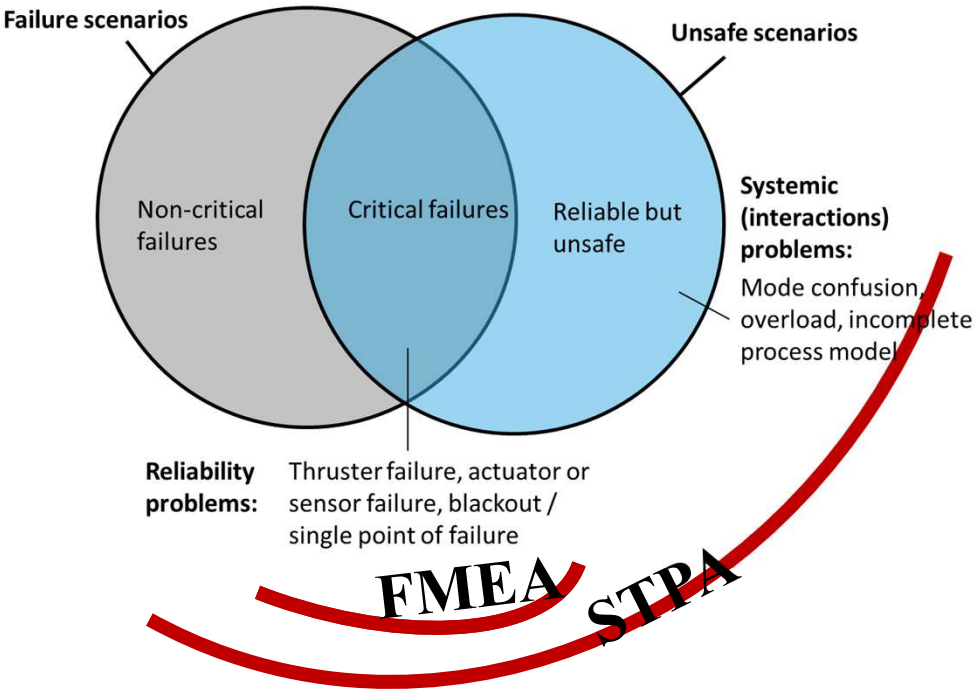
Safety methods

Traditional vs. modern methods

- FMECA, FTA, ETA
- Systems Theoretic Process Analysis (STPA) (compatible with ISO 26262)



- In complex systems: Safety is not linked to reliability / redundancy
- Blackout is one potential causal factor for collision, contact, grounding



