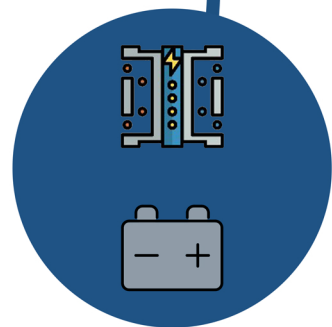
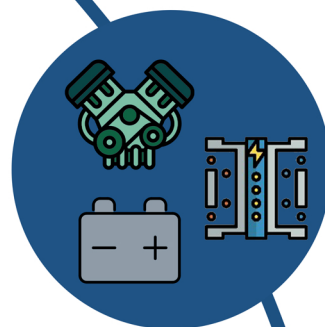
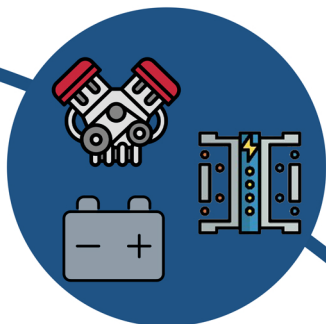
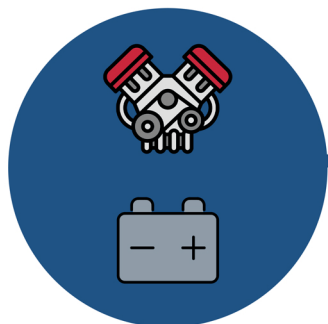


Designing Future-Proof Superyachts

A Methodological Approach towards Zero-Emissions Systems Integration

Steiner Andrea



Designing Future-Proof Superyachts: A Methodological Approach towards Zero-Emissions Systems Integration

by

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ABSTRACT

The maritime industry is progressively transitioning towards sustainable practices, with a significant focus on integrating zero-emission power generation systems. However alternative fuels and technologies implementation on large scale is still pending.

Ships and especially yachts today are designed just for their immediate needs with no future consideration taken into account. This thesis addresses the need for adaptable power room designs in superyachts, facilitating the integration of zero-emission power generation systems as technology evolves. The primary aim is to develop a design method enabling easy retrofitting and future-proofing of yacht power rooms.

The research identifies the current design methods limitation where power rooms are designed for specific scenarios without considering future adaptability. To address this gap, the thesis proposes a three-step design method: layout concepts, design rationale, and a layout evaluation model. This model evaluates power room layouts based on Connection Costs and Retrofit Costs, offering indicators to assess future-proofing capabilities of power rooms arrangements.

A future-proof road-map based on four different scenarios was identified. By applying the design method to these scenarios, various layout concepts were developed, refined based on expert opinions and then evaluated with the model. The results highlight key practices for future-proofing power rooms, such as prioritizing connections between zero emissions power generation systems and auxiliary systems, pre-arranging transport equipment, and designing access openings to facilitate easy retrofitting.

This research underscores the need for a flexible approach to power room design, ensuring superyachts can transition smoothly to zero-emission operations in the coming years.

Keywords: Engine Room retrofit, Design for future-proof, Zero-emission yacht

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I was lucky, I found what I love to do early in life. Since I was a kid I spent hours looking at ships and boats maneuvering at Salerno port. I have always been fascinated by everything that floats and moves across water, and when it came time to decide what to study and what to dedicate my life to, it was not a difficult decision to opt for marine engineering.

As I approach the conclusion of this thesis, I feel it represents a turning point in my life: after the long journey of study and education I began 19 years ago, this thesis marks the end, at least for now, of my formal studies, but, I hope, not of my learning. During this journey, I have met wonderful people who have taught me a lot, both technically and personally. I would like to take this occasion to express my appreciation for those who have helped me become the person I am today.

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CONTENTS

Abstract	i
Acknowledgements	iii
List of Figures	vii
List of Tables	ix
Abbreviations	xi
1 Introduction	1
1.1 Background.....	1
1.2 Research Gap.....	2
1.3 Research Objective	3
1.4 Research question	3
I Literature Review	4
2 Current Power Room and Future Systems	5
2.1 Current Power Plants.....	5
2.1.1 Diesel-Direct Power Plants	5
2.1.2 Diesel-Electric Power Plants	5
2.1.3 Diesel-Batteries Power Plant.....	6
2.2 Systems in a current Power Room	7
2.2.1 Engine Room	9
2.2.2 Battery Room.....	9
2.2.3 Switchboard Room	10
2.3 Current Design Method	10
2.3.1 Engine Room	11
2.3.2 Battery Room.....	12
2.3.3 Switchboard Room	12
2.3.4 Final Considerations on Current Design Method	12
2.4 Future fuels for yachting.....	13
2.5 Methanol.....	13
2.5.1 Methanol Engine	14
2.5.2 Methanol Fuel Cells.....	14
2.6 Auxiliary Systems	16
2.6.1 Auxiliary system for alcoholic ICE.....	17
2.6.2 Auxiliary system for alcoholic FC.....	18
2.7 Conclusion to the chapter	19

3	State-of-the-art of Future-Proofing	20
3.1	Current Retrofit Solutions	20
3.1.1	Retrofit Solutions	20
3.1.2	Applicability to Yachts.....	21
3.2	Current Retrofit Techniques.....	21
3.2.1	Power Room Retrofit Paths	22
3.2.2	Access Opening Options.....	23
3.2.3	Moving Equipment for Retrofit	24
3.3	Future-Proofing Approaches.....	24
3.4	Changeability	25
3.5	Retrofittability	26
3.5.1	Design for Retrofit.....	26
3.5.2	Design for Modularity.....	27
3.6	Versatility	28
3.7	Robustness	29
3.7.1	Robustness for future-proof tanks.....	30
3.7.2	Robustness for future-proof pipes	30
3.8	Conclusion to the Chapter	31
II	Design Method	32
4	Design Method	33
4.1	Purpose of the design method	33
4.1.1	Design Method Steps	33
4.2	Layout Concepts.....	34
4.3	Design Rationale	35
4.3.1	Design Rationale Steps Explanation	36
4.4	Layout Evaluation Model	36
4.4.1	Model Structure	36
4.4.2	Reference systems.....	39
4.5	Retrofit Costs.....	40
4.5.1	Total Transport Factor.....	40
4.5.2	Create Access Factor	42
4.5.3	Versatility Factor.....	45
4.6	Total Connection Costs	46
4.7	Systems designed for Robustness	47
4.8	Practical Example of the Layout Evaluation Model	47
4.8.1	Total Connection Costs for the practical example.....	48
4.8.2	Total Retrofit Costs for the practical example.....	49
III	Method Application and Results	50
5	Scenarios explanation	51
5.1	Systems in the different scenarios	51
5.1.1	Building Blocks dimensions and other data	52
5.2	Scenario 0.....	54
5.3	Scenario 1	55

5.4	Scenario 2	56
5.5	Scenario 3	57
5.6	Connections	58
5.7	Peculiarities of layout design with zero-emission systems	61
5.7.1	Safety Measures and Regulatory Compliance	61
5.7.2	Complexity of Connections	62
6	Method Application	63
6.1	Key Assumptions.....	63
6.1.1	Power Room Dimensions	63
6.1.2	Filling Grade	63
6.1.3	Advancements in Fuel Cell Technologies.....	64
6.1.4	Exclusion of Batteries from the Design Method	64
6.1.5	Switchboards	64
6.2	Layouts concepts	65
6.3	Integrating the Experts' Opinions.....	69
6.3.1	Switchboard Position	70
6.3.2	Empty Side in the Power Room	70
6.3.3	Corridor Design	70
6.3.4	Power Room Directly Accessible via the Tender Garage.....	70
6.3.5	Generators in Transversal Direction.....	71
6.3.6	Structural Issues	71
6.4	Filtered and Refined Layouts	72
7	Results	74
7.1	Total Connection Costs	74
7.2	Moving Equipment	75
7.3	Access Opening Configurations.....	76
7.3.1	Current Power Room Layout - X.0.....	76
7.3.2	No systems on one side of the Power Room- X.3 and X.3.B.....	77
7.3.3	Wider corridor - X.4 and X.4.B.....	77
7.3.4	Wider corridor above one Power Generation System - X.5.....	78
7.4	Total Retrofit Costs	79
7.4.1	From Scenario 0 to Scenario 1.....	79
7.4.2	From Scenario 0 to Scenario 2.....	80
7.4.3	From Scenario 0 to Scenario 3.....	82
7.4.4	From Scenario 1 to Scenario 3.....	82
7.4.5	From Scenario 2 to Scenario 3.....	83
7.4.6	From Scenario 1 to Scenario 2.....	84
7.5	Results summary	85
7.6	Discussion on the Results	87
7.6.1	Accuracy of the results.....	88
8	Validation and Verification	90
8.1	Structural Validation	90
8.2	Performance Validation	92

9 Conclusion and Discussion	95
9.1 Conclusions.....	95
9.1.1 Summary.....	95
9.1.2 Design Guidelines.....	95
9.2 Design Method Limitations.....	96
9.3 Further Research	97
9.3.1 Recommendations for Further Research on Batteries	97
9.3.2 Recommendations for Further Research on Switchboards and Electric Distribution Onboard.....	97
9.3.3 Recommendations for Further Economic Implementation of the Method.....	98
9.4 Personal reflection	98
 References	 100
 Appendices	 114
A Alternative Fuel Engines	114
B Ventilation Calculations and Requirements	115
B.1 Ventilation System with generators.....	115
B.2 Ventilation System with fuel cells	116
B.3 Ventilation results for the different scenarios	116
C Power Room layouts in all scenarios	118
D Results for all possible combinations	128
E Feadship Confidential	136

LIST OF FIGURES

Figure 2.1	Power plant configurations (adapted from Geertsma et al., 2017 and Inal et al., 2022)	6
Figure 2.2	Double vs Single layer engine room	7
Figure 2.3	Double-deck Diesel-Batteries power room layout (adapted from Feadship project 716)	8
Figure 2.4	Design phases (adapted from Mavris and DeLaurentis, 2000)	11
Figure 2.5	Schematic working principle of methanol fuel cells (Siqens GmbH, 2023)	15
Figure 2.6	Development trend of SOFCs power density (adapted from L. Fan et al., 2023 according to Feadship’s suppliers data)	16
Figure 2.7	Wärtsilä MethanolPac system (Wärtsilä, 2023e)	17
Figure 3.1	Different types of AOs	23
Figure 3.2	Rails vs Chain and Tackle for transportation in a PR	24
Figure 3.3	Structure of future-proofing approaches (developed from Coenen et al., 2015, Erikstad and Rehn, 2015, Rehn et al., 2018 and Pruijn, 2023)	25
Figure 4.1	Design Method Steps	34
Figure 4.2	Design Rationale steps applied to the Design Method (adapted from le Poole et al., 2022)	36
Figure 4.3	Structure of the Layout Evaluation Model	37
Figure 4.4	Manhattan versus Euclidean distance (Poullis, 2022)	38
Figure 4.5	Flow chart for methodology decision	39
Figure 4.6	Reference systems used in the model	40
Figure 4.7	External Steel plating position (adapted from Eyres and Bruce, 2012)	44
Figure 4.8	1m ² of PR side (adapted from Feadship 710)	45
Figure 4.9	Practical Example 3D visualization with reference system	48
Figure 4.10	Practical example 3D visualization with connections and AOs	48
Figure 4.11	CM for practical example	49
Figure 5.1	Systems involved in the different scenarios	51
Figure 5.2	Flow diagram for Scenario 0	55
Figure 5.3	Flow diagram for Scenario 1	56
Figure 5.4	Flow diagram for Scenario 2	57
Figure 5.5	Flow diagram for Scenario 3	57
Figure 5.6	Connection Matrices for the different scenarios	60
Figure 6.1	Current double layer PR - Layout 0.1	66
Figure 6.2	Layouts with no components on one side of the PR	67
Figure 6.3	Layouts with wider corridors	68
Figure 6.4	Layouts with the PR directly accessible via the TG	68
Figure 6.5	Layouts X.8 - PGSs rotated in transversal direction	69

Figure 6.6	Layouts 1.4 vs 1.4.B - No systems on one side of the PR.....	73
Figure 7.1	Total Connection Costs results.....	74
Figure 7.2	TRC comparison between the different moving equipment options	75
Figure 7.3	Layout 0.1 with possible AO configurations	76
Figure 7.4	Layout 0.4 with possible AO configurations	78
Figure 7.5	Total Retrofit Costs from Scenario 0 to Scenario 1	79
Figure 7.6	Impact of the different retrofit factors from Scenario 0 to 1	80
Figure 7.7	Total Retrofit Costs from Scenario 0 to Scenario 2 showing only C&T installed ...	81
Figure 7.8	Impact of the different retrofit factors from Scenario 0 to 2	81
Figure 7.9	Total Retrofit Costs from Scenario 0 to Scenario 3 showing only C&T installed ...	82
Figure 7.10	Total Retrofit Costs from Scenario 1 to Scenario 3 showing only C&T installed ...	83
Figure 7.11	Total Retrofit Costs from Scenario 2 to Scenario 3 showing only C&T installed ...	83
Figure 7.12	Total Retrofit Costs from Scenario 1 to Scenario 2 showing only C&T installed ...	84
Figure 7.13	Impact of the different retrofit factors from Scenario 1 to 2	85
Figure 7.14	TCC vs TRC for vessel not in dry-dock with AO already present.....	87
Figure 7.15	TCC vs TRC for vessel not in dry-dock with AO already present for Scenario from 0 to 1 with error bars	89
Figure 8.1	Design method validation by using the Validation Square (Pedersen et al., 2000).	90
Figure 8.2	Yacht Sport ER block layout (adapted from Feadship’s project 796).....	93
Figure 8.3	Sport’s TG showing the bulkheads AO and the way out (adapted from Edmiston, 2024).....	93
Figure C.1	Layout X.1 - Based on the current PR.....	118
Figure C.2	Layout X.2 - No switchboard on the aft of the PR	119
Figure C.3	Layout X.3 - No systems on one side of the PR.....	120
Figure C.4	Layout X.3.B - No systems on one side of the PR - FC on the upper deck	121
Figure C.5	Layout X.4 - Central wider corridor.....	122
Figure C.6	Layout X.4.B - Central wider corridor - FC on the upper deck.....	123
Figure C.7	Layout X.6 - TG close to the PR.....	124
Figure C.8	Layout X.7 - TG above the PR	125
Figure C.9	Layout X.8 - PGSs rotated in transversal direction.....	126
Figure C.10	Single layer tank deck PR layout	127
Figure C.11	Current single layer PR layout	127
Figure D.1	Total Retrofit Costs from Scenario 0 to Scenario 1	128
Figure D.2	Total Retrofit Costs from Scenario 0 to Scenario 2	129
Figure D.3	Total Retrofit Costs from Scenario 0 to Scenario 3	130
Figure D.4	Total Retrofit Costs from Scenario 1 to Scenario 3	131
Figure D.5	Total Retrofit Costs from Scenario 2 to Scenario 3	132
Figure D.6	Total Retrofit Costs from Scenario 1 to Scenario 2	133
Figure D.7	Total Retrofit Costs from Scenario 1 to Scenario 2	134
Figure D.8	Total Retrofit Costs from Scenario 1 to Scenario 2	135

LIST OF TABLES

1.1	Future-proof scenarios	2
2.1	Systems and related BBs in a current Diesel-Batteries ER (adapted from Feadship 710).	8
2.2	Technical characteristics of different types of fuel (Harmsen, 2021 and 't Hart et al., 2023)	13
2.3	Characteristics of various Methanol engines (adapted from Karvounis et al., 2023 and Wouters et al., 2023)	14
2.4	Comparison of fuel cells technologies (adapted from Tronstad et al., 2017)	16
3.1	Current Retrofit Solutions	20
3.2	Retrofit solutions vs their main cons	21
3.3	Comparison of different ways to take systems in and out of an Engine Room (adapted from Whitehaven, 2021 and Coenen et al., 2015)	22
3.4	Access Openings types.....	23
3.5	Moving equipment for retrofit (adapted from MAN ES, 2020, Zhongyuan, 2022 and WinGD, 2023a)	24
3.6	Modular Retrofittable Engine Room Concepts	28
3.7	Dual Fuel Ships	29
3.8	Future-Proof Approaches vs Scenarios.....	31
4.1	Inputs to the layout evaluation model	37
4.2	Steel works in man-hours per tonne (Butler, 2013)	43
4.3	Correction factor for AO position (adapted from Butler, 2013)	44
4.4	Pipes, Ducts and Cables densities (ρ) on the different walls of the PR	45
4.5	Engine VF from Diesel to DF (developed in accordance with Lloyd's Register, 2023)	46
4.6	Practical example BBs' dimensions and positions	47
4.7	I/O positions for practical example BBs	49
4.8	AOs characteristics for the practical example	49
5.1	Average Feadship characteristics	51
5.2	Subsystems involved in the different scenarios	52
5.3	Main data for generators	53
5.4	Main data for Fuel Cells	53
5.5	Auxiliary systems BBs dimensions	54
5.6	Interfaces between the different systems	59
5.7	Weight connection factors (adapted from Poullis, 2022).....	60
5.8	Input and output position referred to the different BBs.....	61
6.1	Single vs Double layer PR main dimensions for an average Feadship.....	63
6.2	Switchboards dimension on average Feadship (adapted from ABB, 2020 and ABB, 2011)	65
6.3	Building blocks color legend.....	65
6.4	Design Rationale	71

7.1	Possible AO configurations for layouts X.1.....	77
7.2	Possible AO configurations for layouts X.4 and X.4.B.....	78
7.3	Best layouts and AO configurations and relative TRC for the different future-proof pathways - without the need to bring the vessel to dry-dock.....	85
7.4	Best layouts and AO configurations and relative TRC for the different future-proof pathways - accepting the vessel to go to dry-dock.....	86
A.1	Dual Fuel Engines.....	114
B.1	Ventilation requirements in the different scenarios	116

ABBREVIATIONS

AC Alternating Current.

AFFF Aqueous Film-Forming Foam.

AiP Approval in Principle.

AO Access Opening.

ARAFFF Alcohol Resistant Aqueous Film-Forming Foam.

BB Building Block.

BR Battery Room.

C&T Chain and tackle.

CAF Create Access Factor.

CAP Create Access Penalty.

CM Connection Matrix.

DC Direct Current.

DF Dual Fuel.

DI Direct Injection.

DMFC Direct Methanol Fuel Cell.

DPF Diesel Particulate Filter.

EGATS Exhaust Gas After Treatment System.

EMS Energy Management System.

EMSA European Maritime Safety Agency.

EoH Ease of Handling.

ER Engine Room.

ESS Energy Storage System.

FC Fuel Cell.

FG Filling Grade.

FPS Fuel Preparation Space.

GT Gross Tonnage.

HP High Pressure.

HT High Temperature.

HVAC Heating, Ventilation, and Air Conditioning.

ICE Internal Combustion Engine.

LFP Low Flash Point.

LHV Lower Heating Value.

LNG Liquefied Natural Gas.

LOA Length Over All.

LT Low Temperature.

PEM FC Proton Exchange Membrane Fuel Cell.

PFI Port Fuel Injection.

PGS Power Generation System.

PM Particulate Matter.

PR Power Room.

RMFC Reformed Methanol Fuel Cell.

RPI Retrofit Penalty Indicator.

SCR Selective Catalytic Reduction.

SI Spark Ignition.

SOFC Solid Oxide Fuel Cell.

SR Switchboard Room.

TCC Total Connection Cost.

TCO Total Cost of Ownership.

TG Tender Garage.

TRC Total Retrofit Cost.

TTF Total Transport Factor.

TTP Total Transport Penalty.

VF Versatility Factor.

WHRS Waste Heat Recovery System.