https://gcaptain.com/incident-photo-week-marco-polo/

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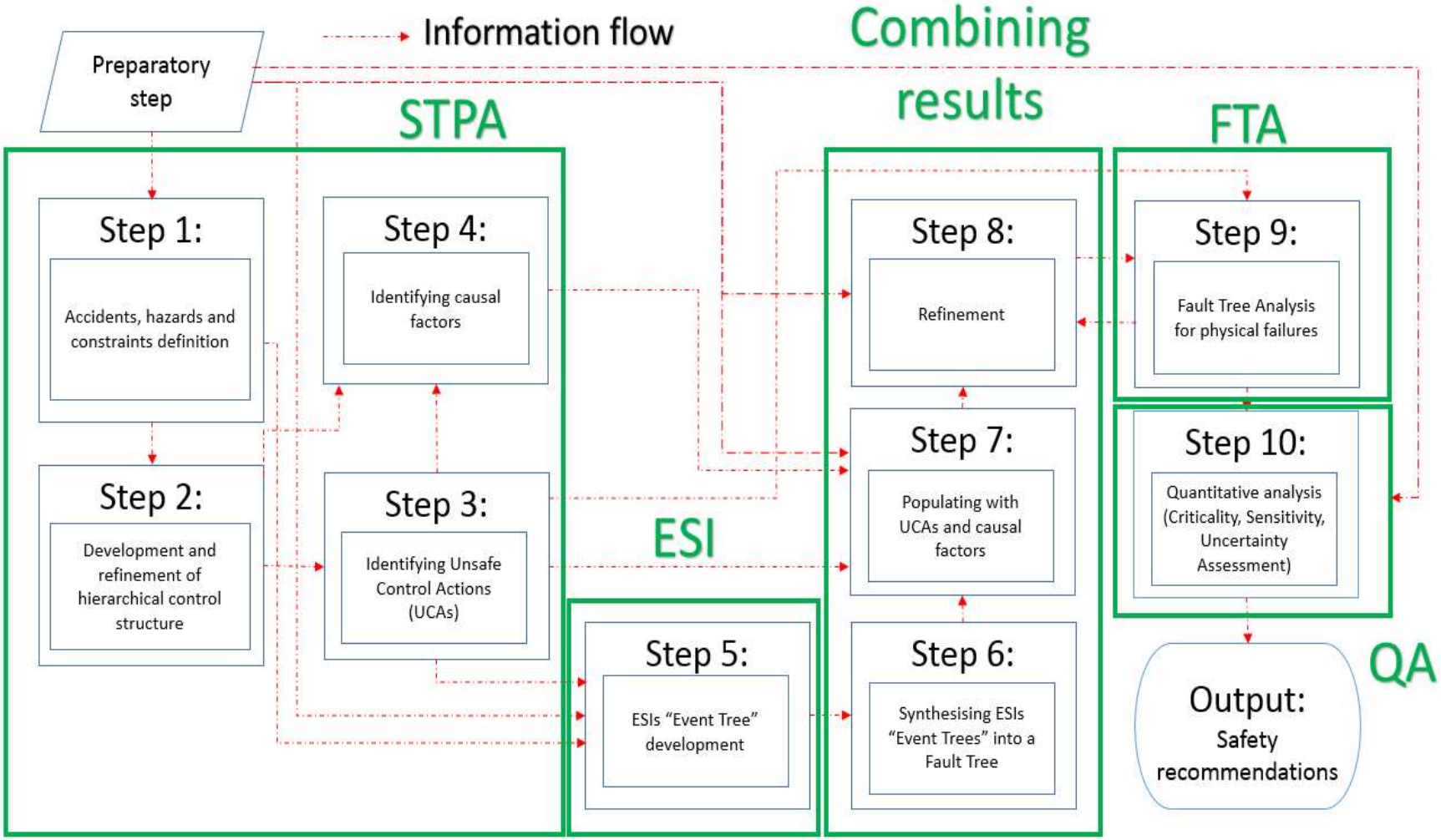
Employed Safety Analysis Method



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Employed metrics

Lifecycle cost & Lifetime emissions

$$LCC = CAPEX + \sum_{n=1}^{Y} \frac{OPEX_n}{(1+d_r)^n} \qquad CAPEX = \sum_{s} C_{c,s} N_s P_{nom,s}$$

$$OPEX = \sum_{k=1}^{OPH} \sum_{ft} d_{f,k} fc_{ft,k} \frac{C_{ft}}{10^6} + \sum_{s} C_{m,s} P_{k,s}\ h_k + M_{con}$$

$$LTCO_2 = \sum_{n=1}^{Y} \sum_{k=1}^{OPH} \sum_{ft,k} C_{CO2,ft}\ fc_{ft,k}$$

$$LTNOx = \sum_{n=1}^{Y} \sum_{k=1}^{OPH} \sum_{s} EF_{NOx,ft,s}\ P_{k,s} h_k$$

$$LTSOx = \sum_{n=1}^{Y} \sum_{k=1}^{OPH} \sum_{ft} EF_{SOx,ft}\ fc_{ft,k}$$

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Employed metrics

Safety metric: frequency of blackout

$$FOB = \sum_{p=1}^{q} OP_p FOB_p \qquad FOB_p = \lambda_p \, LTH$$

	System components	Equation
Operating components	**Software, hardware, communication and sensors failures**	$p_i^{OC} = \lambda_i t$
	Parts with preventive maintenance where a single component failure out of r identical will lead to event occurence	$p_i^{OC} = \sum_{1}^{r} \binom{r}{1} \left(T_i^{\beta_i - 1} \lambda_i^{\beta_j}\right)^r \left(1 - T_i^{\beta_i - 1} \lambda_i^{\beta_i}\right)^{1-r} t$
	Parts with preventive maintenance where all the r identical components must fail for event occurrence	$p_i^{OC} = \left[\left(T_i^{\beta_i - 1} \lambda_i^{\beta_i}\right)^r + r T_i^{\beta_i - 1} \lambda_i^{\beta_i} \left(\frac{\lambda_i}{\lambda_i + \mu_i}\right)^{r-1} + \left(\frac{\lambda_i}{\lambda_i + \mu_i}\right)^r\right] t$
Safety systems	Tested standby equipment that does not function (except for software failures)	$p_i^{SS} = 1 + \frac{\left(e^{-\lambda_i T_i} - 1\right)}{\lambda_i T_i}$
	For safety system/functions with continuous monitoring does not function	$p_i^{SS} = \frac{\lambda_i}{\lambda_i + \mu_i}\left(1 - e^{-(\lambda_i + \mu_i) T_i}\right)$
	Safety functions with periodical testing do not function	$p_i^{SS} = 1 + \frac{\left(e^{-\lambda_i T_i} - 1\right)}{\lambda_i T_i}$
	For software failures in safety functions	$p_i^{SS} = PFD_i$
	Unavailability due to periodical maintenance of standby equipment where r standby components are involved	$p_i^{SS} = \left(\frac{1/T_i}{1/T_i + \mu_i}\right)^r$

Reliability metric: Generator sets availability

$$A = 1 - U$$

$$U = \sum_{P=1}^{N_P} OP_p \, U_P$$

$$U_P = \prod_{1}^{N_G} U_G$$

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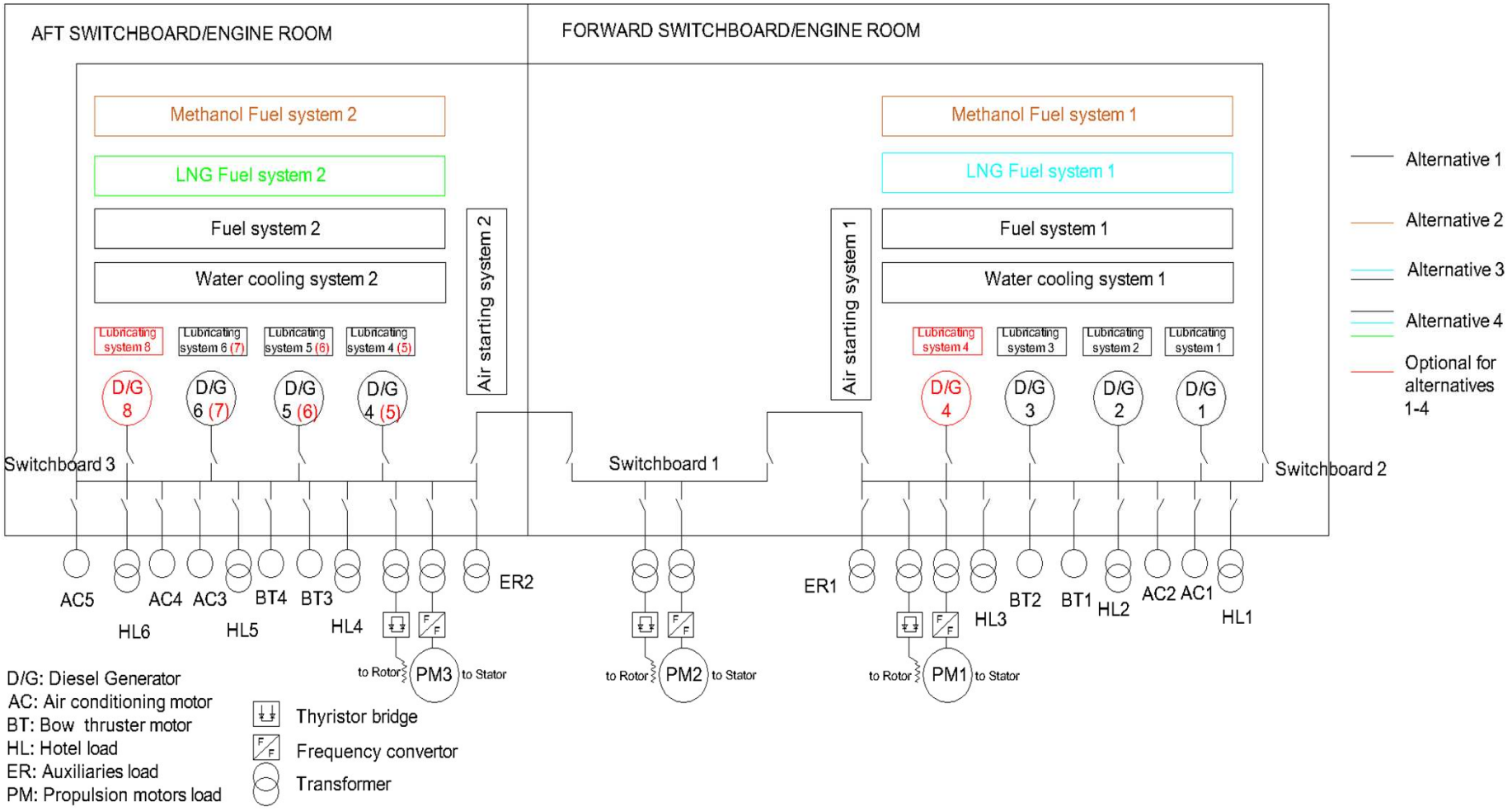
Investigated System