YETI Yacht Environmental Transparency Index.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN WRITING

During the preparation of this work the author used ChatGPT and Google Gemini in order to enhance the quality of the English text. After using these tools and services, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

1. INTRODUCTION

1.1. BACKGROUND

Over the past decade, the shipping industry has faced significant pressure to reduce its environmental performance, particularly in light of the International Maritime Organization’s goals to cut greenhouse gas emissions by 20% by 2030 and by 70% by 2040 relative to 2008 levels (International Maritime Organization, 2023a). These ambitious objectives have led to a growing interest in exploring alternative fuels and energy systems that can provide a more sustainable performance for ships and yachts.

Shipping contributes around 3% to global greenhouse gas emissions, with the yacht fleet responsible for just 0.4% of this total (Odendaal, 2021). While this proportion may appear negligible, a different framing can reveal the significant environmental impact of yachts. In 2019, emissions from the biggest 300 yachts alone amounted to 2.8×10^8 kg/CO₂-Eq, equivalent to the emissions of 10.6 million inhabitants of Burundi (Lynch et al., 2019). Additionally, besides greenhouse gases, yachts also generate substantial local environmental impact in the areas they operate due to emissions of harmful pollutants like SO_x, NO_x and particulate matter (PM)(Bergqvist et al., 2015).

Increasing social pressure on yacht owners, coupled with initiatives like the Yacht Environmental Transparency Index (YETI) are driving the industry towards more sustainable practices (Mallet, 2022). Given the yachting sector’s historical reputation for innovation within the maritime industry, advancements in this domain are expected to influence broader changes across the maritime sector (de Figueiredo, 2018). This thesis will be developed in collaboration with Feadship, a market leader reality building pure custom yachts in the range from 50m to 120m, standing out for its commitment to innovation and sustainability (Feadship, 2023a).

Although in recent years there has been growing exploration of alternative fuels and technologies for potential integration into the shipping industry, their implementation on a large scale is still pending (DNV, 2023). For the yachting sector, alcoholic fuels alongside bio-diesel are the preferred option (La Colla, 2023); while among the various energy converters, fuel cells and internal combustion engines emerge as prominent contenders for yachts, each with distinct advantages. The former promises reduced noise, higher efficiency, and no local pollution (van Biert et al., 2016), while the latter offers a more compact size and lower costs (Baccioli et al., 2021).

Given this adaptable approach, major stakeholders have developed a future-proof roadmap that focuses on three scenarios, summarized in Table 1.1 (Feadship, 2022, Oceanco, 2022, Lateral Naval Architects, 2023 and Sanlorenzo, 2023). The challenge lies in replacing current power generation systems with new technologies powered by alternative fuels, thus potentially net-zero emissions.

The current design method employed by the yachting industry proves to be complex and costly for retrofitting superyachts with new technologies (Boote et al., 2012), as it only focuses on immediate design requirements and future retrofit is not taken into consideration (Bouyssou et al., 2023). The absence of a dedicated design approach for future-proofing yachts introduces complexity when contemplating future retrofits in various scenarios involving the adoption of new fuel systems and the replacement or retrofitting of diesel ICEs with alternative fuel engines, or even the integration of FCs.

Table 1.1: Future-proof scenarios

#	Scenario	Propulsion power	Hotel load	No noise and vibration	Technology readiness
0	Diesel ICEs + Batteries	Diesel ICEs + Batteries	Diesel ICEs + Batteries	Batteries Only	Already applied
1	Diesel ICEs + Fuel cells + Batteries	Diesel ICEs + Batteries	Fuel cells + Batteries	Hotel Load Only	Short-term
2	Alternative fuel ICEs + Fuel cells + Batteries	Alternative fuel ICEs + Batteries	Fuel cells + Batteries	Hotel Load Only	Short-term
3	Fuel Cells + Batteries	Fuel Cells + Batteries	Fuel Cells + Batteries	Always	Mid-term

It is worth noting that it is difficult to determine if the yacht will truly achieve net-zero emissions. While the power generation systems can produce no harmful local emissions, the overall impact on global warming will depend on the fuel production chain. Therefore, achieving a completely net-zero emission yacht ultimately relies on the owner’s choices when purchasing fuels. However, for the purposes of this thesis, a “zero-emission” yacht will be defined as one equipped with power generation systems that, given an appropriate fuel production chain, can achieve net-zero emissions.

Feadship, [2022](#) anticipates these technologies will meet superyachts’ entire energy demand within a decade, requiring retrofitting of existing vessels. The cost-effective and efficient retrofit of superyachts necessitates careful consideration of various factors during the design and construction process. According to industry experts (Ingram, [2023](#), Velema, [2022](#) and Posthuma de Boer and Loeff, [2024](#)), key aspects to be taken into account include:

1. Assessment of current and future power systems: it is particularly important to investigate current and future power generation systems as well as their requirements in terms of safe and efficient operation.
2. Pre-arrangement: Determining influential factors for pre-arrangement involving a strategic layout and infrastructure plan to accommodate future retrofit needs. This means considering factors such as available space, route in and out of the engine room and moving equipment placement.
3. Future regulations for new technologies: Anticipating and complying with regulations related to the adoption of new technologies, is crucial. Staying ahead of evolving industry standards and regulatory frameworks ensures the superyacht is designed with future compliance in mind.

1.2. RESEARCH GAP

The current state of the superyacht industry reveals a significant research gap in the design method for the integration of zero-emission systems during future retrofits. Presently, superyachts are designed to meet immediate operational needs without strategic considerations regarding future technological advancements and regulatory changes aiming at making the industry more sustainable. This short-term approach complicates the retrofit process, making it costly and inefficient. There is a lack of a design method taking into account future-proof considerations, ensuring yachts can be easily retrofitted with new technologies as they become available. Existing design methods do not allow for easy transition between different power generation systems, which is instead crucial for adapting to future technologies.

1.3. RESEARCH OBJECTIVE

This thesis aims to develop a design method addressing this gap in superyacht industry practices, specifically focusing on enabling efficient retrofitting with zero-emission systems over the next decade. This method will be drawn from the analysis of current challenges and future opportunities, integrating them into the design phases, and considering upcoming technological advancements. The objective is to ensure that superyachts constructed today are adaptable and ready for cost-effective and environmentally friendly zero-emission system retrofits in the future, aligning with industry decarbonization goals.

1.4. RESEARCH QUESTION

To achieve this, a main research question and several subquestions are posed. All these questions will guide the development of subsequent chapters. The main research question this Master's thesis will answer is:

How can a future-proof engine room, that facilitates the integration of zero-emission systems during future retrofit of superyachts, be designed?

As anticipated, to answer the main research question, multiple sub-questions have been formulated:

1. *What is the current state-of-the-art of engine rooms onboard yachts and what are the projected future power systems that can serve as zero-emission solutions for superyachts - Chapter 2*
2. *What are the currently employed retrofitting techniques and what innovative approaches can be proposed to advance the retrofit process for superyachts and enable seamless integration of zero-emission systems? - Chapter 3*
3. *How can a systematic design method be developed to address the challenges of integrating future power systems while ensuring practicality in the design process? - Chapter 4*
4. *How do different scenarios, varying in terms of power system configurations and integration complexities, impact the layout and design considerations of power rooms in superyachts? — Chapter 5*
5. *How can the proposed design method be practically applied to evaluate multiple power room layouts tailored to specific yacht scenarios? - Chapter 6*
6. *What insights and conclusions can be drawn from the analysis of the evaluated power room layouts in terms of their feasibility, effectiveness in accommodating zero-emission systems, and potential implications for the future design and retrofitting of superyachts? - Chapter 7*
7. *How can the validity and reliability of the proposed design method be assessed through validation and verification processes, ensuring it accurately represents real-world conditions and effectively addresses the challenges of retrofitting superyachts with zero-emission systems? - Chapter 8*

By addressing these subquestions, this research aims to develop an understanding of the challenges, opportunities, and design considerations related to retrofit superyachts with zero-emission systems. The answers to these subquestions will form the basis for creating a design method that enables the integration of future power systems while aligning with the industry's commitment to emissions reduction and sustainability.

Part I

Literature Review

2. CURRENT POWER ROOM AND FUTURE SYSTEMS

To gain insights into the potential configuration of a future power room aboard a yacht, an analysis of the structure and design of contemporary power rooms on board yachts and future power generation systems will be performed, therefore addressing the first subquestion of the thesis: “*What is the current state-of-the-art of engine rooms onboard yachts and what are the projected future power systems that can serve as zero-emission solutions for superyachts*”.

This chapter will give an overview of power plants commonly found aboard yachts in section 2.1. Subsequently, the focus will shift to Diesel-Batteries power plants, taken as starting point for this thesis. An analysis and a classification of the systems present in a current Diesel-Batteries power room will be drawn based on spatial allocation with a description of the main systems and components. For the purpose of this thesis, all areas with systems part of the power plant will be referred to as the “Power Room”. Then, in section 2.3, the current design method of these areas will be described, before delving in section 2.4 - 2.6 into an analysis of new power generation systems and their requirements specifically in terms of auxiliary systems.

2.1. CURRENT POWER PLANTS

There are currently more than 10800 yachts afloat in the world which are diverse from each other (SuperYacht Times, 2023), however they all feature three main power plant options shown in Figure 2.1:

1. Diesel-Direct
2. Diesel-Electric
3. Diesel-Batteries

2.1.1. Diesel-Direct Power Plants

The Diesel-Direct power plant is the most traditional configuration, used in the yachting industry for over a century (Kalinina, 2021). As shown in Figure 2.1a, this plant involves a diesel engine directly connected to a propeller through a shaftline, and a gearbox for four-stroke engines. The main advantages are its simplicity, low cost, and reduced maintenance compared to the other two systems (Lean-Vercoe, 2015).

However, Diesel-Direct power plant have significant drawbacks, particularly space utilization. The engine’s direct connection to the propeller forces its placement near the stern (Klein Woud & Stapersma, 2008), and the tilted shaftlines often require the engine room to span over two decks (Lean-Vercoe, 2015). This spatial requirement can constrain the vessel’s layout and reduce available space.

2.1.2. Diesel-Electric Power Plants

Diesel-Electric power plants have been in use since the early 20th century, with a significant resurgence in the late 1980s (Brusso & Dev, 2020). In this configuration, diesel generators produce power converted into electricity for propulsion and hotel loads (Hansen & Wendt, 2015). The flexibility of this power plant allows the engine room to be placed away from the propellers, optimizing space usage and

potentially allowing for a single layer engine room which, as illustrated in Figure 2.2 guarantees an upper deck entirely dedicated to guests (Lean-Vercoe, 2015).

Despite these advantages, Diesel-Electric systems are more complex and have higher initial costs than Diesel-Direct systems. Their complexity can also lead to increased maintenance requirements and potential reliability issues, especially for the electrical components (Abma et al., 2018).

2.1.3. Diesel-Batteries Power Plant

Diesel-Batteries combine diesel generators and battery systems as sources of power (Chin et al., 2022). These systems can operate individually or in combination, providing flexibility and efficiency. Diesel-Batteries systems have been significantly developed over the past decade and are now considered the cutting edge in yacht power plants.

According to Inal et al., 2022, Diesel-Batteries power plant can be considered an hybrid power plant, particularly called series hybrid. However, for the purpose of this thesis as hybrid power plants are intended those power plants with hybrid drives (both mechanical and electrical), that in Inal et al., 2022's work have been called parallel and series-parallel hybrid power plants. The series hybrid power plant, shown in Figure 2.1c, will be called Diesel-Batteries power plant. In this power plant, the electric motor always drives the propeller, with power supplied by either a generator set or an energy storage system. It is similar to the Diesel-Electric one but it features also one or more energy storage systems (Kolodziejcki & Michalska-Pozoga, 2023).

Diesel-Batteries systems offer several advantages, including the ability to operate silently on battery power alone for short distances or while at anchor (Overton, 2022b), reducing emissions and noise. However, this configuration still relies on diesel generators, meaning it is not an entirely zero-emission solution.

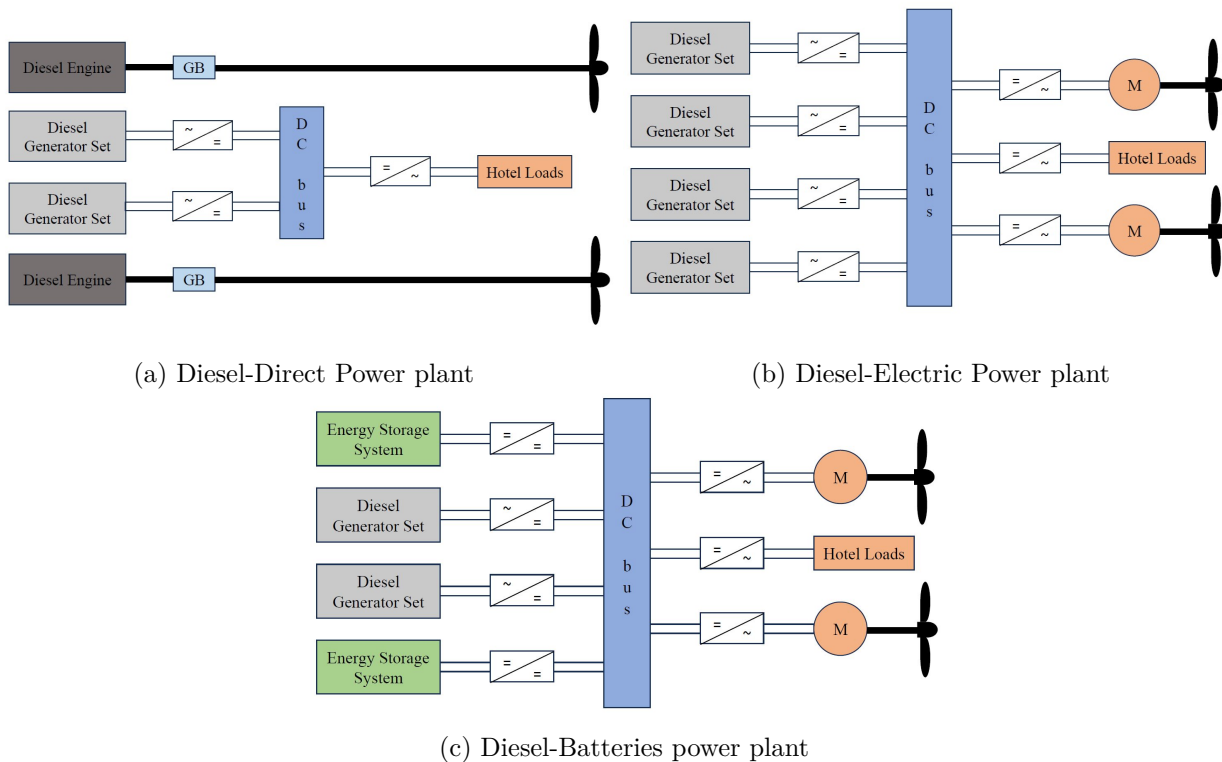
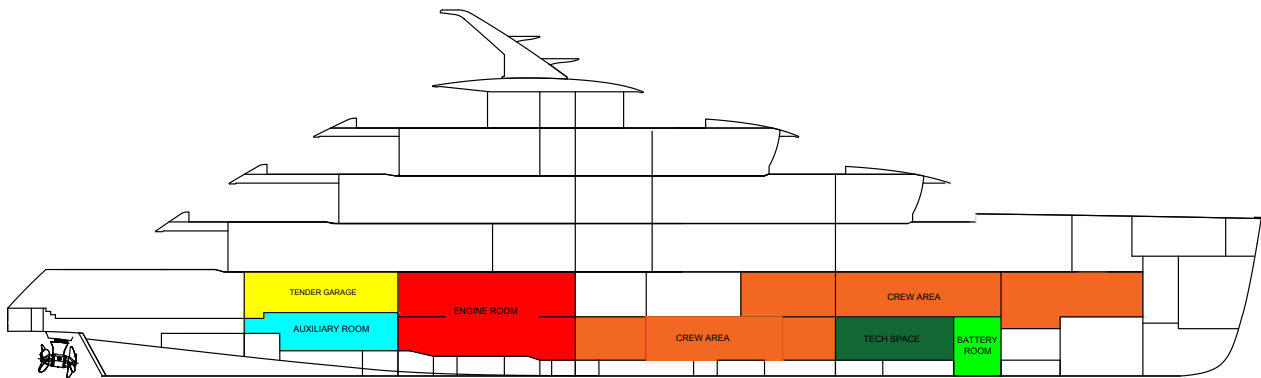
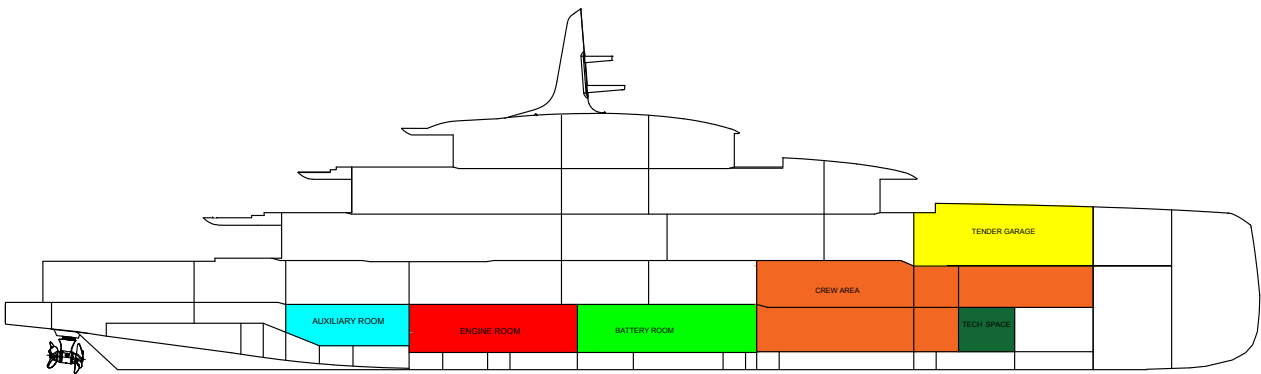


Figure 2.1: Power plant configurations (adapted from Geertsma et al., 2017 and Inal et al., 2022)



(a) Double layer engine room (adapted from Feadship project 716)



(b) Single layer engine room (adapted from Feadship project 710)

Figure 2.2: Double vs Single layer engine room

The direction the yachting industry has undertaken is the Diesel-Batteries power plant (Bottino, 2020) which will therefore be taken as starting point for this thesis. The insights gained in this section lead to specific requirements for the design method that will be developed. The method will need to address the absence of zero-emission power plant onboard yachts. Thus, it will need to facilitate the integration of hybrid power plants that can be easily converted to incorporate future zero-emission technologies. Additionally, the method will address the spatial requirements and flexibility of different power plant configurations, with a focus on accommodating hybrid systems today and zero-emission systems during future retrofits.

2.2. SYSTEMS IN A CURRENT POWER ROOM

A Diesel-Batteries power plant involves many varied systems. Lot of them, due to regulatory requirements and space limitations, are not allocated within the confines of the actual engine room but in adjacent, segregated spaces, as shown in Figure 2.2 and 2.3. The location of these spaces differs a lot based on the complexity of the power plant, and on the hull shapes (Klein Woud & Stapersma, 2008).

Figure 2.3 reports the most relevant areas of a Diesel-Batteries yacht on the tank and lower decks. Among them, this thesis will focus specifically on the spaces related to power plant, thus on rooms hosting power generation systems (PGS), energy storage systems (ESS) and energy management systems (EMS). These rooms are specifically the engine room (ER - red in the figure), the switchboard rooms (SR - grey in the figure) and the battery room (BR - green in the figure).

As it can be noticed from Figure 2.3, there are many other areas on the same decks of the ones just described. However, these areas usually host systems that are not related to propulsion and to power plant but rather systems relevant for the hotel features of the yacht. For the purpose of this thesis, which focuses on yacht future-proofing, it will be assumed that these areas will not change across the scenarios presented in Table 1.1 and therefore will not be addressed.