Total installed power: 72 MW



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Investigated Alternatives

Alternatives	Fuel type	Generator sets type	Emission reduction technology
1	HFO or LSHFO	Diesel generator sets	Selective Catalytic Reactor (SCR) and scrubber
2	Methanol & MDO	Dual Fuel generator sets	-
3	HFO & Natural Gas & MDO	Combination of diesel generator sets with dual fuel generator sets	-
4	Natural gas & MDO	Dual Fuel generator sets	-

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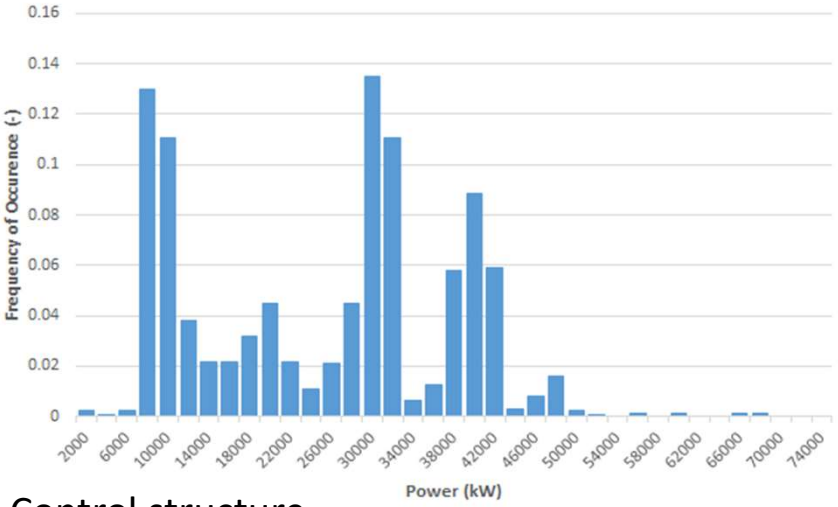
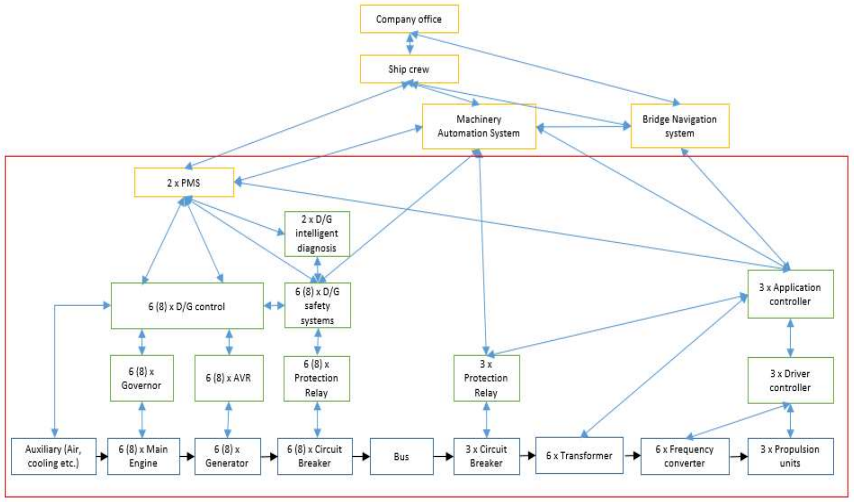
Analysis Input Parameters

Operating profile



Control structure



Equipment type	Capital Cost (€/kW)	Maintenance Costs
D/G Set	490	0.012 (€/kWh)
Dual Fuel Generator Set	740	0.012 (€/kWh)
Scrubber	70	0.395 (€/kg SO_2 removed)
SCR	40	0.006 (€/kWh)

	Price (€/t)	CO_2 emission factor (kg CO_2/ kg fuel)
HFO (IFO 380)	300	3.021
LSHFO (LS380)	350	3.075
LNG	250	2.750

Type of data used for input	Number of used parameters	Example
Design data	50	Number of speed sensors installed on each D/G
Operating data	15	Percentage of type vessel is in sailing mode
Maintenance inspection intervals	29	Testing of circuit breaker capability
Maintenance duration	18	Maintenance duration of each D/G
Failure rates for components	175	The failure rate for PMS hardware

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Input parameters

Estimated parameters
Transformer failure rates
Communication lines failure rates
Sensors failure rates
Sea chest failure rates
Failure rates for fuel system
Failure rates for optical sensors
Faults for shaft sealing system
Fire failure rate in the engine room
Fuel filters failure rate
Generator set and electrical components failure rates
Electrical components failure rates
Software failure
Circuit breaker failures
Failure rates for marine engine pistons
Information on β_i factors of Weibull distributions
Generator set fault tripping due to oil mist detector and control malfunction = 7.38 10^{-6} [h^{-1}]

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Results

Optimal configurations for each alternative

Fuel type	Alternative solutions	Operating profile	1st Engine Type Fuel Emissions reduction technologies Number (-) x Unit Nominal Power	2nd Engine Type Fuel Emissions reduction technologies Number (-) x Unit Nominal Power	Engine rooms layout details
HFO or LSHFO	1	a	D-G sets HFO SCR & Scrubber 4 x 10 MW	D-G sets HFO SCR & Scrubber 4 x 8 MW	Engine room No 1: 2 units for each engine type Engine room No 2: 2 units for each engine type
Methanol & MDO	2	a	DF-G sets Methanol Not included 4 x 11 MW	DF-G sets Methanol Not included 4 x 7 MW	Engine room No 1: 2 units for each engine type Engine room No 2: 2 units for each engine type
HFO & Natural Gas & MDO	3	a	DF-G sets NG (stored in LNG form) Not included 4 x 12 MW	D-G sets LSHFO SCR 2 x 12 MW	Engine room No 1: 2 units of type 1 & 1 unit of type 2 Engine room No 2: 2 units of type 1 & 1 unit of type 2
Natural gas & MDO	4	a	DF-G sets NG (stored in LNG form) Not included 4 x 11 MW	DF-G sets: NG (stored in LNG form) Not included 4 x 7 MW	Engine room No 1: 2 units for each engine type Engine room No 2: 2 units for each engine type
HFO	Baseline	a	D-G sets HFO not included 3 x 12 MW	D-G sets HFO not included 3 x 12 MW	Engine room No 1: 3 units Engine room No 2: 3 units

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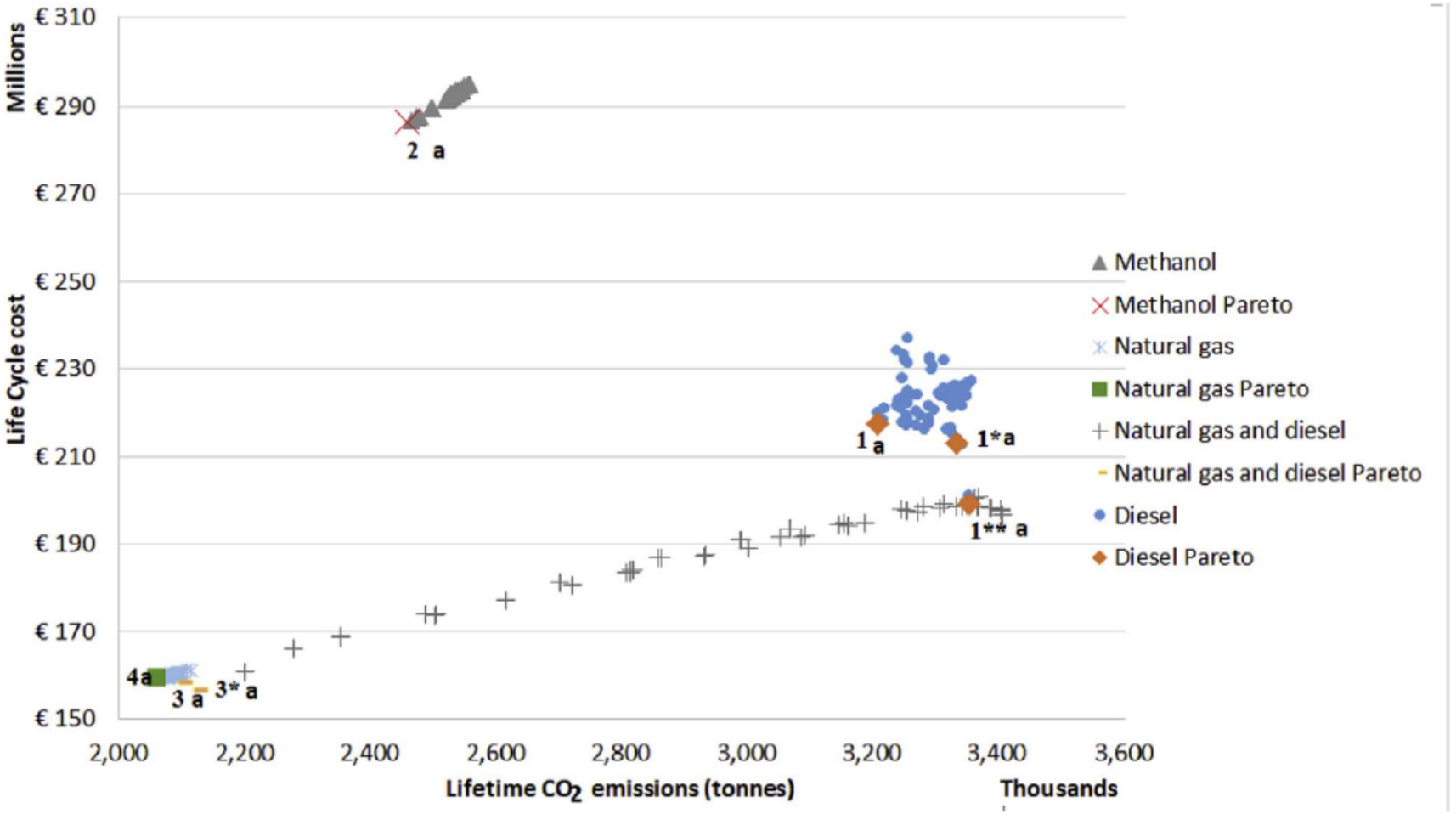
Results