Figure 2.3: Double-deck Diesel-Batteries power room layout (adapted from Feadship project 716)

The components outlined in the three areas treated in this thesis (Engine, Battery and Switchboard rooms) onboard a Diesel-Batteries yacht are reported in Table 2.1. These components are part of bigger systems and for the purpose of this thesis they have been grouped in Building Blocks (BBs). Specifically, 16 BB types have been identified, 12 of them in the ER and then the AC-DC and DC-DC switchboards in the switchboard room and the batteries with their dedicated ventilation system in the battery room.

Table 2.1: Systems and related BBs in a current Diesel-Batteries ER (adapted from Feadship 710)

NR	Building Block	NR	System	NR	Building Block	NR	System
4	Generator	4	Generator	2	Seawater cooling system	2	Seawater Pump LT
4	SCR+ DPF	4	Exhaust SCR	1	HT Cooling System	1	Sea inlet Crossover
		4	Exhaust DPF	3		Seawater pump	
1	Diesel Supply	4	Fuel oil pump soot filter	1		Heat Exchanger	
		4	Fuel supply unit soot filter	2	Circulating Pump HT		
		4	Fuel oil pre-filter	1	Pressure Vessel HT System		
		1	Fuel oil overflow tank	1	Heat Exchanger		
1	Diesel Transfer	1	Fuel oil transfer pump	1	Electric Water Heater		
		1	Fuel oil feed pump	1	Fresh water Skid		
		1	Fuel oil separator	1	Fresh water pre filter		
		1	Fuel oil filler feed pump	1	Watermaker unit Duplex		
		1	Manual fuel oil pump	4	Watermaker pump		
		1	Fuel oil Manifold	2	Fresh water manifold		
		1	Fuel oil FNV filter	2	Fresh water pump		
1	Oil Lubrication	1	Fuel counter	2	ER ventilation fan		
		1	Clean lubrication oil pump	2	Fan frequency drive		
		1	Dirty lubrication oil pump	1	Diesel Bunkering		
		1	Clean lubricating oil tank	1	Bunker Station		
1	LT Cooling System	1	Clean lubricating oil pistol	12	AC- DC Switchboards		
		1	Dirty lub oil suction hose	28	DC- DC Switchboards		
1	LT Cooling System	1	Heat Exchanger	2	Batteries		
		2	Circulating Pump LT	2	Battery Rack		
2	Ventilation system	2	BR ventilation fan	2	Ventilation system	2	Fan frequency drive

2.2.1. Engine Room

The most relevant area of Figure 2.3 is the engine room, where the power generation and its support systems are located. Here, pivotal systems are the power generation ones with the auxiliary systems needed to guarantee efficient and safe operation of the former ones:

- Generators: nowadays they are commonly diesel driven and used to generate electrical power both for thrusters and hotel service (Geertsma et al., 2017).
- Ventilation system: it serves to ensure an adequate supply of oxygen for fuel combustion and to facilitate the dissipation of heat emitted by the engines to maintain a temperature equilibrium within the ER (Heinen & Hopman, 2022).
- Exhaust Gas After Treatment System (EGATS): consists in a Selective Catalytic Reduction (SCR) and Diesel Particulate Filter (DPF) (Nicholls, 2020). It deals directly with the exhaust from the generators with the former component relying on catalysis for NO_x reduction (Cheng & Bi, 2014) and the latter on a high particulate matter trapping effectiveness used to control the PM emissions (Vora et al., 2020).
- Fuel System: it groups two BBs (Diesel Supply and Diesel Transfer) that are responsible for supplying fuel to generators and transferring fuel to different tanks (Klein Woud & Stapersma, 2016). On superyachts, it is placed in the ER to contain the strong odors emitted, without facing regulatory limitations for this arrangement.
- Lubrication Oil System: it is responsible for lubricating bearings, gears and cylinders allowing the generators to work properly (Klein Woud & Stapersma, 2016).
- Water Cooling System: it is composed of three BBs (LT, HT and seawater cooling). Operating at different temperatures and with multiple heat exchangers, this system refrigerates combustion air, oil lubrication and cools down generators parts (Klein Woud & Stapersma, 2016).
- Waste Heat Recovery System (WHRS): it uses heat created by other systems such as generators to produce power or heat other components. It exists in various types but the most used onboard yachts is the HT Water Cooling WHRS in which the HT water is driven through heat exchangers that provide heat to other consumers after cooling down generators (Singh & Pedersen, 2016).

2.2.2. Battery Room

The Battery Room is the area of the Diesel-Batteries power plant that is home to the Energy Storage Systems (ESSs). This system can be based on different technologies but nowadays the most used one for maritime application are Li-ion batteries, that offer high energy density and relatively low costs (Georgescu et al., 2018 and Amir et al., 2023). That is why this area is usually called “Battery Room”. Other ESSs such as supercapacitors and flywheels are not considered for the purpose of this thesis due to their lower energy density and higher costs (Z. Zhou et al., 2013 and Mutarraf et al., 2018). Batteries produce DC current that has to be used via DC-DC switchboards (Verma & Kumar, 2021). As shown in Table 2.1, besides battery racks, this area accommodates just a ventilation system with an exhaust and a supply fan to guarantee the proper and safe condition for this system to operate.

As illustrated in Figure 2.3, this area is separate from the effective Engine Room, due to the combustibility of current batteries that for safety reason can not be allocated in the ER. However, considering the advancements in batteries technology, in the future batteries combustibility can not represent an issue anymore allowing to place batteries into the Engine Room or decentralized in the yacht. This will be later explained in subsection 6.1.4 and subsection 9.3.1

2.2.3. Switchboard Room

The switchboard room is the area of the vessel where the Energy Management System (EMS) is located. This system is mainly composed by AC and DC switchboards which are directly supplied by the distinct sources of electrical power and are intended to distribute electrical energy to the ship service (Wärtsilä, 2023b).

The EMS manages all power sources in relation to energy requirements from the different loads (Rathor & Saxena, 2020). It is the effective intelligent core of the Diesel-Batteries power plant (Kanellos, 2014), and it has a great impact on fuel consumption, dynamic performance and service life of the power sources (generators and ESSs) (Han et al., 2014). Therefore, it also addresses operation cost minimization and emission reduction (Accetta & Pucci, 2019).

2.3. CURRENT DESIGN METHOD

As mentioned in the previous section, in a current Diesel-Batteries powered yacht the most important technical spaces are the engine room, the battery room and the switchboard room. These areas must be designed with accuracy since each one of them has requirements and characteristics that must be taken into consideration during all design phases. The design phases employed by Feadship (Odendaal, 2021) are the same ones presented by Ni and Zeng, 2019:

1. **Concept Design:** at this stage, owner requirements are translated into naval architecture and engineering components. The main features of the vessel are proposed and the most relevant systems are taken into account while the internal layout, also of technical spaces, is usually proposed with a block disposition. This step relies on standards and generic guidelines that can differ depending on the ship type. For full-custom yachts such as Feadship ones, these guidelines are very generic as the client requirements and perspective are the real driving aspects of the design.
2. **Preliminary Design:** in this phase the exact dimensions and properties of the yacht are established. This involves defining the power requirements and drafting general arrangements, including the technical spaces. The engine room, battery room, and switchboard room layouts drafts are created ensuring all components are appropriately allocated, meeting both functional and spatial requirements.
3. **Contract Design:** this stage ends with a signed project between the owner and the yard. At this point, the general arrangement with all systems the vessel will feature are defined and their accurate disposition is given.
4. **Detail Design:** This is the final designing stage, it translates the contract design into detailed working plans that will be used by the shipyard during the construction. These plans guide the shipyard during the actual construction process, ensuring each element is built according to the precise requirements defined earlier.

As shown in Figure 2.4, what makes designing a vessel a complex task is the rapidly reducing design freedom, the early lock of costs and the limited understating of the design problem up front.

For the purpose of this thesis it is particularly relevant to understand how the design phases just outlined apply to the design of the technical area presented in section 2.2.

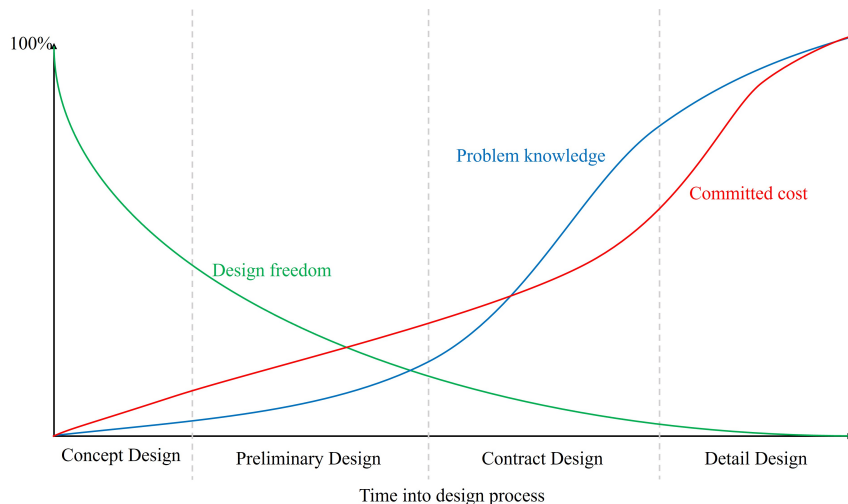


Figure 2.4: Design phases (adapted from Mavris and DeLaurentis, 2000)

2.3.1. Engine Room

As explained in subsection 2.2.1, the engine room is responsible for providing power to the propulsion and the hotel loads. It is therefore reasonable that the main driver for the design of an engine room is the power required, meaning the sum of propulsion and hotel power.

The power needed for propulsion is a function of the top speed required which is discussed and agreed with the owner in the concept design phase, while the hotel power depends on the dimensions, systems and number of guests that the yacht will fit. However, since the propulsion power is usually around ten times bigger than the hotel power (Thomas, 2023), it is safe to assume that the engine room design is in the first place driven by the propulsion power and so by the maximum speed required.

Once the power required is chosen, the following step is understanding the volume and dimensions that the engine room will need. These are mainly driven by the amount of air that is required both for powering the engines combustion and for cooling the machinery (Woodyard, 2009). The amount of air can be accurately calculated via engine manufacture's data and regulations formulas. Knowing the amount of air that has to be supplied it is also possible to determine the casing dimensions and types, central or two on the side. Since often casing goes up to the mast, it has important consequences also on the layout of the upper decks.

Other important decisions that have to be taken in the concept design phase of a yacht concern the decks occupied by the ER, thus if it is single layer or double layer, and its location onboard. The PR location onboard Diesel-Batteries yachts does not have specific requirement however, it is usually on lower deck to create distance between sources of noise and vibrations and the guests area (Verburg, 2014), and to reduce the center of gravity of the vessel. In the longitudinal direction it is usually allocated a bit aft mid-ship, to take advantage of the maximum beam of the yacht.

Finally, also the disposition of the different systems into the Engine Room, is determined in the Concept and Preliminary Design phases, particularly it is performed as Building Block layout. The various BBs presented in Table 2.1 are allocated into engine rooms, keeping into account two major factors: safety and BBs' disposition with respect to each other. Safety considerations determine which systems can be placed in the ER and which must be segregated, such as batteries and switchboards. On the other hand BB disposition in relation to one another is effectively the driver layout factor in the concept and preliminary design phases.

As described in subsection 2.2.1, all systems in the ER are related and connected to each other or at least to the PGS, ESS and EMS. As will be later detailed in section 5.6, the connections among the several systems can be of different types. They can be easier to install and with low cost as small water pipes or huge, complex to install and with relatively high cost, as ducts. This results in a layout that accounts only for low connections with no consideration on the easiness of retrofit.

2.3.2. Battery Room

This is a relatively new space onboard yachts and ships and its dimensions depend mainly on the batteries capacity and the operational requirement needed from them which, as mentioned before, can differ a lot from yacht to yacht (Overton, 2022a). Once it is chosen what the batteries will serve to in accordance with the owner, it is possible to establish the room dimensions. Even if this room does not require any ventilation in normal operation it has some specific requirements in accordance with classification societies such as emergency ventilation in case of overheating and a proper fire-fighting system (International Maritime Organization, 2023b).

2.3.3. Switchboard Room

Also in this case room dimensions are a function of the yacht systems and characteristics. Based on the number and dimensions that the switchboards will have, it will be possible to determine the room area (Krčum et al., 2021), considering that this has to be a working space where one or two crew member can access and work easily. In this instance as well, the lack of a proper method leaves the dimensions decision to the designers' expertise, that can use comparison to former built yachts.

The room's placement within the yacht layout is intricately linked to the position of the generators. This strategic alignment is driven by the necessity to minimize the length of cables connecting the generators and the electric motors to switchboards, ensuring their practicality and efficiency (Klein Woud & Stapersma, 2008).

2.3.4. Final Considerations on Current Design Method

The current design method is primarily focused on the power generation and auxiliary systems that the yacht will have at the time of delivery. It does not take into account that current PGS will undergo major changes in the years to come and across the vessel's lifecycle. This lack of foresight results in a design that is not future-proof. To ensure that yachts can adapt to future technological advancements and regulatory changes, it is essential to develop a design method that considers the following:

- **Future Retrofit:** The design method should facilitate easy modifications and upgrades to the power generation systems and auxiliary systems throughout the yacht's lifecycle. This includes considering the ease of removal and reinstallation of systems.
- **Flexibility and Adaptability:** The layout should be flexible enough to accommodate new technologies, such as zero-emission systems, without requiring extensive redesign or reconstruction.
- **Long-term Planning:** By anticipating future changes and incorporating them into the initial design phase, yachts can achieve a higher degree of sustainability and operational efficiency over their entire lifecycle.

In conclusion, the current design method must evolve to include an approach that ensures yachts are future-proof, allowing them to easily integrate emerging technologies that are explored in the following sections.

2.4. FUTURE FUELS FOR YACHTING

There is currently a lot of uncertainty about which will be the future fuel in the maritime sector, due mainly to storage, safety, production and availability (Foretich et al., 2021). According to many experts it will not be a single fuel to replace diesel but various ones (Raucci et al., 2023 and Lin and Fox, 2023). Among them the most promising ones are Methanol, Ammonia, Bio/E-Diesel, Hydrogen, Ethanol and LNG (Y. Wang, Cao, et al., 2022), which characteristics are reported in Table 2.2.

Given the various set of green fuels that are currently taken into consideration for the future, many shipping company and shipbuilders, are considering a multi-fuel approach. They are not betting on a single fuel but they are keeping an open-mind approach to different ones to see which one in the future will have the greatest availability, lowest price and most developed technologies to be used with.

Properties	Unit	Diesel Oil	Methanol	Ethanol	Hydrogen	Ammonia	LNG
Chemical Structure	-	$C_{12}H_{26}-C_{14}H_{30}$	CH_3OH	C_2H_5OH	H_2	NH_3	C_nH_n
Density (liquid)	kg/m ³	830	790	789	73.22 (20K)	680 (20K)	419
Boiling point	°C	180-360	65	78.2	-253	-33	-161.4
Lower heating value	MJ/kg	46.2	19.9	26.7	120.2	18.6	48-50
Flash point	°C	78	11	12	-	-	-136
Energy density LHV	GJ/m ³	38.35	15.72	21.07	8.8	12.65	20.53

Table 2.2: Technical characteristics of different types of fuel (Harmsen, 2021 and 't Hart et al., 2023)

The yachting builders, among which Feadship, in their roadmaps towards zero emissions have selected methanol as the preferred net-zero option and bio-Diesel (particularly the HVO type) as transition fuel (Feadship, 2022). As explained by La Colla, 2023, the selection was based on six main criteria: storage, hazards, technology readiness level, emissions regulations and availability.

Besides methanol which is being well studied and applied in the maritime industry, at least in ICEs; in the long period, Ethanol appears as a very interesting marine fuel both for ICEs and FCs due to its higher energy density and larger availability ('t Hart et al., 2023). For this reason, even if the technology readiness is way less advanced compare to methanol, this fuel and can cover an important role on yacht future-proofing.

Although for Ethanol there is a lack of expertise in the maritime field, all the most important classification societies are addressing it with the same rules and regulations of methanol (ABS, 2022 and Bureau Veritas, 2022 and Lloyd's Register, 2023). For this reason, the rest of the chapter will focus mainly on methanol as power generation systems and auxiliary systems for this fuel already exist. However, since classification societies are treating these two alcoholic fuels in the same way, it can be assumed that for ethanol, once ICEs and FCs will be available, they will be similar to methanol ones and the auxiliary systems needed will be the same. Moreover, it can also be expected that blends of methanol and ethanol can be used as yacht fuel (Di Iorio et al., 2023).

2.5. METHANOL

Having selected alcoholic fuels for yachting's future, this section will now delve into their propulsion system requirements. There are mainly of two different types of power generation systems: Internal Combustion Engine (ICE) and Fuel Cell (FC). They can work either alone or combined or with an Energy Storage System, as showed in the different future-proof scenarios in Table 1.1. Both Methanol and Ethanol can work with these two different technologies even if their state-of-the-art is different.

This section will analyze specifically Methanol Engines and Fuel Cells, trying to figure out their most important characteristics, recent advancements and future perspective.

2.5.1. Methanol Engine

A methanol engine is an internal combustion engine that can work or with the Diesel or with the Otto cycle. Especially in recent years many have been developed, often as dual fuel engine but not only.

Currently, there exist three main variants for a methanol engine that depends mainly on the ignition system. These are shortly described below while their main characteristics are summarized in Table 2.3.

- Port Fuel Injection (PFI): it is a Dual Fuel engine that falls under the category of Compress Ignition engine. Methanol is injected into the intake ports before the intake valves. The fuel mixes with the incoming air in the intake manifold, forming an air-fuel mixture before entering the combustion chamber (Yin et al., 2023).
- High Pressure Direct Injection (HP DI): it is also a Dual Fuel Compress Ignition engine but in this case methanol is directly injected into the combustion chamber, right before ignition, under high pressure (Dong et al., 2020).
- Spark Ignition (SI): this is a single fuel engine that works only with methanol which is injected in a mixture with air and then it is compressed and ignited with a spark plug (Wouters et al., 2023).

	PFI	(HP) DI	SI
Fuel	Dual fuel: Methanol and Diesel		Methanol Only
Combustion Process	Diesel Cycle	Diesel Cycle	Otto Cycle
Diesel Replacement	Low	High	100%
Top Power (75%)	Only on Diesel	Also on Methanol	Only on Methanol
Complexity	Least complex	Complex HP fuel injection	Complex engine
Exhaust Aftertreatment	Required	Not strictly required	Not required

Table 2.3: Characteristics of various Methanol engines (adapted from Karvounis et al., 2023 and Wouters et al., 2023)

For the purpose of this thesis which focuses on future-proof pathways the most relevant ones are those engines that can be converted from a previous existing Diesel ICE. These are PFI and (HP) DI while currently the SI is being developed only as new engine and not also as retrofitted one. Related to this, a study commissioned by Feadship to Scandinaos in 2021 evaluated three ICEs retrofit (CAT C18, MTU 2000 and MTU 4000) or to MD97 utilizing original unit injector fuel system design or adding on a dual fuel system, and highlighted that injectors and parts related to the high-pressure fuel system are critical components for DI methanol ICEs and that retrofitting bigger engines (as MTU 2000 and MTU 4000) is easier than smaller ones, mainly due to lack of available space in the cylinder head of smaller ICEs, making not possible the addition of a new injection system (Molander et al., 2021).

2.5.2. Methanol Fuel Cells

Fuel cells are increasingly researched and utilized for maritime applications (Elkafas et al., 2023). Especially in the yachting field, besides emission reduction, they offer numerous advantages such as higher efficiency, reduced noise and vibrations and reduced maintenance (Xing et al., 2021).

The methanol fuel cells can be either powered directly by methanol or through a reformer that convert methanol into hydrogen which is then used in the fuel cell. Below these two different FCs types are shortly discussed, and their schematic working principle are shown in Figure 2.5.

- Direct Methanol Fuel Cells (DMFCs): they operate by introducing a methanol-water blend to the anode side. Within this mixture, a catalyst (typically platinum) splits the mixture into hydrogen and carbon dioxide. This process separates hydrogen molecules into protons and electrons. The electrons travel through an external circuit, generating electricity, while the protons move across the electrolyte to the cathode, where they interact with oxygen, ultimately forming water (Ahmed et al., 2022).
- Reformed Methanol Fuel Cells (RMFCs): they work by converting methanol into a hydrogen-rich gas within a reformer. This gas is directed to the anode, where hydrogen molecules undergo a split into electrons and protons. The protons move through a proton-conducting membrane to the cathode, while the electrons travel through an external circuit, creating electrical energy. At the cathode, oxygen from the air combines with protons and electrons, ultimately producing water (Sazali et al., 2020).

Both these fuel cell types offer distinct advantages. However, for the purpose of this thesis, it is essential to note that DMFCs supply a maximum voltage of 0.3–0.5 V, making them suitable for portable power applications below 260 W (Kazeroonian & Rahimpour, 2023) which is definitely not applicable for yachts. Therefore, only RMFCs will be considered in this thesis.

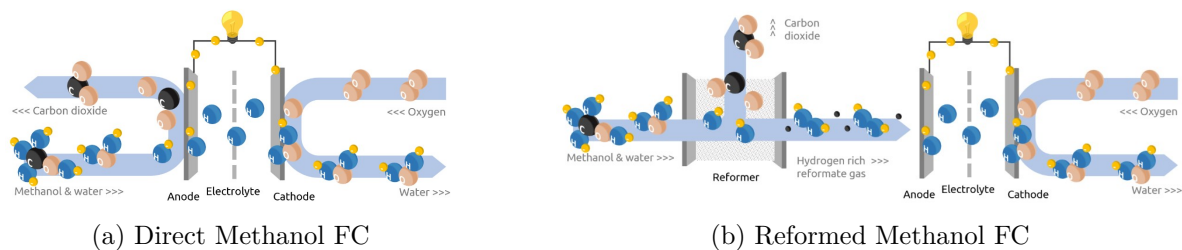


Figure 2.5: Schematic working principle of methanol fuel cells (Siqens GmbH, 2023)

Considering RMFCs, according to Tronstad et al., 2017 that analyzed seven different types of fuel cells based on many different characteristics, the three most promising technologies for shipping, according to the attributes presented in Table 2.4 are:

- Low-Temperature Proton Exchange Membrane Fuel Cells (LT-PEM FCs): they operate at low-temperature using a solid polymer electrolyte membrane.
- High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEM FCs): they also use a solid polymer electrolyte membrane but able to tolerate higher temperatures, making them more resilient to contamination.
- Solid Oxide Fuel Cells (SOFCs): they operate at very high temperature using use a solid ceramic electrolyte. It is important to notice that in this FC type the reformation process takes place directly inside the cell.

	LT-PEM FC	HT-PEM FC	SOFC
Temperature [°C]	50-100	200	500-1000
Electrical efficiency	50-60 %	50-60 %	60% (85% with WHRS)
Lifetime	Moderate	Low	High
Maturity	Moderate	Low	Moderate
Sensitivity to fuel impurities	Moderate	Moderate	Low

Table 2.4: Comparison of fuel cells technologies (adapted from Tronstad et al., 2017)

The comparison presented in Table 2.4 is based on the EMSA study on the use of fuel cell in shipping (Tronstad et al., 2017), which find confirmation also in the paper by van Biert et al., 2016 and in the thesis by Sjölin and Holmgren, 2019, besides being also well aligned with a study conducted by Feadship comparing existing methanol fuel cells technologies (Alkemade et al., 2023).

Even if it will be stated more clearly in the following subsection 5.1.1 and subsection 6.1.3 it is worth noting that currently FCs do not have the power density of diesel generators but, as shown in Figure 2.6, it is expected that they will meet it around 2040-2045. SOFCs (for which the trend is shown) are expected to be the first to reach this objective, but the same assessment can be made for other FC types with a different power density forecast leading to a different time at which a full replacement of engines by fuel cells can be expected.

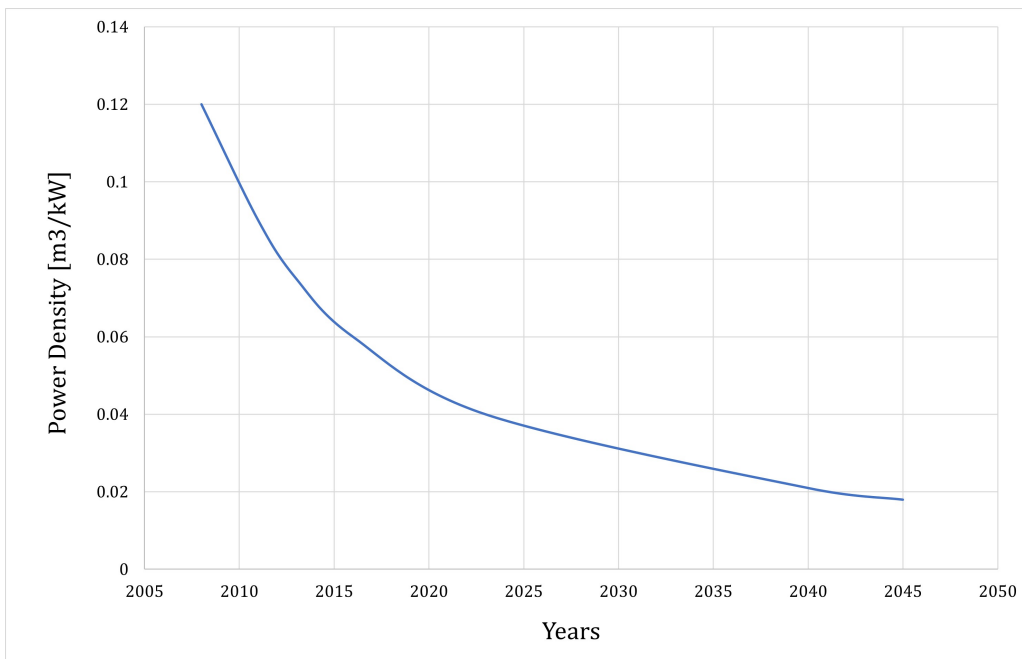


Figure 2.6: Development trend of SOFCs power density (adapted from L. Fan et al., 2023 according to Feadship's suppliers data)

2.6. AUXILIARY SYSTEMS

As diesel ICE, both FCs and ICEs, whether operating on methanol or ethanol, require some auxiliary system that guarantee their safe and efficient operation. Most of these systems have already been described in subsection 2.2.1 and here will just be mentioned, outlining eventual peculiarities that a certain system may require to run on an alcoholic fuel.

2.6.1. Auxiliary system for alcoholic ICE

Looking at the systems analyzed in subsection 2.2.1, big changes switching to methanol or ethanol as fuel for an ICE can be found in the fuel system and in the exhaust gas treatment system, while the other systems (Ventilation, Oil Lubrication, Water Cooling and WHRS) do not vary too much.

Fuel System

A schematic of a methanol fuel system is presented in Figure 2.7 where it can be seen that the most relevant changes if compared to a Diesel fuel system are the Nitrogen system, described below, and the Fuel Preparation Space (FPS). The latter consists of one or two rooms which must be separate and segregated from the engine room, it hosts all the systems needed for fuel preparation purposes such as pumps, valves, heat exchangers and filters (Wärtsilä, 2023e). This room has particularly strong safety requirements such as fire and gas detection, low oxygen level detection system, fire-fighting equipment, and bilge equipment (Lloyd's Register, 2022). The idea is that all the systems hosting a low-flashpoint fuel must be double contained, but since it is difficult to double-wall a pump or other machinery, they are all located into a double-contained room. It is a complete new requirement compared to diesel fueled ships, that often makes retrofitting to alcoholic fuel even harder. When addressing the future-proof challenge it must be taken into consideration (Harmsen, 2021).

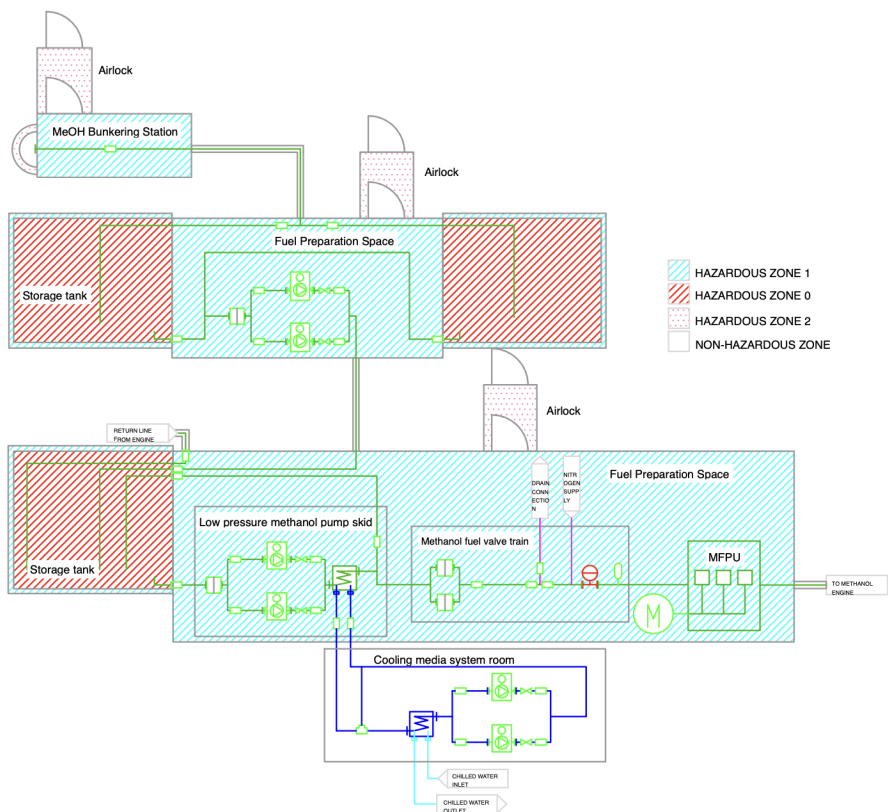


Figure 2.7: Wärtsilä MethanolPac system (Wärtsilä, 2023e)

Nitrogen System

The Nitrogen system serves to keep tanks blanketed and inerted. It basically consists of a small buffer tank and a Nitrogen generator which can also be located in the engine room but have to be provided with at least 6 air-change per hour (International Maritime Organization, 2020).

Alcohol Resistant Aqueous Film Forming Foam

When dealing with alcoholic fuels onboard ships a new dedicated fire-fighting systems is required (Buitendijk, 2022). The type that can be used is an Alcohol Resistant Aqueous Film Forming Foam (ARAFFF) system that serves to create a fire extinguishing foam able to extinguish large alcoholic fuel pool fires (Marine Safety Forum, 2020).

Exhaust Gas After-Treatment System

As outlined by Aakko-Saksa et al., 2023 and Wissner et al., 2023 using alcoholic fuel a great emission reduction can be achieved, however some emissions persist as NO_x , or also SO_x and PM ones if using a PFI or DI engine. For this reason, and due to the fact that emission regulations will become even stricter in the future, alcoholic Internal Combustion Engines need to be equipped with an exhaust gas after-treatment system to lower as much as possible their harmful emissions (American Bureau of Shipping, 2021).

In the end, it is possible to affirm that even if running an ICE with a sustainable alcoholic fuel exhaust gas after-treatment system is need. But this system can be smaller than the one used with a diesel engine as the emissions that it has to deal with are less (Zannis et al., 2022). The only exception regards the Spark Ignition engine where if using water injection it is possible to reach Tier III emission regulations without the need for an EGATS (Zincir & Deniz, 2021)

2.6.2. Auxiliary system for alcoholic FC

While alcoholic ICEs even if powered with a different fuel work approximately as Diesel ICEs, fuel cells are a completely new technology and work in a complete different way. For this reason, the systems that FCs need to operate are very different from the one needed by a Diesel ICE. Moreover, there are some auxiliary systems needed by an ICE that are not required by FCs such as a Lubrication Oil System or an Exhaust Gas After-Treatment System (Gray et al., 2022).

First of all the Fuel System is really different from a Diesel one, but it is approximately as the one for an alcoholic ICE with a dedicated FPS, already described in subsection 2.6.1; except for PEM FCs where the reformer is separate from the cell and there is the need to add water to it and thus the need for a water condenser (Purnima & Jayant, 2017).

Then it is important to notice that FCs need a DC converter to make sure that the power will be delivered by the fuel cells to the bus and not vice versa, and to get the voltage of FCs to the voltage of the main bus (Debenjak et al., 2015). Then the other auxiliary systems (Ventilation and Waste Heat Recovery) and their main characteristics are described below.

Ventilation System

This works exactly as the one for an engine room with an ICE, with one or more supply fans and exhaust fans that allow an air flow into the room. However, if for an engine room ventilation was needed to have adequate air for the combustion and dissipate heat, in a fuel cell room, a correct amount of air is required to provide oxygen at the cathode side of the FC and to maintain the environment safety in case of leak (International Maritime Organization, 2022).

Regarding the use of air for the dissipation of the heat produced, it is relevant only for SOFC. In the case of PEM FC cooling is achieved trough water cooling (Bargal et al., 2020) while in case of SOFC the temperatures are too high and water would evaporate, thus cooling is achieved trough air but this may require bigger ventilation ducts and fans (J. Fan et al., 2023). It is worth mentioning

that even if today seems not feasible, there is some research going on about SOFC cooling with other methods such as with saturated water or with liquid metals, as testified by Promsen et al., 2020 and J. Fan et al., 2023 articles.

Waste Heat Recovery System

The WHRS for fuel cells really depends on their type. In case of PEM FC, the waste heat recovery system is associated to the water cooling and is particularly similar to the one of an ICE described in subsection 2.2.1. While, in case of SOFC since the cooling happens through air, there is the need for a different WHRS that uses the heat present in air to improve the Fuel Cell efficiency.

Many WHRSs have been studied in recent years to improve FC efficiency. Tse et al., 2011 studied a SOFC combined with an absorption heat pump in a trigeneration system to drive HVAC and electrical base-load systems specifically for a superyacht. They found that using a WHRS it was possible to achieve up to 53% improvement in the overall system efficiency compared to the conventional system (without WHRS). While Ouyang et al., 2020 designed and analyzed a novel combined system for marine power generation including an SOFC–GT subsystem, the S-CO₂ recompression cycle, and the KCS achieving 71.37% of efficiency of the whole system (38.65% higher than that of the SOFC alone). Lastly an extensive summary of all the different waste heat recovery technologies was presented by Herweijer, 2022 which outlined that no system outperforms the others simultaneously across all three investigated aspects of efficiency, size, and cost, and trade-offs will be required when selecting a waste heat recovery technology.

2.7. CONCLUSION TO THE CHAPTER

This chapter addressed the research subquestion “*What is the current state-of-the-art of engine rooms onboard yachts and what are the projected future power systems that can serve as zero-emission solutions for superyachts?*”. The analysis focused on the latest advancements in yacht engine room designs and emerging technologies aimed at achieving zero emissions. First, traditional power plants and technologies used in yacht engine rooms were analyzed in section 2.1 and subsection 2.2.1. The Diesel-Batteries power plant was set as the baseline and the different PGS, ESSs and auxiliary systems were described.

In section 2.3, the focus shifted towards the current design method, highlighting that it primarily emphasizes immediate design needs neglecting strategic considerations of retrofitting with new PGS. Alternatives among new sustainable fuels and PGSs were later investigated in section 2.4 - 2.5 identifying alcoholic fuels (methanol and ethanol) as the most promising options. Methanol demonstrated advanced availability and technologies in the short/midterm, while ethanol offered long-term promises with non-toxicity and higher energy density. Both fuels could be converted into power using ICEs and Fuel Cells FCs, with Methanol ICEs being more mature, while FCs faced significant advancements.

The challenges and requirements associated with implementing these PGSs were investigated in section 2.6 particularly exploring the auxiliary systems new PGSs require to work safely and efficiently. Key takeaways are the need of these systems for specific tanks and pipes, dedicated fuel preparation spaces and unique safety systems such as a Nitrogen and an ARAFFF one. It is therefore possible to state that the implementation of new sustainable systems in current engine rooms is proven complex given major differences compared to traditional systems. The following chapter will analyze current retrofit technologies and techniques and point out future-proofing theories helpful in the development of a design method addressing the challenges to future-proof engine rooms onboard yachts.

3. STATE-OF-THE-ART OF FUTURE-PROOFING

The future systems to reach zero-emission in the yachting field were discussed in the chapter above, however how to integrate these systems in an engine room during a future retrofit is still unaddressed. This chapter will focus on “*What are the currently employed retrofitting techniques and what innovative approaches can be proposed to advance the retrofit process for superyachts and enable seamless integration of zero-emission systems?*”. First of all a quick overview of current retrofit technologies is given, then current techniques to move systems in and out the yachts are discussed and in the end, the different approaches on how to future-proof a vessel are presented in section 3.4 - 3.7.

3.1. CURRENT RETROFIT SOLUTIONS

According to Krikke, 2015 definition, retrofit is “the installation on-board ships of state-of-the-art or innovative components or systems” and is mainly driven by the need to meet new regulatory energy and emission standards (Christiansen et al., 2021). Besides this reason that is particularly applicable to commercial shipping, retrofit in the yachting industry is also based on ethical and social grounds (Mallet, 2022).

As already mentioned, the technologies available today and the production of green fuels still make zero-emission shipping and yachting a difficult target for the whole global fleet. Despite this, the emission regulations are becoming more and more severe, resulting in ship and yacht owners to recur to retrofit solutions to make their vessels compliant with the latest regulations, but still not zero-emission. This section will focus on the current retrofit solutions that are available in today’s shipping industry. These solutions will be shortly described and their application to the yachting field will be discussed.

3.1.1. Retrofit Solutions

Currently there exist many retrofit solutions for existing ships that are applied to increase ships’ efficiency and consequently lower the emissions or just for the second purpose. Some of them have been summarized in the research by Allal et al., 2018. The most important and used ones are summarized in Table 3.1

Table 3.1: Current Retrofit Solutions

Category	Technology	Working Principle	Reference
Increase Efficiency	Bulbous Bow Retrofit	Optimize the bulbous bow form and size, lowering ship resistance	Allal et al., 2018
	Energy Saving Devices	Located near the propeller to reduce its energy losses	Spinelli et al., 2022
	Air Lubrication System	Reducing hull’s resistance by injecting an air layer below it	Giernalczyk and Kaminski, 2021
	Wind Propulsion Technologies	Wind force to assist ship propulsion and reduce engine consumption and emissions	Y. Wang, Zhang, et al., 2022
Lower Emission	EGATS	Remove NO _x and SO _x emissions from the exhaust gas	J. Zhou and Wang, 2020
	Carbon Capture System	Capture CO ₂ from the exhaust gas and store it onboard	Ros et al., 2022

3.1.2. Applicability to Yachts

The technologies presented above are all theoretically applicable to yachts, however their employment is limited to a few cases. This is caused by different reasons depending on the technology which mainly are the space they take, the unaesthetic of the solution and the fact that they impact on yacht's efficiency and emissions only while it is sailing, which, as mentioned, is only for a small time of its life. Thus, their impact on the overall efficiency of a yacht is not so consistent to justify a refit. A short analysis of the reason why these retrofit options are not applicable to yachts are presented in Table 3.2

A special consideration pertains to EGATS which is the retrofit option that have the minor impact on the vessel due to its relatively small dimensions. Despite this, retrofitting a ship with such a system is often a complex challenge since old engine rooms are not thought to host it (D'Amore et al., 2023). The task becomes even more complex onboard yachts where the space is much smaller (Lardy, 2020). However, the stringent emission regulations of the past decades have moved shipowner to adopt these technologies progressively both for new constructions and for retrofits (Zannis et al., 2022).