Pareto solutions for the investigated alternatives



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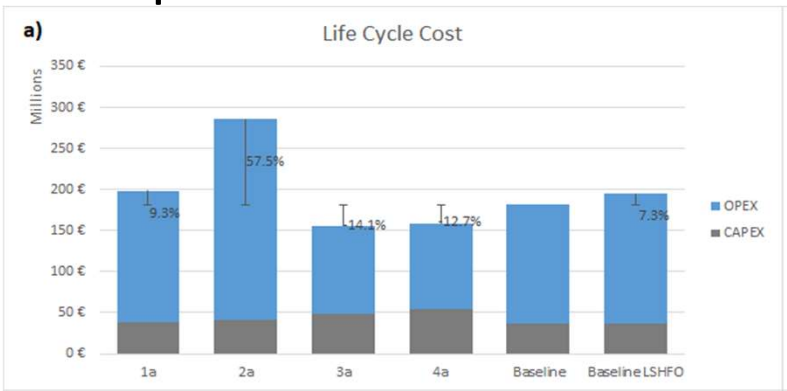
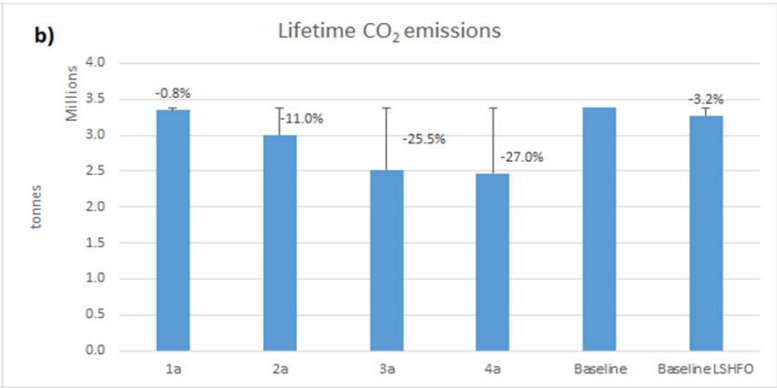
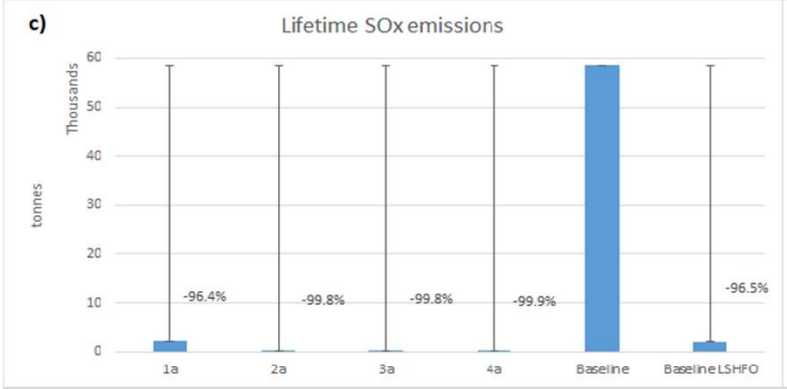
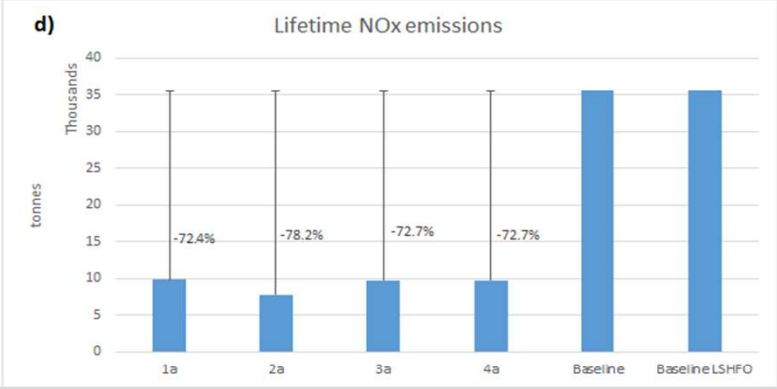
Results