Table 3.2: Retrofit solutions vs their main cons

Technology	Main Cons
Bulbous Bow Retrofit	Impact only while sailing
Energy Saving Devices	Impact only while sailing
Air Lubrication System	Impact only while sailing
Wind Propulsion Technologies	Impact only while sailing + Unaesthetic
Exhaust Gas After Treatment System	Space + Already applied on new-builds
Carbon Capture System	Space

In conclusion, it is possible to state that none of the analyzed technologies represents an interesting retrofit solution in the yachting industry given their difficult applicability to these kinds of vessels. Among them the Exhaust Gas After Treatment System (EGATS) do constitute an important system that is currently installed on all new-build yachts (Nicholls, 2020). van der Vliet, 2021 analyzed some of the systems mentioned and other (such as solar panels and anti-fouling) and their applicability to yachts. From its conclusions it is possible to understand that although all these systems are interesting in terms of energy saving and emissions reduction, they do not represent a complete zero-emission solution that can help in future-proofing an engine room.

Furthermore, most of these systems are located outside the technical space identified in chapter 2 as "Power Room" which is the actual focus of this thesis. Therefore, for the purpose of this thesis, none of the previously mentioned technologies will be taken into account. Nevertheless, as mentioned in subsection 2.2.1, the starting point of the thesis will be an engine room equipped, among others, with an Exhaust Gas After Treatment System.

3.2. CURRENT RETROFIT TECHNIQUES

There are several reasons why a superyacht may undergo a refit such as interior changes, structural works or systems upgrade. The most common cause of retrofit a change in the ownership which is often related to interior works (Beckett, 2015), while as already outlined, at present days retrofit of yachts systems occur to have a lower TCO or for ethical reasons related to owners that want a greener vessel. It is worth mentioning that superyachts must undertake an important survey every 5 years that oblige them to spend some time in a dry-dock and it is time and cost saving to schedule important

retrofit at the same time (Beckett, 2015). On the other hand engines must undergo a big maintenance after a certain amount of hours of operation which vary usually between 16,000 and 24,000 hours depending on the engine (Jensen & Jakobsen, 2017), thus if the refit involves only the engine it is worth scheduling it in coincidence with this big maintenance work.

In the context of the engine room, retrofits typically involve installing new systems or replacing older ones. The former often focuses on EGATSS or other systems to reduce the vessel’s environmental impact. The latter aims not only to lower emissions but also to enhance systems efficiency by upgrading or replacing with newer ones.

3.2.1. Power Room Retrofit Paths

retrofitting an engine room onboard a yacht presents a significant challenge due to limited space availability. Nowadays, as testified by previous works (such as Whitehaven, 2021 and Coenen et al., 2015) and by Feadship’s yards project managers, shipyards employ three primary approaches, detailed in Table 3.3, for system installation or removal.

Table 3.3: Comparison of different ways to take systems in and out of an Engine Room (adapted from Whitehaven, 2021 and Coenen et al., 2015)

	Tender Garage	Ventilation Channel	Hole in the hull
Pros	Closed to the ER Movement equipment present Few pipes and cables on the way	Straight from ER to outside No additional openings Few pipes and cables on the way	Big dimensions Easy path out of the ER
Cons	Limited dimensions due to door size Part of walls must be removed for larger machinery	Limited dimensions due to ducts size Complicate movement	Limited dimensions due to girder spacing Vessel must be in dry-dock

The “*hole in the hull*” method proves relatively straightforward for moving large machinery. This approach involves creating a hatch beneath the yacht, particularly feasible in the stern area without a double-bottom, requiring no repaint below the waterline. Moreover, engine room walls designed for easy assembly and disassembly, like those developed by Alara-Lukagro (Alara-Lukagro, 2023), offer flexibility to reach the stern area without big efforts. The only limitations of this approach are the need for the vessel to be in dry-dock during refit operation and the girder dimensions, which define the maximum hole dimensions that can be arranged. However, on superyachts primary girders are usually spaced at 2.4m and 4.8m off centerline with a span of 9.6m between bulkheads (Roy et al., 2008), allowing for holes big enough to move in and out even the biggest machinery.

Size limitations also impact the other two pathways, the “*tender garage*” and the “*ventilation channel*”. The latter is particularly constrained due to limited casing dimensions and occasional obstructions along the path. Although this pathway involves minimal removal of pipes and cables and does not require an additional opening, it is typically chosen only when systems are dismantled into smaller parts. However, this option is less favored due to the significant time and effort required to dismantle and reassemble systems directly within the engine room.

On the other hand, the preferred approach is to install and remove systems entirely rather than in pieces, as it often proves to be more efficient in terms of time and cost savings (Schoonhoven, 2018). The pathway through the tender garage (TG) offers distinct advantages, especially when it is located adjacent to the engine room. In such cases, a direct path without the need for pipes and cables removal is possible, particularly if the TG and TG are connected via a door. If the door size is insufficient, engine room walls designed for easy assembly and disassembly can be utilized (Alara-Lukagro, 2023).

3.2.2. Access Opening Options

As mentioned in the previous subsection, there exist different paths that can be used to carry in and out systems. These paths always involve Access Openings (AOs) which are doors, hatches or similar which connect the PR spaces among each other or the PR itself to the outside of the vessel or to other areas, such as the tender garage, which are then directly connected to the outside. The AOs can be categorized as “*Present*”, “*Soft Patch*” and “*To be created*”. The main characteristics of these AO types are exposed in Table 3.4.

It must be stated that depending on its location onboard the present AO can vary a lot, indeed if it is internal to the yacht it just consists of a door or of easily dismountable walls, as exposed in subsection 3.2.1; while if serves to connect the yacht to the outside it is usually a foldable hatch, as the one show in Figure 3.1a, that onboard current yachts are particularly used for TG and balconies (Gauert, 2022).

Moreover, while the AO “*To be created*” refers to an AO where no pre-engineering or pre-arrangement work has been done, the soft patch is an area of the hull or bulkheads that has been pre-engineered and arranged to be easily opened and then re-closed during specific operations, such as a retrofit (WETA San Francisco Bay Area, 2020). It is not effectively “soft” but it is a simple part of the structure where structural components are minimized. It is usually located between main structural elements to maintain structural rigidity, containing only minor girders that can be easily cut out and reinstalled. As shown in Figure 3.1b (where the girders are still to be reinstalled while the steel plate has already been closed) this area does not host any pipes and cables (or just easily dismountable ones).

Table 3.4: Access Openings types

	Present	Soft patch	To be created
Initial cost	Very high	Medium	Very low
Pre-engineering complexity	Very high	High	Very low
Steel works during retrofit	No	Yes	Yes
Pipes and cables work during retrofit	No	No	Yes



(a) Foldable door of TG (Superyacht News, 2017)



(b) Soft patch (Chidambaram Shipcare, 2022)

Figure 3.1: Different types of AOs

3.2.3. Moving Equipment for Retrofit

Currently, there exist mainly three moving equipment to transport systems and components in and out of a vessel during a retrofit. These have been reported with their pros and cons in Table 3.5.

Table 3.5: Moving equipment for retrofit (adapted from MAN ES, 2020, Zhongyuan, 2022 and WinGD, 2023a)

	New Installation	Handleability	Weight
Hands	Not Required	Very easy	Limited to 23kg
Rails	Easy	Complex	Not limited
Chain and Tackle	Complex	Easy	Not limited

The decision on the transport equipment to be used is based on some key considerations. First of all the transport by hands by operators has to be preferred as it does not require the installation of any transport mean and have the highest handleability. However, this option is very limited due to man work force capacity and to work laws that in the Netherlands, as in many other countries of the world, allow the workers to carry manually a maximum weight of 23 kg (Dutch Labour Inspectorate, 2012).

Regarding the other transportation means, it is assumed that they have no restrictions in terms of weight to deal with the systems in the PR. Among rails and Chain and Tackle (C&T), that are shown in Figure 3.2, if there is any system already installed that is the one to be preferred, if there is none the decision can differ whether the PR is on one or two layers, and on the path required. If the system has to be lifted vertically C&T will for sure be needed, while if there is no such need, the preferred choice are rails as they are easier to install.



(a) Engine removal via rails (MAN ES, 2020)



(b) Engine installation with C&T (Amico & Co, 2024)

Figure 3.2: Rails vs Chain and Tackle for transportation in a PR

3.3. FUTURE-PROOFING APPROACHES

The previous sections outlined as none of the current retrofit technologies can fulfill the requirement for a zero-emission yacht and highlighted the current retrofit techniques, however they do not guarantee an easy and economic engine room retrofit. Here comes the second part of the subquestion “*What innovative approaches can be proposed to advance the retrofit process for superyachts and enable seamless integration of zero-emission systems?*” that led to the concept of “*Future-Proofing*”.

Defined by the Cambridge Dictionary as the act of “design something so that it can still be used in the future, even when technology changes” (Cambridge Dictionary, 2023), future-proofing for ships or yachts involves preparing them for future tasks. This readiness includes compliance with future rules and regulations, particularly those related to zero-emission technologies (Vartdal, 2019).

There exists different design approaches that can be used while future-proofing a yacht. As visualized in Figure 3.3, future-proofing can be achieved via Changeability or Robustness. Changeability can be reached by Versatility or by Retrofittability which in turn can be obtained with two different design approaches: Design for Retrofit and Design for Modularity (Coenen et al., 2015, Erikstad and Rehn, 2015, Rehn et al., 2018 and Pruijn, 2023).

This approaches will be detailed across the following sections and the concluding section 3.8 will outline the ones that better fit the yachting industry and this specific thesis.

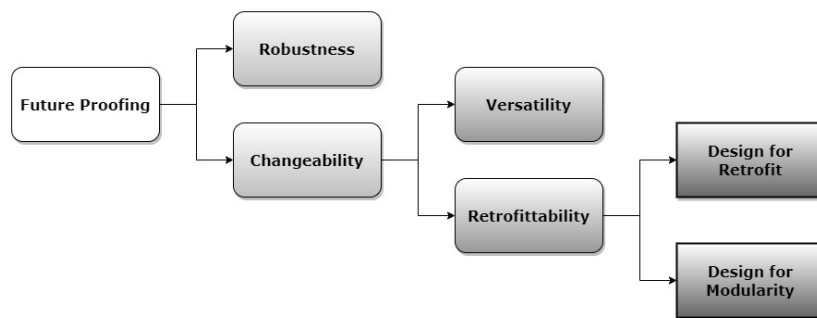


Figure 3.3: Structure of future-proofing approaches (developed from Coenen et al., 2015, Erikstad and Rehn, 2015, Rehn et al., 2018 and Pruijn, 2023)

3.4. CHANGEABILITY

This term collects under itself other change-related system properties such as flexibility, adaptability and agility (Rehn, 2018). But in general, changeability is the ability of a system, in this case of a vessel, to change form, function or operation (de Weck et al., 2012). According to Rehn et al., 2018 on ships and yachts changeability can usually be reached in two different ways:

- Versatility: the ability of a system to satisfy diverse needs, without change of form.
- Retrofittability: the ability of a system to satisfy diverse needs, by change of form.

Even though Rehn et al., 2018 study primarily addressed technical equipment for non-transport vessels rather than the systems within the engine room, its significance lies in the comparison between retrofittability and versatility. The research concluded that, despite being case-specific, retrofittability holds particular value due to its potential for increased upside at a relatively low upfront cost, whereas versatility, while possessing good potential, comes with higher upfront costs. Furthermore, it was emphasized that on a general basis, multi-functional ships should be versatile, while single-functional ships (as yachts) should be retrofittable.

Before delving into retrofittability and versatility, additional insights on changeability are provided. As outlined by Deluigi et al., 2019, in the first design stages, it is relevant to have a method able to quantify the changeability of a vessel. This was first presented by Rehn et al., 2019 which identified two different approaches:

- Bottom-up approach: calculating the expected reduced cost and time of performing a change for a given design alternative.
- Top-down approach: Using End State Filtered Outdegree (FOD) or End State Relative FOD (RFOD) to quantify changeability between states.

The bottom-up approach calculations were also later simplified and used by Deluigi et al., 2019 and by Sullivan and Rossi, 2023. Moreover, these two publications identified guidelines for enhancing vessels' changeability during the concept design phase that increase vessels changeability not only in the design phase but all over their lifecycle, which are ideality, simplicity, modularity, integrability and autonomy.

Nevertheless, when it comes to future-proofing the power room on a yacht or a ship, beyond power systems, also the fuel supply system (tanks, pipes, etc...) must be thought for changeability. Christiansen et al., 2021 highlight that transitioning a vessel designed for Fuel Oil, as most of the yachts today (Johnson, 2021), to operate on LNG, ammonia, or methanol requires the installation of a new fuel supply system. However, given the complexity of retrofitting the whole supply systems, the aim, especially on superyachts, is to have a robust fuel system able to operate both with diesel and with low-flashpoint fuels as discussed in section 3.7. On the other hand, the power systems will be retrofitted, necessitating a retrofit-friendly design method, two different ones are explored in section 3.5.

3.5. RETROFITABILITY

As mentioned earlier, retrofitability is the ability of a system to satisfy diverse needs, by change of form (Rehn et al., 2018). One such need that a yacht may encounter throughout its lifecycle is the transition to greener fuels. However, overlooking future retrofit considerations during the initial design stages, where the highest degree of freedom exists, as shown in section 2.3, complicates future retrofit endeavors, especially for an engine room. For this reason in recent years two different design approaches have emerged: "Design for Retrofit" and "Design for Modularity".

Both of these approaches fall under the Design for X (DFX) category, a generic term encompassing methodologies adopted to enhance both the design product and the design process from a specific perspective represented by X (Huang, 1996).

3.5.1. Design for Retrofit

Coenen et al., 2015 pioneered the "Design for Retrofit" approach, emphasizing the significance of incorporating retrofit considerations in the early stages of design. This approach introduces a "Retrofit Penalty Indicator" (RPI), consisting of two key components: the "Total Transport Penalty" (TTP) and the "Create Access Penalty" (CAP). TTP factors in penalties related to transporting machinery in the engine room for removal and installation (Equation 3.2), while CAP considers whether vertical or horizontal openings for machinery substitution need creation and assesses the complexity of this operation.

$$RPI = TTP + CAP \quad (3.1)$$

where

$$TTP = E_{oH} \cdot FG \cdot (LT_H \cdot TP_H \cdot CP_H + LT_V \cdot TP_V \cdot CP_V) \quad (3.2)$$

$$CAP = A_{H_{AO}} \cdot (UC_H + DCA_H) + A_{V_{AO}} \cdot (UC_V + DCA_V) \quad (3.3)$$

In the previous equations the subscripts H and V stands for Horizontal and Vertical directions.

EoH is the Ease of Handling measured as $EoH = a \cdot V_{box} \cdot m_{box}^{0.5}$ where V and m are respectively the volume and the mass of the boxes to be replaced while a is a scaling factor considered equal to $0.01 \frac{kg^{0.5} \cdot m^3}{100}$. FG is the Filling Grade which is measured as $FG = \frac{\sum V_{box}}{V_{ER}}$ where the numerator is the sum of box volumes of the ER components while the denominator is the total volume of the ER.

Regarding the other terms of Equation 3.2, LT is the length trajectory that represents the transport routes of equipment, TP is the transport penalty that indicates if additional transportation means are to be provided, and CP is the crossage penalty that accounts for passing through complex elements of the room, like tanks.

In Equation 3.3, the term A_{AO} is the Area of Access Openings to be created based on rates that give hours/ton steel to be replaced. The mass of steel to be replaces is of course proportional to the dimensions of the opening and thickness of the plate and it measured as Unit Cost (UC). If such an access hole also requires refit of ducting and cabling, this access hole penalty should be multiplied also with a complexity factor, called Ducts/Cables/Armatures factor (DCA).

Besides the exploration by Coenen et al., 2015, the ‘‘Design for Retrofit’’ methodology is not prominently featured or extensively studied in current literature. Nevertheless, the literature dedicated to ship maintenance is notably comprehensive, offering insights relevant to the concept of retrofitability.

The majority of these papers concentrate on methods for determining when to subject a ship to ordinary or extraordinary maintenance, with a predominant focus on the economic aspects of maintenance. Despite this emphasis, some studies have delved into the impact of incorporating future maintenance considerations into early ship design. Notably, Turan et al., 2009 developed an efficient method aiding designers in making informed decisions about structural optimization during the early design phase while considering future maintainability.

Even if more focus on detail engineering rather than on the early design stage, the study by Zhang et al., 2020 primarily centers on ship systems remaining pertinent to the Design for Retrofit approach. This study introduces a disassembly modeling method that accounts for the relationship between general parts and fasteners. The proposed method facilitates a smoother and quicker disassembly of ship components, a crucial aspect when executing a retrofit.

3.5.2. Design for Modularity

Design for Modularity is a design approach that aims at addressing how it is possible to decompose and encapsulate ship system elements to enhance both design and manufacturing efficiency, as well as improve ship operational performance (Erikstad, 2019).

Modularity serves as a crucial facilitator for providing flexibility to navigate future uncertainties (Erikstad & Rehn, 2015), such as future fuels. The US Navy recognizes the combination of modularity and flexibility as a primary strategy for minimizing time and costs associated with modernizing in-service vessels, allowing them to adapt to future operating scenarios (Schank et al., 2016).

Four primary types of modularity, as outlined by Salvador et al., 2002, include component swapping, combinatorial, bus, and sectional. Among these, component swapping modularity holds particular significance in the context of retrofitability. This modularity type enables different configurations and rapid refits while maintaining predefined locations for each equipment type, ensuring the availability of appropriate interface slots (Erikstad, 2009).

Besides initiative and projects focusing on modularity retrofit for diverse operational tasks throughout a vessel’s lifecycle; different concepts have been developed in recent years using modularity

to future-proof a vessel and its engine room. Table 3.6 provides a summary of the most pertinent projects in this domain.

Table 3.6: Modular Retrofittable Engine Room Concepts

Company	Ship type	Concept	Reference
Kongsberg Maritime	Container Vessel	Modular plug-and-play containers beneath the stacks house the fuel system, featuring an easily retrofittable, upgradable, and convertible design.	Midtbo, 2021
Bakker Sliedrecht	Not specified	Standard containers, connected to the on-board energy network, currently host LNG generators or batteries, easily substitutable with containers for new technologies.	Ammerlaan, 2023
ETA Shipping	Short-sea Cargo Vessel	Modular plug-in propulsion design, easy to be retrofitted with green fuels. Not clear how.	von Ubisch, 2021
Future Proof Shipping	Inland Container Vessel	Upgrade the current engine room with a modular propulsion system hosted in containers. Power systems incorporate modular hydrogen tanks and fuel cells, easily adaptable for future modifications.	Future Proof Shipping, 2023

3.6. VERSATILITY

As previously discussed, in accordance with Rehn et al., 2018, adopting the definition from de Weck et al., 2012, versatility stands as the system’s capacity to meet diverse needs without altering its form. In maritime contexts, a versatile vessel facilitates faster and more cost-effective adaptations compared to a retrofittable counterpart, despite a higher initial cost.

Examples of versatile ships encompass those capable of transporting various cargo types, or multi-purpose vessels (in the offshore domain), or those equipped with dual fuel engines (Rehn & Garcia, 2018). The versatility of ships designed to transport different cargo types has been extensively studied by Stopford, 2009, who introduced a lateral cargo mobility indicator measuring a vessel’s ability to carry various cargo types. While the versatility of multi-purpose offshore vessels has been treated by Rehn et al., 2018.

However, in the realm of future-proofing, the category of utmost interest is dual fuel engine ships. These vessels possess the capability to operate with two distinct types of fuel with minor or none modifications. Presently, the majority of such ships can run on either Diesel or LNG, with an increasing number being designed to accommodate ammonia and methanol (Bartlett, 2024). These vessels are either equipped with a dual fuel engine, capable of running on both diesel and methanol, or a diesel engine that, with minor modifications, can become dual fuel-enabled for methanol or ammonia, often referred to as methanol-ready or ammonia-ready. An overview of the dual fuel engines available in the current market or forthcoming is presented in Table A.1.