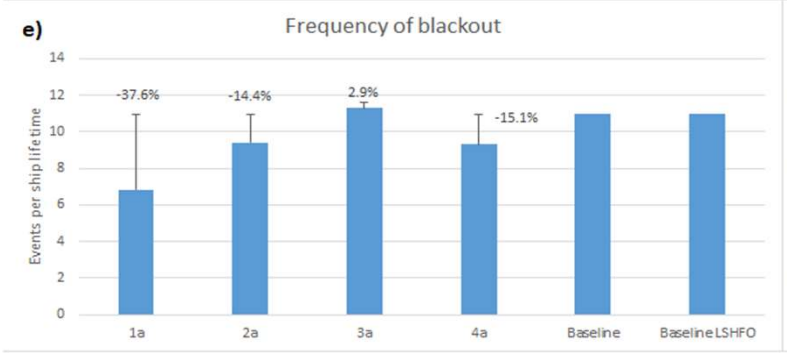
Comparative assessment of alternatives

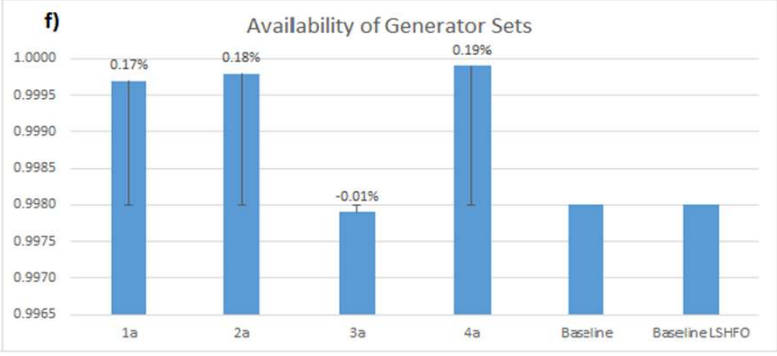












HFO or LSHFO	1a
Methanol & MDO	2a
HFO & Natural Gas & MDO	3a
Natural gas & MDO	4a
HFO	Baseline