Recent years have witnessed the integration of versatile dual fuel systems into numerous ships, encompassing both newly constructed vessels and retrofitted ones. According to Clarkson’s Green Technology Tracker, approximately 5.5% of the shipping fleet’s capacity is currently alternatively fueled, projected to increase to 6.5% by 2025. The order book indicates that 48% of its total capacity is earmarked for alternatively fueled vessels (Mandra, 2023). Table 3.7 provides a concise summary of noteworthy dual fuel applications, showcasing how vessels of various types can be equipped with methanol or ammonia dual fuel engines, underscoring versatility as the preferred choice in ship design for cargo and working vessels.

Table 3.7: Dual Fuel Ships

Company	Ship Type	Engine	Fuels	Project	State	Reference
Stena Lines	Ro-Pax	4 x Wärtsilä Sulzer 8ZA40S	Diesel and Methanol	Retrofit	Delivered	Wärtsilä, 2023c
Maersk	Container	MAN B&W 6G50ME-LGIM	Diesel and Methanol	Newbuild	Delivered	Moore, 2023
Wallenius Wilhelmsen	Ro-Ro	MAN B&W 7S60ME-LGIM	Diesel and Methanol	Newbuild	Ordered	Blenkey, 2023
Aasen Shipping	General Cargo	Wärtsilä (unk)	Diesel and Methanol	Newbuild	Ordered	Riviera News, 2023
Boskalis	Hopper Dredger	Unk.	Diesel and Methanol	Newbuild	Ordered	Bovenizer, 2023
CMA CGM	Container	MAN B&W G80ME	Diesel and Ammonia	Newbuild + Future Retrofit	Delivered	Atchison, 2023a
Grieg Maritime	Bulk Carrier	MAN B&W 5S60ME	Diesel and Ammonia	Newbuild + Future Retrofit	Ordered	Atchison, 2023b
JPN H2YDRO	Short-sea Ferry	Volvo Penta D13	Diesel and Hydrogen	Newbuild	Delivered	Vodnik, 2021

3.7. ROBUSTNESS

Confining the design to typical usage scenarios renders a system susceptible to the impacts of events not accounted for in the expected circumstances. On the other hand, robustness is the property of systems that empowers them to endure unforeseen or unconventional circumstances (Knoll & Vogel, 2009).

In the context of ship design, robustness gains particular importance when dealing with ship structures (Moan, 2018). It extends its relevance to ship systems as well. Designing robust systems is paramount for ensuring safe navigation, even though evaluating system robustness in the early stages of ship design proves intricate (Scheffers, 2021).

Beyond structural and safety aspects, the concept of robust ship design is gaining increasing significance as a means to future-proof vessels. This approach, extensively explored by Pruijn, 2023, focuses on developing ships designed not only to meet present standards but also equipped with key measures to seamlessly accommodate future fuels. Such a strategy aims to mitigate retrofit costs and time, albeit with a higher upfront cost.

According to Pruijn, 2023, robust design is a distinctive approach to address the uncertainties of the energy transition. Robust design involves creating an integrated solution that competes effectively in diverse situations. Unlike adaptable designs, where functions change frequently, robust designs are adapted more easily when situations change, with alterations implemented once and irreversibly.

Robust design offers vessels designed for contemporary standards but with key measures for future fuel support. This approach maintains competitive costs while significantly reducing conversion expenses when the need arises.

This approach proves to be very important in future-proofing a vessel especially for those systems which complete retrofit would be incredibly time-consuming and expensive such as tanks and pipes. Since retrofitting the whole tanks and pipes of a vessel is extremely complex, it is of primary importance

that, already in the initial design phases, they are thought for robustness making that feasible both with diesel and with sustainable fuels.

Recent years have witnessed the development of numerous concepts, some even receiving Approval in Principle (AiP) from classification societies, promising solutions to these challenges. A concise summary of the most promising concepts is presented below.

3.7.1. Robustness for future-proof tanks

As outlined, robustness plays a pivotal role when designing tanks both for diesel (for current operation) and for low-flashpoint fuels (for future operation). The biggest issues regarding tanks are safety measures needed for low-flashpoint (LFP) fuels and separators to address contamination between different fuel types.

Possible solutions for the contamination issues have been extensively studied by La Colla, 2023 that concluded that a full separation of diesel and methanol can be achieved by utilizing a disc stack centrifuge. On the other hand, for safety related to LFP fuels tanks; there are two possibilities:

- Double barrier tank, also known as cofferdam: a double barrier which can be either filled with air or an inert gas (Lloyd's Register, 2022).
- Single-walled ventilated tank top: this is the concept behind an AiP received by Feadship which aims to mitigate risks by ventilating the space adjacent to tanks (Margerrison, 2023).

Besides Feadship, which as mentioned has received an approval in principle for a single-walled ventilated tank top concept, there are other companies that are working to address the safety and space issues related to LFP fuel tanks:

- Meyer Werft: German shipbuilder, is working on a concept similar to Feadship: the idea is to ventilate the space adjacent to tanks (Sahnen, 2018).
- SRC Group: marine engineering company is developing a storage solution for Methanol tanks using Sandwich Plate System (SPS). Also this solution has recently received an AiP by Lloyd's Register (Bahtić, 2023).

3.7.2. Robustness for future-proof pipes

Beyond tanks, another component that would particularly benefit from Robustness in early stage design and construction are fuel pipes. Thinking to substitute the whole pipe system during retrofit is not feasible, thus different ideas have been developed to have future-proof pipes able to host also LFP fuels. According to the Lloyd's Register rules for these fuels (Lloyd's Register, 2022), the most viable options are:

- Pipes through tanks and cofferdams: the pipes that pass through tanks or cofferdams can be single walled as a protected space surrounds them.
- Double walled pipes: the pipes outside tanks and cofferdams must be double-walled to mitigate the risk related to it.

Among the different options of double-walled pipes, the most advised one is the double-walled welded piping with header which offers a good middle ground between safety and cost. However, it has to be

considered that, as well as for tanks, design and building pipes to be methanol-ready is more expensive but if compared to a future retrofit option it results cheaper, explaining the relevance of robustness for tanks and pipes.

3.8. CONCLUSION TO THE CHAPTER

Theories and techniques for the refit of a superyacht were described in this chapter, answering to “*What are the currently employed retrofitting techniques and what innovative approaches can be proposed to advance the retrofit process for superyachts and enable seamless integration of zero-emission systems?*”. It was outlined how current green refit options can reduce vessels’ footprint but are still not able to make it zero-emissions. For this reason they are not taken into consideration for the purpose of this thesis.

Afterwards, section 3.2 focused on the most technical part of engine room retrofits, analyzing the various techniques and equipment employed to take in and out components from the engine room. Later on, the chapter presented future-proofing theories split into two broad design approaches: robustness and changeability. The latter, further dived into versatility and retrofitability which in turn was sub-categorized into Design for Retrofit and Design for Modularity.

Versatility was found particularly useful when converting an engine from Diesel to Dual Fuel, while when considering the installation of new systems such as fuel cells and auxiliary systems Design for Retrofit emerges as the preferred option. However, there are some systems and components (such as the entire tank and fuel pipes infrastructure as well as the ventilation system) that prove to be excessively intricate and expensive to be retrofitted, emphasizing the importance of robustness in their initial design phases. Thus, to successfully design a future-proof yacht, a mixture of these theories is required depending on the scenario to be reached, as shown in Table 3.8.

The method described in the following chapter 4 will start from these theories and be structured in a three-step approach able to outline good layout and best practices to future-proof yachts power rooms.

Table 3.8: Future-Proof Approaches vs Scenarios

Approach	Future-Proof Scenarios		
	1: Diesel ICEs + FCs + Batteries	2: DF ICEs + FCs + Batteries	3: FCs + Batteries
Robustness	For components complex to retrofit	For components complex to retrofit	For components complex to retrofit
Versatility	N.A.	For Diesel ICEs conversion to DF	N.A.
Design for Retrofit	For FCs and auxiliary systems installation	For FCs and auxiliary systems installation	For FCs and auxiliary systems installation
Design for Modularity	N.A.	N.A.	N.A.

Part II

Design Method

4. DESIGN METHOD

This chapter addresses the research subquestion “*How can a systematic design method be developed to address the challenges of integrating future power systems while ensuring practicality in the design process?*” by proposing a method to future-proof power rooms in superyachts. This method focuses on integrating zero-emission systems during future retrofits. It provides a systematic framework to guide the development, evaluation, and selection of power room layouts adaptable to changes in power systems.

First, in section 4.1, the purpose of the design method is elucidated, highlighting the need for a structured approach to design future-proof power rooms. Then, the chapter outlines the steps of the design method, including layout concepts and design rationale, that are presented respectively in section 4.2 and section 4.3. Finally, the layout evaluation model is presented in section 4.4.

4.1. PURPOSE OF THE DESIGN METHOD

The design method proposed addresses a significant research gap identified in the literature: the lack of a method tailored for designing future-proof power rooms on yachts that can be retrofitted throughout the vessel’s lifecycle. This gap highlights the need for a structured approach that not only speeds up the evaluation of power room layouts but also ensures their resilience to future changes in power systems and regulatory landscapes.

The primary purposes of the design method are: facilitate the rapid evaluation of power room layouts and identify layouts that possess the flexibility and foresight necessary to accommodate potential zero-emission system integration during future retrofits. This is achieved through a structured method encompassing layout concepts, expert opinion filtering, and future-proof evaluation.

The usefulness of the design method lies in its ability to provide designers and engineers with a systematic framework for navigating the complexities inherent to power room design and retrofitting. By synthesizing current industry knowledge, expert insights, and future-oriented methodologies, this approach empowers stakeholders to make informed decisions aimed at enhancing vessel performance, ensuring compliance, and promoting sustainability.

Recognizing the dynamic nature of the maritime industry, characterized by rapid technological advancements and evolving regulations, the method is designed to be proactive. It helps designers anticipate and address challenges related to future power systems integration and regulatory changes by incorporating flexible and adaptable design principles.

The method operates on the premise that power room layouts must not only meet current operational requirements but also possess the adaptability and foresight necessary to accommodate emerging technologies and regulatory shifts. This necessitates an evaluation process that considers factors such as connection costs, retrofit costs, system robustness, and future-proofing potential.

4.1.1. Design Method Steps

To address the main research question, “*How to design a future-proof engine room that facilitates the integration of zero-emission systems during future retrofit of superyachts?*”, a novel design method that unfolds across three main steps is proposed. Below these steps are presented and the graphical flow of the design method is illustrated in Figure 4.1:

1. Layouts concepts - (explained in section 4.2 and then applied in section 6.2): multiple power room layouts are created, drawing from current state of the art and prioritizing ease of retrofit. While theoretically the method could proceed without this step, relying solely on existing layouts for evaluation, the inclusion of new layout concepts ensures a pool of options for evaluation, facilitating the identification of layouts with the highest potential for future-proofing power rooms.
2. Design Rationale - (explained in section 4.3 and then applied in section 6.3): the rationale behind the generated layouts is captured and subsequently these layouts undergo scrutiny from domain experts, providing invaluable insights and perspectives. Through expert feedback, layouts are refined and those deemed inconsistent or impractical are discarded, ensuring that only relevant and viable options are retained for further evaluation.
3. Layouts evaluation model - (explained in section 4.4 and then applied in chapter 7): the retained layouts, endorsed by experts, are subjected to evaluation using a future-proof model. This assessment aims to discern the layouts that best represent future-proofing a yacht, considering the easiness of retrofit and connection costs. Additionally, this evaluation process aims at elucidating best practices for designing a future-proof yacht.

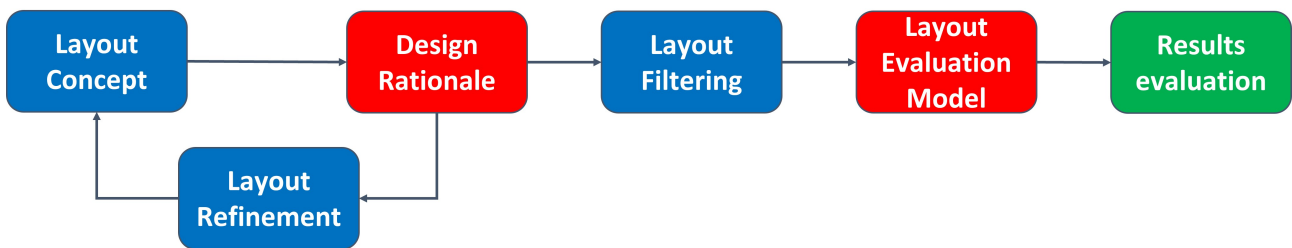


Figure 4.1: Design Method Steps

4.2. LAYOUT CONCEPTS

The goal of this first step is to manually generate a diverse pool of layout options that prioritize ease of retrofit and integration of zero-emission systems while ensuring efficient operation and maintenance across the vessel's lifecycle.

As explained in subsection 2.3.1, the key driven factor in sizing and proportioning systems into a power room is the power demand. Once the power demand of a yacht has been determined, divided between propulsion and hotel load, it is then possible to determine the amount and size of power generation systems that will need to fit into the PR and consequently also the size, dimensions and requirements of the auxiliary systems that have to guarantee proper and safe operations of the PGSs. When designing future-proof PRs, it is mandatory not only to address the type and size of the PGS in the first years of operations but also which PGSs systems will be required throughout the vessel's entire lifecycle, their dimensions and the auxiliary systems they require.

Once all the systems and their dimensions have been determined for the whole vessel's lifecycle, and also the PR dimensions and location are known it is then possible to address the layout disposition of the different systems onboard in the different scenarios considered. To do so, many layout generation tools have been developed, such the one by van der Bles, 2019 that focused on the minimization of PR length and connection costs. However, this method propose a more traditional but practical way of creating layout concepts for later evaluation based on two main pillars:

- Review of existing layouts: examining existing power room layouts from industry standards, previous projects, and case studies. Analyze their strengths, weaknesses, and adaptability to future technologies. This review provides a foundation for understanding conventional approaches and identifying areas for improvement.
- Ease of future retrofit: designing layouts that will facilitate the removal and installation of different systems during future retrofits. This mainly involves considering factors such as accessibility to ensure that future modifications can be implemented efficiently and cost-effectively.

The generation of layout concepts serves as a starting point in the design method, providing a foundation for evaluating the future-proofing capabilities of power room layouts. While theoretically, the method could proceed without this step by analyzing existing layouts, the inclusion of new layout concepts ensures that innovative ideas are taken into consideration. By prioritizing ease of retrofit and integration of zero-emission systems, these concepts contribute to the identification of layouts with the highest potential for future-proofing power rooms aboard superyachts.

It is worth noting that layout concepts can be generated in many ways, and alternative approaches could also fit within this design method. This is due to the fact that the focus of this method and of this thesis is on the evaluation of the future-proofing capability of different layouts, and not on their generation. Thus, it is not particularly relevant how the layout concepts are generated, but they simply serve as a starting point for the evaluation process.

4.3. DESIGN RATIONALE

The design of future-proof power rooms (PR) for superyachts presents a significant challenge. These spaces need to be adaptable to accommodate the integration of zero-emission propulsion systems during future retrofits, while also ensuring efficient operation and ease of maintenance throughout the yacht's lifespan. Traditional design approaches often rely on intuition and past experiences, which may not be sufficient for the complexities of future-proof power room layouts.

This section introduces the second step of the design method based on design rationale for filtering the pool of power room layouts developed after the first step described in section 4.2. Design rationale refers to the underlying reasons, principles, and justifications behind design decisions (le Poole et al., 2022). By capturing and analyzing design rationale, it is possible to gain valuable insights into the thought processes that led to a particular layout proposal.

This section explains how to use design rationale to evaluate the suitability of each proposed layout for future-proof integration of zero-emission systems. By integrating expert feedback within the design rationale framework, this method step aims to:

- Evaluate the strengths and weaknesses of various power room layout proposals based on their underlying justifications and their compatibility with future propulsion technologies.
- Identify potential design flaws or limitations in the layouts that may not be readily apparent in traditional design reviews.
- Facilitate informed decision-making by filtering layouts that demonstrate a strong rationale for future-proof adaptability.

The filtered layouts will then be further analyzed using a model based on mathematical formulas, as described in section 4.4, to determine their performance with respect to connection costs and retrofit

costs. This two-step approach ensures that the most promising layouts, based on both design rationale and objective metrics, are selected for further consideration.

4.3.1. Design Rationale Steps Explanation

Design rationale offers a structured and documented approach for evaluating design decisions. le Poole et al., 2022 and le Poole et al., 2023 explored the application of design rationale in collaborative ship layout design. These works highlight several key aspects of this methodology, two of them are particularly relevant for this thesis, and have been implemented into the design method. As shown in Figure 4.2 these two steps are:

- **Capturing Design Rationale:** this involves documenting the reasoning behind key design choices for each power room layout proposal. This documentation should address factors such as equipment placement, system arrangement, power room accessibility and considerations for future technology integration.
- **Utilizing Expert Feedback:** Integrating feedback from power room arrangement experts is crucial for evaluating the feasibility and future-proof potential of the proposed layouts.

By implementing these key aspects of design rationale, it is possible to evaluate the proposed power room layouts for their suitability in accommodating future zero-emission propulsion systems, filter the layouts that are feasible according to experts' opinions, refine those layouts that require minor adjustments and discard those that are unfeasible according to experts.

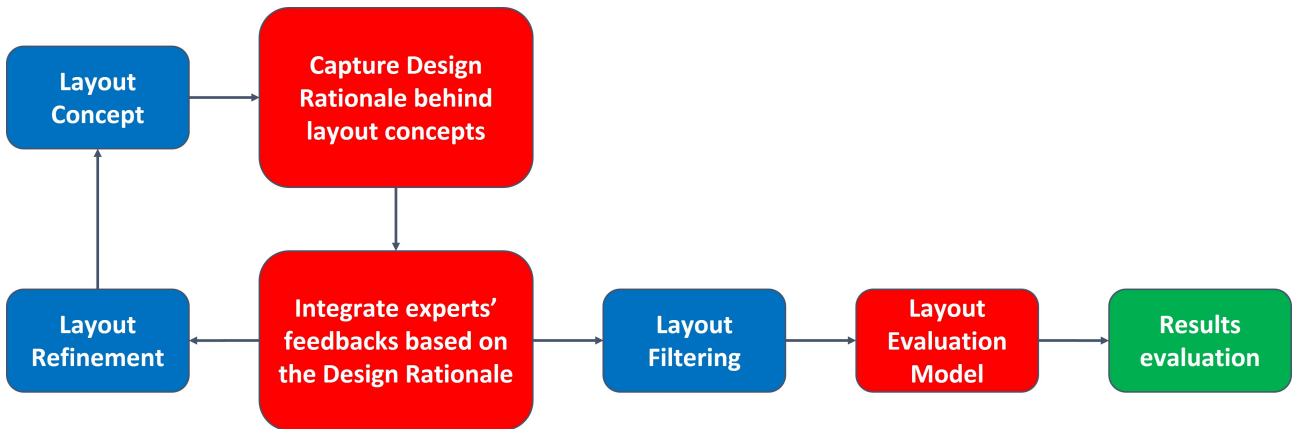


Figure 4.2: Design Rationale steps applied to the Design Method (adapted from le Poole et al., 2022)

4.4. LAYOUT EVALUATION MODEL

Layout Evaluation Model forms the core of the overall design method. It analyzes potential power room layouts based on two primary metrics: Connection Costs (described in section 4.6) and retrofit costs (presented in section 4.5). The former assess the efficiency of the layout in terms of interconnection between systems, while the latter evaluate the ease and cost-effectiveness of adapting the layout to accommodate future operational changes.

4.4.1. Model Structure

The Layout Evaluation Model structure depicted in Figure 4.3, highlight that the model requires various inputs related to building blocks and power room characteristics. Then, based on specific

parameters later presented in section 4.5-4.6, it provides two primary outputs: Total Connection Costs and Total Retrofit Costs, enabling the evaluation of different layout possibilities.