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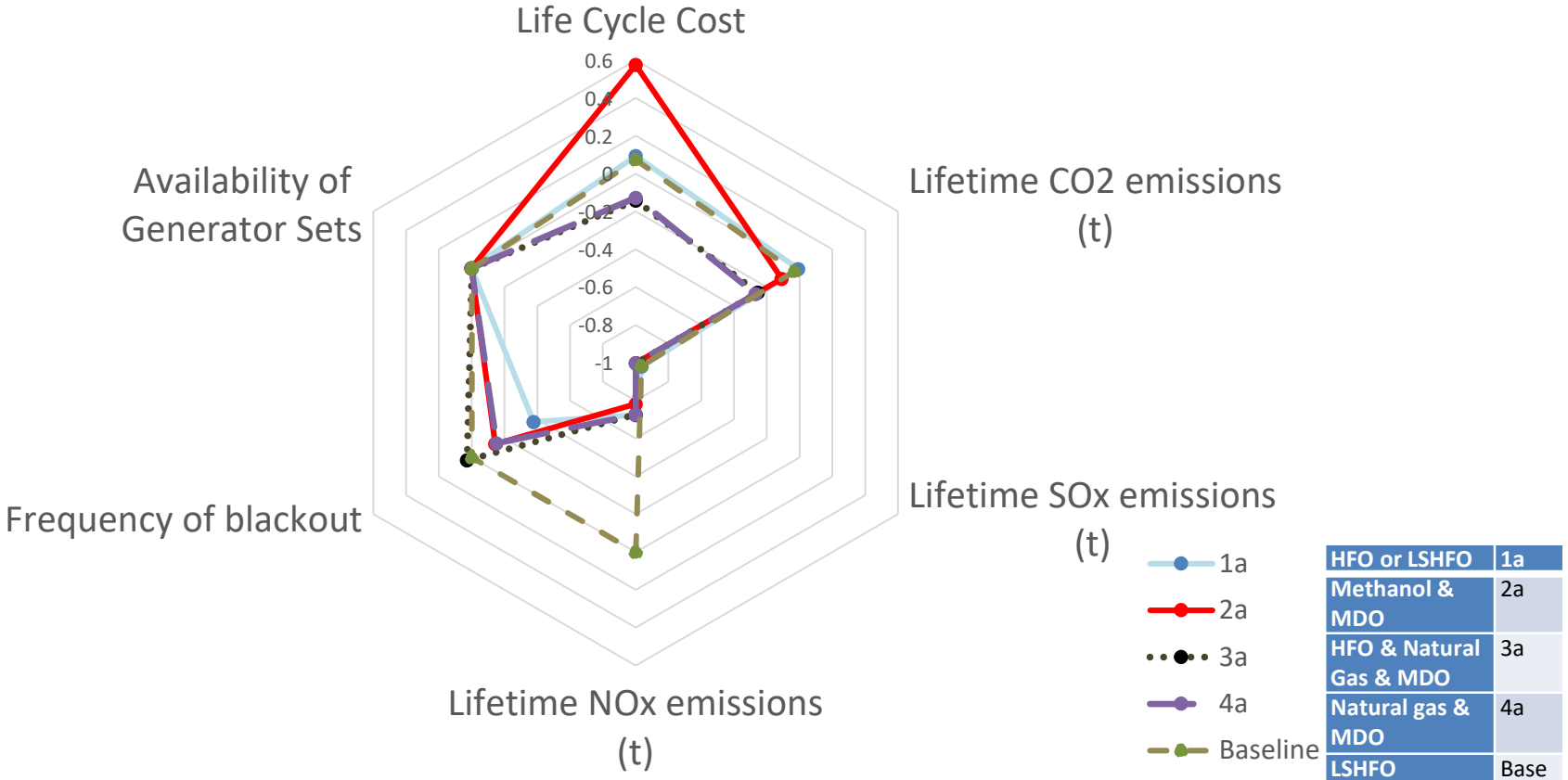
Results

Comparative assessment of alternatives



HFO or LSHFO	1a
Methanol & MDO	2a
HFO & Natural Gas & MDO	3a
Natural gas & MDO	4a
LSHFO	Base line

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Conclusions

- Baseline plant does not satisfy future environmental regulations; new cruise ship power plant designs require alternative solutions
- Operating profile affects G/Ss nominal power without significantly affecting number
- Optimal cruise ship power plant (CO_2 & LCC) does not achieve best safety metrics
- Methanol solutions exhibited reduced emissions and improved safety metrics compared to the baseline, but higher cost (due to methanol price)
- Solutions with DF G/Ss exhibit improved environmental and economic performance without compromising safety – Best alternatives for the future power plants
- Combining DF G/Ss and Diesel G/Ss running on LSHFO performance was close to the best with slightly lower LCC – Also a sufficient solution for future designs
- Operating time the plant runs with one generator set greatly affects FOB – Required as an optimisation objective to reflect the system safety level
- Very high availability due to the increased redundancy – its inclusion as an optimisation objective is not required – Meaningful objective for other ship types
- **Developed approach supports decisions making at the design phase**
- **Valuable tool for optimal design of the cruise and other ships power plants**

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Epilogue

Maritime industry faces huge challenges due to the **explosion in technological developments**, marine systems **complexity**, **big data** and **autonomy**, whilst operating within an environment that becomes increasingly sensitive and a society that grows more and more demanding.

Bold and collaborative initiatives are required to pave the way towards the next generation sustainable marine systems

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