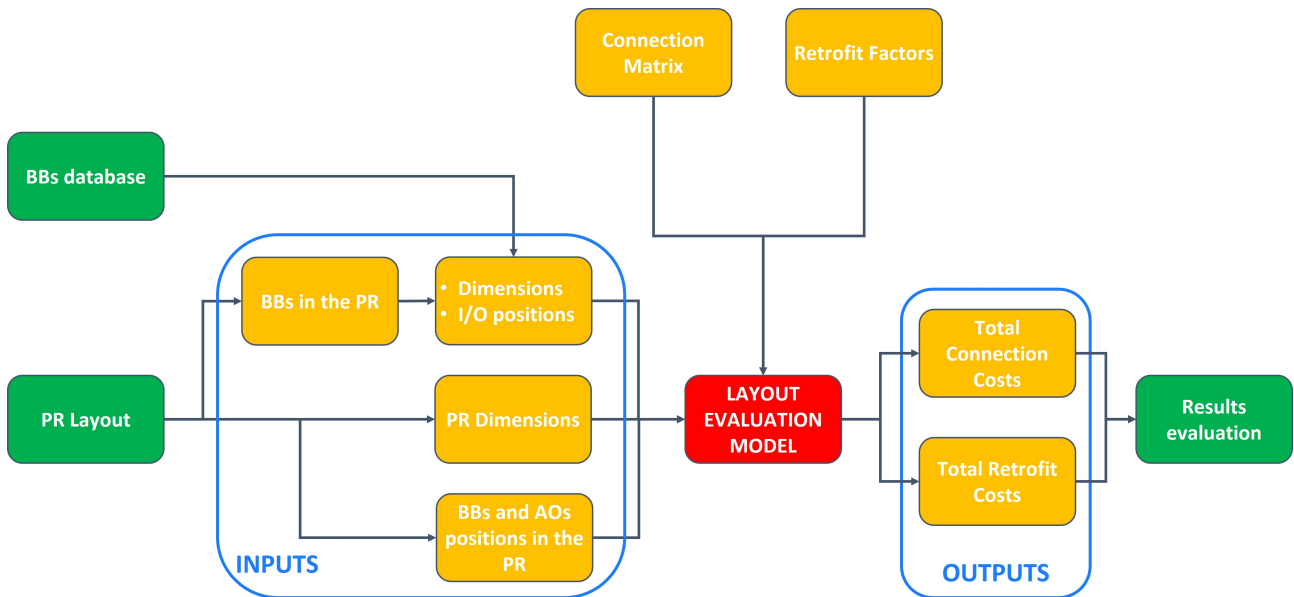


Figure 4.3: Structure of the Layout Evaluation Model

Inputs

The inputs to the layout evaluation model fall into three main categories, Power Room, Building Blocks, and Access Opening, and are reported in the following Table 4.1.

Table 4.1: Inputs to the layout evaluation model

Power Room (PR)	Building Blocks (BBs)	Access Opening (AO)
<ul style="list-style-type: none"> • Dimensions (length, width and height) • Number of decks • Location onboard 	<ul style="list-style-type: none"> • Dimensions (length, width and height) • Weight • Location into the PR • Interfaces position w.r.t. the single BB 	<ul style="list-style-type: none"> • Dimensions (length and width for horizontal AO or width and height for vertical AO) • Location into the PR

For the PR, dimensions, number of decks, and location onboard are essential for understanding the spatial constraints and placement possibilities. BBs inputs include dimensions, weight, location within the power room, and interface positions relative to each block, crucial for assessing easiness of transportation and interconnections with the other BBs.

AO inputs encompass dimensions and location within the power room, pivotal for evaluating accessibility and routing paths. Detailed explanations of the reference system used to determine the BBs’ and AOs’ positions within the PR, as well as interfaces positions relative to each single BBs are provided in the following subsection 4.4.2.

Outputs

As described by Figure 4.3, the model produces two main outputs that serve for layout evaluation:

1. Total Connection Costs (TCC): this output serves to evaluate whether a layout makes sense in terms of BBs disposition into the PR with respect to each other.
2. Total Retrofit Costs (TRC): this other output assesses the future-proofing capabilities of the layouts.

First Output - Total Connection Costs

There are many driven factors to evaluate whether a power room layout is logic. Among them primary importance is given to the Total Connection Costs (TCCs) which has been defined by Poullis, 2022 as the sum of the product of the individual connection distance between two systems and a weight factor given in a connection matrix (CM), which is used to describe the connection type.

As illustrated by Poullis, 2022, two main distance forms exists which are the Manhattan (red, blue and yellow lines in Figure 4.4) and the Euclidean one (green in Figure 4.4) but, as suggested by Poullis, 2022, only the Manhattan distance was considered as a possible and realistic option in a yacht engine room. Equation 4.20 will explain how to properly calculate TCC.

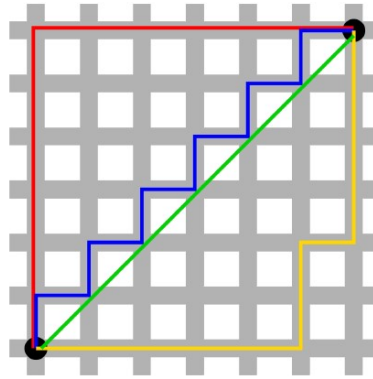


Figure 4.4: Manhattan versus Euclidean distance (Poullis, 2022)

Second Output - Total Retrofit Costs

Retrofit costs are the expenses incurred when modifying a power room to adapt it from one operational scenario to another. Considering retrofit costs during the initial power room design phase is critical for future-proofing the space. By selecting adaptable layouts and components, operators can minimize the effort and expenses associated with future modifications.

A decision flowchart represented in Figure 4.5, was developed with the intention of aiding in the selection of the most suitable methodology among the ones described in chapter 3 (Design for Retrofit, Versatility, or Robustness) based on the extent of modifications necessitated by the new scenario.

The flowchart illustrates a step-by-step process to determine the methodology for transitioning a power room from one scenario (A) to another (B). The initial question determines if minor modifications are sufficient to adapt the existing system to the new scenario. If so, then Versatility is the recommended approach, and Versatility costs will be calculated with the model, as exposed in subsection 4.5.3. Then if minor modifications are not feasible, the flowchart considers if the system needs to be entirely removed and replaced with a new one. If system replacement is necessary, then Design for Retrofit is the appropriate course of action and the Retrofit Costs will be calculated. If removing the system is impractical due to its impact on other parts of the vessel, then Design for Robustness is the recommended approach. This method involves designing the system to function effectively in both the

existing Scenario A and the new Scenario B, in this case there is no cost indicator to be calculated when switching from a scenario to another. As detailed in Table 3.8, to meet the diverse scenario it is not possible to use just one of the presented methodologies but a mixture of them is required, depending on the systems in the different scenarios.

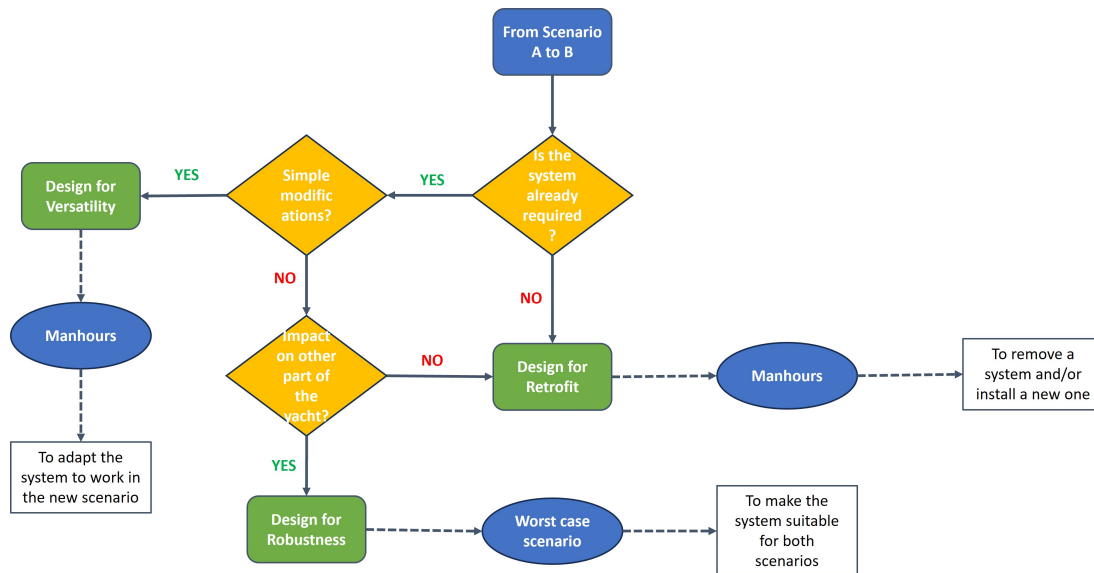


Figure 4.5: Flow chart for methodology decision

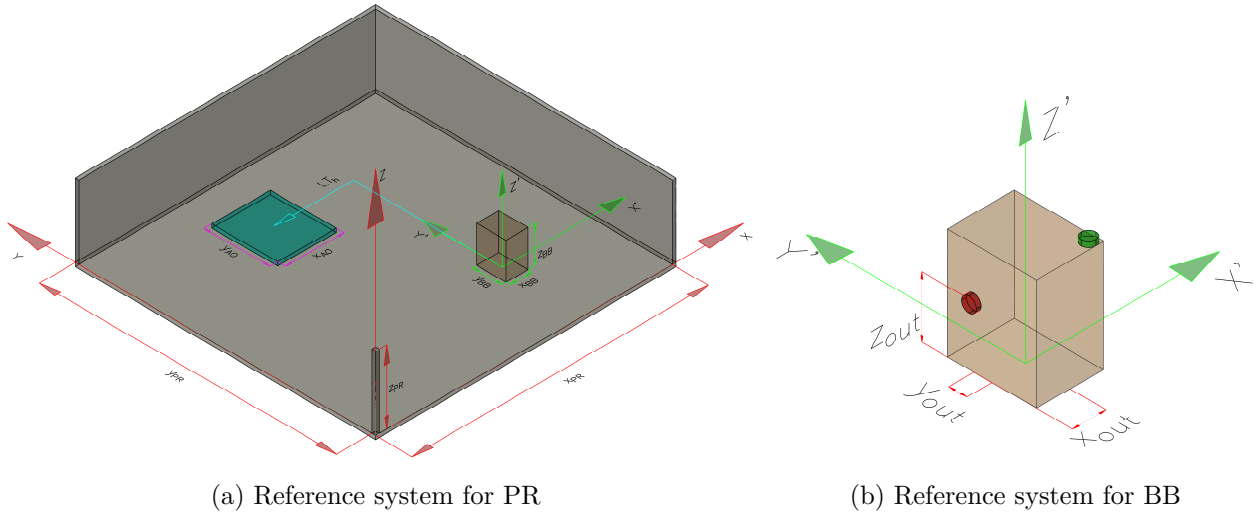
4.4.2. Reference systems

As will be illustrated later, the model often relies on distances calculations, hence to understand and apply the model it is important to acknowledge the reference systems that it uses. In particular two reference systems are defined and shown in Figure 4.6, one to describe the building block and the access opening positions with respect to the power room and the other to highlight the interfaces (input and output) positions with respect to the building block itself.

The first reference system (O, x, y, z) is schematized in red in Figure 4.6a where it is possible to see that it is located at the aft of the PR in the bottom left angle. Moreover, besides showing how to measure the coordinates for the building blocks, the figure shows also how to measure the distance between the BB and the AO, which in this case is in light blue on the floor of the PR. Such a distance will be later defined as length trajectory and is indicated in the figure by LT_h .

As shown in Figure 4.6a, besides the primary reference system there exists also a secondary one (O', x', y', z') presented in green in the figures which, as illustrated in Figure 4.6b, serves to determine the input and output interfaces positions of the BB that are shown in green and red. In Figure 4.6b only the output position is described with red distances but it works the same for the input position.

It is worth mentioning that the interfaces positions shown in Figure 4.6b as well as the BB and AO position presented in Figure 4.6a are just for demonstrative purpose and do not represent real nor realistic configurations.



(a) Reference system for PR

(b) Reference system for BB

Figure 4.6: Reference systems used in the model

4.5. RETROFIT COSTS

As exposed in subsection 3.5.1, according to Coenen et al., 2015, the Total Retrofit Costs (TRC) are given by the sum between the Total Transport Factor (TTF) and the Create Access Factor (CAF), however to consider also the systems that are just converted to work in future scenarios an additional factor called Versatility Factor (VF) is also considered in this thesis, leading to the following equation:

$$TRC = TTF + CAF + VF \quad (4.1)$$

All these parameters are expressed in man-hours and together serve to evaluate the easiness of retrofitting a PR to a certain future-proof pathway (from one scenario to another).

4.5.1. Total Transport Factor

The Total Transport Factor (TTF) is a factor which evaluates the man-hours needed to move a certain building block from its current position to the access opening that makes the power room communicating with the outside of the yacht. TTF was defined by Coenen et al., 2015 as in Equation 4.2:

$$TTF = EoH \cdot FG \cdot (LT_H \cdot TP_H + LT_V \cdot TP_V) \quad (4.2)$$

The terms in the previous equation are defined as follows:

Ease of handling

Ease of Handling (EoH) represents the easiness of handling a certain building block.

$$EoH[-] = a \cdot V_{BB} \cdot m_{BB}^{0.5} \quad (4.3)$$

Where V and m are respectively the volume and the mass of the building block while a is a parameter initially set as $a = 0.01 \frac{kg^{0.5} \cdot m^3}{100}$

Filling Grade

Filling Grade (FG) is the ration between the volume of all the building blocks and the volume of the Power Room:

$$FG[-] = \frac{\sum_{i=1}^N V_{BB}}{V_{PR}} \quad (4.4)$$

Length Trajectory

Length Trajectory (LT) is the distance from the block position to the access opening, with H or V subscript representing the trajectory in horizontal or vertical direction. These have been defined by Coenen et al., 2015 as the transport routes of the system from its position to access opening. Below the equations that account for this transport route have been formulated considering, among the distance types presented in Figure 4.4, the Manhattan one. Moreover, a distinction was made between two main cases: whether the AO are on the same layer of the BB or if they are on separate layers.

If the access opening is on one side of the PR on the same layer of the building block (e.g. in Figure 4.6a), the LT_H factor will be

$$LT_H[m] = |x_{BB} - x_{AO}| + |y_{BB} - y_{AP}| + \frac{L_{BB}}{2} \quad (4.5)$$

where the factor $\frac{L_{BB}}{2}$ takes into consideration the fact that the reference systems refers to the center of the BB and that to carry out the whole BB, it is needed to sum half of its length.

On the other hand, if the access opening is on a different layer from the building block, the LT_H factor must account for the path from the BB position the horizontal access opening (AO_h) position (as in Figure 4.6a) and from there to the vertical access opening (AO_v) position, thus the formula would become:

$$LT_H[m] = |x_{BB} - x_{AO_h}| + |y_{BB} - y_{AO_h}| + |x_{AO_h} - x_{AO_v}| + |y_{AO_h} - y_{AO_v}| + \frac{L_{BB}}{2} \quad (4.6)$$

The LT_V has to be considered only if the building block is on a different layer from the access opening that leads out of the PR and will be given by the following equation:

$$LT_V = z_{BB} - z_{AO_v} \quad (4.7)$$

Transport Penalty

According to Coenen et al., 2015, Transport Penalty (TP) is a factor that accounts for the transport equipment used (the ones considered in this thesis have been described in subsection 3.2.3) and whether it is already present or needs to be installed. However, in Coenen et al., 2015's work, no equation to properly calculate this transport penalty in man-hours so that it can be added to the others TRC factors have been formulated. Thus Equation 4.8 and the parameters used in it, presented in Equation 4.9 - 4.11, have been formulated according to existing systems and experts' advises. Particularly Equation 4.8 has been formulated in such a way to relate the transport factor both to the transport equipment used and to the mass of the BB that has to be moved, accounting also for a complexity factor k to consider the eventual temporary installation of the transport mean and a difficulty factor d_f to account for the specific complexity of using such transport mean in a vessel's PR.

$$TP[h/m] = k \cdot t_f \cdot m_{BB} \cdot d_f \quad (4.8)$$

Where:

- m_{BB} is the mass of the building block to be moved
- k is a weight factor that considers whether and what transport mean has to be installed:

$$k[-] = \begin{cases} 1 & \text{if there is no additional transport mean needed} \\ 5 & \text{if there is the needed to install rails} \\ 10 & \text{if there is the need to install C\&T (and temporary beams)} \end{cases} \quad (4.9)$$

- t_f is a transport factor which defines the velocity at which a BB can be transported and is dependent on the transport mean:

$$t_f\left[\frac{h}{m \cdot kg}\right] = \begin{cases} 0.1 & \text{for BBs moved by hands} \\ 0.05 & \text{for BBs moved by rails} \\ 0.02 & \text{for BBs moved by a C\&T} \end{cases} \quad (4.10)$$

- d_f is a difficulty factor which keeps into consideration the difficulty of moving a BB with a certain transport mean in a vessel's PR.

$$d_f[-] = \begin{cases} 1 & \text{for BBs moved by hands} \\ 0.5 & \text{for BBs moved by rails} \\ 0.7 & \text{for BBs moved by a C\&T} \end{cases} \quad (4.11)$$

As explained in subsection 3.2.3, the decision on the transport equipment to be used is based on three main considerations, which are the maximum weight they can carry, their handleability and their easiness of installation. The weight factors k and d_f have been chosen arbitrarily to account for the complexities in installing and operating certain moving equipment in a PR; after discussion with experts they have been refined in accordance to existing retrofit example and in the end validated and verified in chapter 8. For what concerns the transport factor t_f presented in Equation 4.10, regarding the value for rails as transport mean it has been retrieved from existing systems such the 10 t skidding system by Malm Orstad, 2024 and related to the desired unit of measure ($\frac{h}{m \cdot kg}$) upon calculations. While for Chain & Tackle (C&T), given the lack of references for precise systems and weights, it was discussed with Feadship's yard project managers (with have 30+ years of experience combined) that this transport equipment must have a transport factor (t_f) lower than the one for rails. Moreover, such a system, which is usually used in yachts and smaller ships PRs, has been compared to effective overhead cranes in big ship's engine rooms, as the one described in WinGD manuals (WinGD, 2023a), and the t_f value was tuned and presented in Equation 4.10 so that the one for C&T resulted way lower than a comparable one for overhead cranes.

4.5.2. Create Access Factor

The Create Access Factor (CAF) is a factor that accounts for the need of creating one or more additional access openings in the yacht to carry in and out the systems. These additional access openings are needed when the systems are too big to be carried out via existing openings such as corridors, doors or others.

The CAF accounts both for the amount of steel that need to removed and replaced as well as for eventual pipes or cables that must be removed to create a direct path out of the PR and then reinstalled

after the completion of the retrofit. As the Total Transport Factor, also the CAF is evaluated in man-hours.

Revising and integrating the formulation presented by Coenen et al., 2015, the Create Access Factor formula used is based on three main terms:

$$CAF = SF + DF + CF \quad (4.12)$$

The terms in CAF equation are the Steel Factor (SF), the Ducts and Piping Factor (DF) and the Cables Factor (CF).

Steel Factor

SF stands for the steel factor and evaluates the man-hours need to remove and replace the steel to create the access opening. Simplifying the equation presented by Butler, 2013 (which accounted also for eventual curvature), it can be calculated as

$$SF[manh] = w \cdot UC_s \cdot c = (A_{AO} \cdot t \cdot SG) \cdot UC_s \cdot c \quad (4.13)$$

Where

- w is the mass of steel that has to be removed and replaced which is given by the product between
 - the area of the access opening (A_{AO}),
 - the thickness of the steel (t) in that part of the vessel
 - the specific gravity of the steel (SG) which for common steel is 7.84 but it is common practice for estimators to use 8 (Butler, 2013).
- UC_s is the Unit Cost in man-hours per tonne for the steel removal, it has been presented by Butler, 2013 as function of the steel thickness and the different value used are listed in Table 4.2,
- c is a correction factor that assume different values depending on the position where the access opening has to be created, its values are in Table 4.2 while the position of the different external steel plating are described in Figure 4.7.

Table 4.2: Steel works in man-hours per tonne (Butler, 2013)

Plate thickness [mm]	Man-hours per tonne
< 6	250
8	245
10	240
12.5	230
16	220
18	210
20	200

Location	Position	c [-]
External	Side shell plating	1
	Bottom shell plating	1.12
	Keel plating	1.4
	Deck plating	1.15
	Garboard plating	1.25
	Bilge strake	1.25
Internal	PR floor	1
	PR roof	1
	PR wall	1
	Bulkhead	1.2

Table 4.3: Correction factor for AO position (adapted from Butler, 2013)

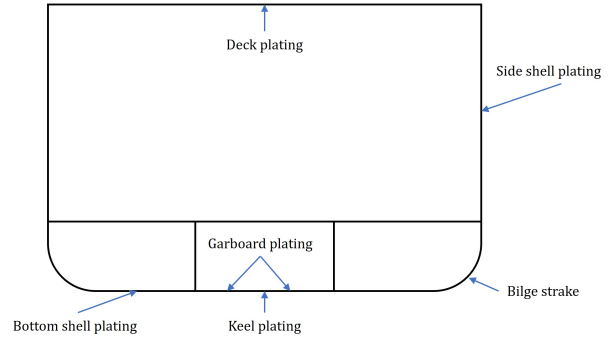


Figure 4.7: External Steel plating position (adapted from Eyres and Bruce, 2012)

Ducts and Pipes Factor

DF is the ducts and pipes factor which takes into consideration the presence of pipes and ducts in the position where the access opening has to be created. This factor has been described by Butler, 2013 as function of the pipes length and diameter.

$$DF = UC_d \cdot c_1 \cdot c_2 \cdot L_d \quad (4.14)$$

Where UC_d is the Unit Cost in man-hours for replacing one meter of pipes as function of the diameter. c_1 and c_2 are correction factors for particular shapes or positions while L_d is the pipe length. However it would be extremely complex and would probably result with inaccurate estimations trying to determine the length and diameter of every pipe and duct in a certain position of the Power Room at this early design stage. Here born the idea of having density factors for pipes, ducts and (as explain in the next paragraph) also for electric cables, shown in Table 4.4 and then estimate the factors DF and CF based on this density factor.

Especially by analyzing the values presented by Butler, 2013, it was possible to establish that for pipes made with 40 steel the man-hours required for removing and replacing one square meters of them are 840 while for 80 steel pipes this number rises to 1000 man-hours. These figures were established by considering the area as a function of pipe length and diameter. For instance for pipes with 10mm of diameter the length to cover one square meter will be 100m while for pipes with 50mm the total length to cover one square meter will be 20m. To be conservative the value for 80 steel type will be used, thus the pipes Unit Cost per square meter will be $UC_d^{(m^2)} = 1000 \frac{manh}{m^2}$, while a correction factor k was considered after discussion with Feadship experts to consider the differences between ducts, flanged and welded pipes:

$$k[-] = \begin{cases} 1.1 & \text{for ducts} \\ 0.8 & \text{for flanged pipes} \\ 1 & \text{for welded pipes} \end{cases} \quad (4.15)$$

Then by considering the densities factors in Table 4.4 on the AO position it will be possible to determine the man-hours required for removing and re-installing pipes and ducts, as function of the cables and ducts densities (ρ_d) and of the access opening area (A_{AO}):

$$DF[manh] = k \cdot UC_d^{(m^2)} \cdot \rho_d \cdot A_{AO} \quad (4.16)$$

Cables Factor

CF is the cables factor which accounts for the costs of removing and re-installing electric cables on the AO position. Butler, 2013 described it as function of the cables cores and their area and length. However, also in this case it would be particular complex in a preliminary design stage to determine the cables cores, areas and length and the decision was to opt for a densities factor on the different areas of the room as shown in Table 4.4.

As for the pipes also in this case it was established a Unit Cost per square meter for removing and replacing electric cables. After an analysis of the different values presented by Butler, 2013, the average costs per square meter in man-hours for cables with different cores was found to be equal to $UC_c^{(m^2)} = 1300 \frac{manh}{m^2}$. Then the cables factor can be calculated as:

$$CF[manh] = UC_c^{(m^2)} \cdot \rho_c \cdot A_{AO} \quad (4.17)$$

	Ducts [m ² /m ²]	Flanged pipes [m ² /m ²]	Welded pipes [m ² /m ²]	Cables [m ² /m ²]
Sides	0	0.15	0.15	0.15
Front	0	0.1	0.1	0.1
Back	0	0.1	0.1	0.1
Floor	0	0.05	0.05	0
Roof	0.05	0.1	0.1	0.1

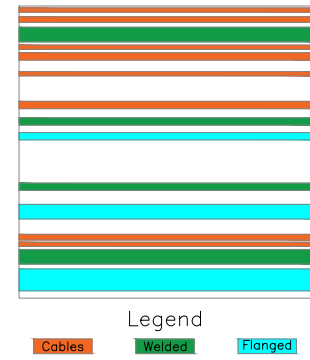


Table 4.4: Pipes, Ducts and Cables densities (ρ) on the different walls of the PR

Figure 4.8: 1m² of PR side (adapted from Feadship 710)

It is worth noting that the densities of ducts, pipes and cables are basically the projected area on the wall occupied by the different elements per square meter of wall. An example of these projected areas (densities) on one square meter of PR side is reported in Figure 4.8 while Appendix E shows how intricate a PR onboard a real yacht is also in terms of pipes, cables and ducts.

4.5.3. Versatility Factor

The versatility factor (VF) accounts for those costs that occur when minor modifications to a system are needed to allow it to operate in a scenario diverse from its original one.

Butler, 2013 provided some general cost values that account for the different possible retrofit operations on engines and other systems, linking them to specific systems characteristic. For instance retrofit costs of engines were related to power output while retrofit costs of pumps to capacity. Overall, it can be stated that the versatility factors are given by the product between a system characteristic (C) and its versatility cost (VC) per characteristics:

$$VF[manh] = C[x] \cdot VC\left[\frac{manh}{x}\right] \quad (4.18)$$

Thus, in the case of an engine where the system's characteristic is the power output the versatility factor is:

$$VF_{engine}[manh] = P[kW] \cdot VC\left[\frac{manh}{kW}\right] \quad (4.19)$$

As will be shown in chapter 5, for the purpose of this thesis, the only systems that incur in versatility costs when going from one scenario to another are the generators when retrofitting from Diesel to Dual Fuel. However, given the low readiness level of engine retrofit kits from diesel to methanol and that figures regarding the man-hours per kW required to retrofit an engine to methanol still have not been released by the suppliers, the estimations used are the ones presented in Table 4.5 gained after interview with Technical Manager at Feadship Refit & Service with 24 years of experience specifically in the field of engine retrofit. It is worth mentioning that the values presented in the table below are estimations that apply to all the different types of methanol ICE exposed in subsection 2.5.1.

Table 4.5: Engine VF from Diesel to DF (developed in accordance with Lloyd's Register, 2023)

Power output [kW]	Engine conversion cost [manh]
0-500	120
501-1000	140
1001-2240	160

4.6. TOTAL CONNECTION COSTS

Connections within the power room are vital components that link various systems together. They encompass a range of physical interfaces, including electrical cables, fuel pipes, and air ducts, facilitating the interaction and functionality of different systems (Poullis, 2022). Understanding the significance of connections is crucial for designing efficient power room layouts, as they influence the overall performance, safety, and operational efficiency of the vessel (De Vos, 2018).

In the context of this thesis, connections play a crucial role in the design method by shaping the layout evaluation process. Rather than focusing solely on the ease of retrofit, connections serve as indicators of the logical coherence and practicality of a layout configuration. A layout with excessive connections length may indicate inefficiencies or impractical arrangements, highlighting the importance of evaluating connection in the different configurations. Despite they can also play a role on the Retrofit Costs in this thesis they have considered as a separate indicator just to assess the logical consistency of PR layouts.

The formula used to establish the total connection costs was given by Drira et al., 2007 and later implemented by van der Bles, 2019 and Poullis, 2022. However, they all considered only the connections on a same level, while in this case to be able to address also the connections on multiple layers of a power room, also the distance along the z coordinate was introduced:

$$\sum_{i=1}^N \sum_{j=1}^N CM_{ij} \cdot d_{ij} = \sum_{i=1}^N \sum_{j=1}^N CM_{ij} \cdot (|x_{i_{out}} - x_{j_{in}}| + |y_{i_{out}} - y_{j_{in}}| + |z_{i_{out}} - z_{j_{in}}|) \quad (4.20)$$

In this equation, d_{ij} represent the distance between the output position of component i and the input position of component j in rectilinear (or Manhattan) form, as shown in Figure 4.4.

4.7. SYSTEMS DESIGNED FOR ROBUSTNESS

As mentioned earlier, the systems that have a huge impact on other areas of the yacht besides the Power Room will be designed for Robustness, thus able to work both in the current scenario and in a future one. After interviews the only system that has a huge impact on other part of vessel and cannot be designed for versatility or for retrofit is the Ventilation System. Indeed, it is not doable to remove the casing ducts and replace with bigger or smaller ones. They spread over many areas of the yacht, usually up to the mast also through luxurious spaces, and the amount of work to remove and replace them would be enormous not justifying it.

Hence the choice is to design the ventilation system for robustness, meaning that the ventilation onboard should be able to fulfill the requirements of the power room in the delineated scenarios. The method used to calculate the PR ventilation requirement in scenario 0 is retrieved directly from the ISO 8861:1998, 1998 and it is described in section B.1, then the differences in the ventilation requirements and calculations with the use of Fuel Cells are analyzed in section B.2.

4.8. PRACTICAL EXAMPLE OF THE LAYOUT EVALUATION MODEL

In this section, to get a better understanding on the working of the model a practical example is provided. This practical example does not represent neither an existing power room nor a realistic one but serves just to explain the model and its calculations in an easier way. As shown in its 3D representation in Figure 4.9, it presents a 2 layers PR with just 5 Building Blocks (BBs) which dimensions and positions are reported in Table 4.6. The dimensions taken are the same that will be considered in the real model application in chapter 4 and that are presented in chapter 5. On the other hand, the two layer PR is considered with both length and width equal to $8m$ while the height of the 1st layer is equal to $2m$ and the one of 2nd layer to $2.3m$.

Table 4.6: Practical example BBs' dimensions and positions

	Dimensions			Weight [t]	Position		
	Length [m]	Width [m]	Height [m]		X [m]	Y [m]	Z [m]
Diesel gensets	4.204	1.693	1.747	7.131	4.500	6.500	0
LT cooling system	1.750	4.340	1.000	1.500	1.375	2.670	0
Diesel supply	0.600	0.800	1.000	1.000	4.000	6.500	2.000
SCR+DPF	3.953	0.935	1.500	0.600	7.200	4.250	2.000
AC-DC converter	0.644	0.900	2.000	0.700	0.322	4.250	2.000

The BBs' positions refers to the reference systems described in subsection 4.4.2 which is also shown in red in Figure 4.9. As stated earlier the reference system of the PR (O, x, y, z) is located on the stern side in the bottom left corner with x-axis in longitudinal direction, y-axis in transversal and z-axis in vertical direction. Moreover to properly calculate the TCC the position of the input and output interfaces, has to be defined, thus a secondary reference system is needed. This is indicated by (O', x', y', z') and it is located in the center of the floor of every BB.

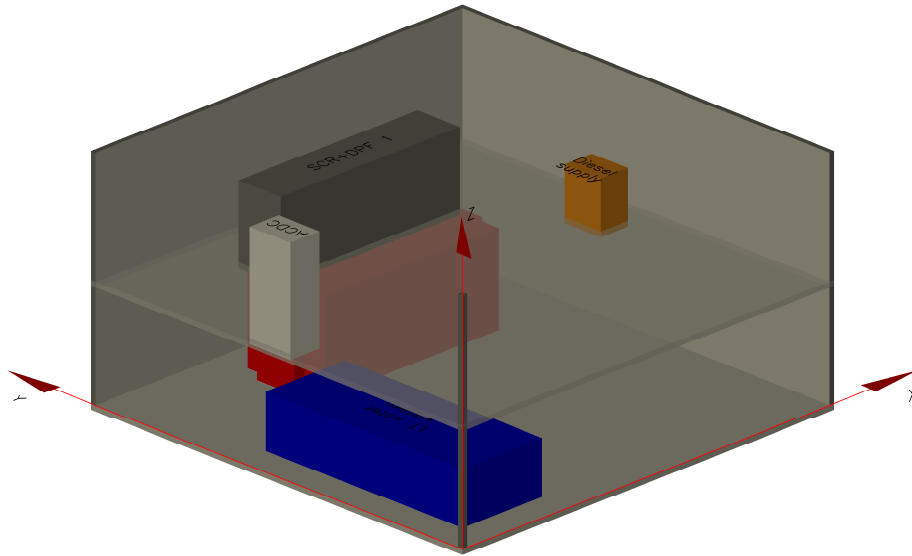
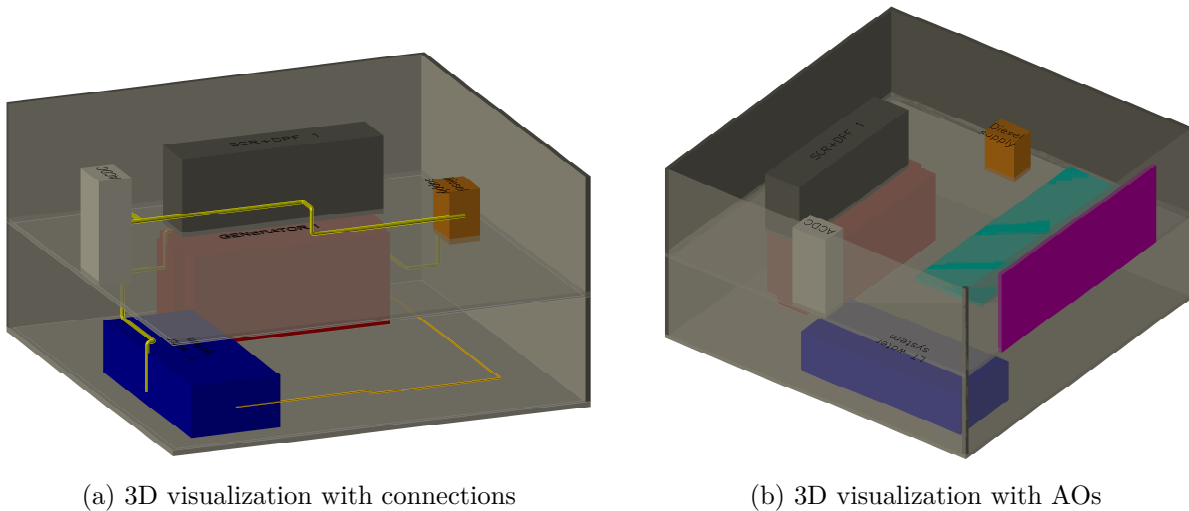


Figure 4.9: Practical Example 3D visualization with reference system



(a) 3D visualization with connections

(b) 3D visualization with AOs

Figure 4.10: Practical example 3D visualization with connections and AOs

4.8.1. Total Connection Costs for the practical example

As shown in Figure 4.10a, the different BBs in the PR are connected with pipes and cables and depending on the BBs the connections can be of different types. The connections among the difference systems have been considered and weighted with the same values later used in the real application of the model, reported in Table 5.6 and 5.7, while the connection matrix for this practical example is shown in Figure 4.11. The interfaces positions presented in Table 4.7 are the same used in the real application of the model presented in Table 5.8. It is important to note that in this case the measures are not in meters but have to be multiplied for the BBs' dimensions. X and Y can range from -0.5 to 0.5 while Z from 0 to 1. For instance if the input position of a certain BB is $(0.5; 0.5; 1)$ it means that the interface position is on the top of the BB in its forward right corner.

	Input			Output		
	X	Y	Z	X	Y	Z
Diesel genset	0.5	0	0.25	-0.5	0	0.75
LT cooling system	0	-0.5	0.25	-0.5	0	0.5
Diesel supply	0	-0.5	0.5	0	0.5	0.5
SCR+DPF	-0.5	0	0	0.5	0	0.75
AC-DC converter	0.5	0	0.5	0.5	0	0.5

Table 4.7: I/O positions for practical example BBs

TOY EXAMPLE	Diesel genset	LT cooling system	Diesel supply	SCR+DPF	AC-DC converter
	Diesel genset	2	1	3	1
LT cooling system	1	0	0	0	1
Diesel supply	1	0	0	0	1
SCR+DPF	3	0	0	0	0
AC-DC converter	1	1	1	0	

Figure 4.11: CM for practical example

Considering the CM presented in Figure 4.11, and applying Equation 4.20 it is possible to establish the TCC of this practical example. Without applying the weight factors $\sum_{i=1}^N \sum_{j=1}^N d_{ij} = 57.3m$ while considering the different weight factors in Figure 4.11, thus prioritizing certain connection types, $TCC = \sum_{i=1}^N \sum_{j=1}^N CM_{ij}d_{ij} = 86.9m$

4.8.2. Total Retrofit Costs for the practical example

For the purpose of this practical example the total retrofit costs (TRC) for the removal of a generator via two access openings will be calculated. Both the AOs will be considered of the “*To be created type*” among the ones described in subsection 3.2.2, so they require work both for steel and for pipes and cables removal. The two AOs for which the generator will pass are shown in Figure 4.10b respectively in light blue the horizontal one and in fuchsia the vertical one, their dimensions and positions are reported in Table 4.8

Location	Dimensions			Position		
	Width [m]	Length/Height [m]	Thickness [mm]	X [m]	Y [m]	Z [m]
Vertical	5.6	2	8	4.0	0	2.0
Horizontal	5.6	1.8	8	5.2	2.4	2.0

Table 4.8: AOs characteristics for the practical example

Considering the absence of systems to be converted, among the terms in Equation 4.1, the one representing versatility costs (VC) will be equal to 0 in this case. For what concerns the other two terms: Total Transport Factor (TTF) and Create Access Factor (CAF) they have been calculated applying respectively Equation 4.2 and Equation 4.12. For the TTF it was calculated that to remove the generator it has to be transported for $2m$ in vertical direction and for $10.5m$ in horizontal direction. Then it was calculated $EoH = 0.33$ and $FG = 0.21$ and considering the C&T to be installed as transport equipment both for horizontal and vertical transportation $TP_h = TP_v = 99.8h/m$, all this terms applied in Equation 4.2 leads to $TTF = 87.6manh$

On the other hand the CAF is calculated in Equation 4.12 summing the steel factor (SF), the pipes and ducts factors (DF) and the cables factor (CF) and applying the equations and parameters presented in subsection 4.5.2. Summing the contributions of both the AOs described in Table 4.8 these term result respectively as $SF = 334manh$, $DF = 5393manh$ and $CF = 3494manh$ for a total $CAF = 9221manh$ which summed to the TTF leads to a Total Retrofit Cost $TRC = 9308manh$.

Part III

Method Application and Results

5. SCENARIOS EXPLANATION

The previous chapters introduced a design method aimed at future-proofing power rooms, focusing on adaptability for future retrofits rather than being fixed to the initially allocated systems.

This chapter outlines four distinct scenarios that, as shown in Figure 5.1, vary in terms of the types and configurations of generators, fuel cells, and batteries. They are central to addressing the research subquestion: *“How do different scenarios, varying in terms of power system configurations and integration complexities, impact the layout and design considerations of power rooms in superyachts?”*

The chapter explores each scenario’s characteristics and implications for power room layout and design. First of all section 5.1 details the systems present in different scenarios, followed by explanations of each scenario in section 5.2 - 5.5. Considerations regarding connections and specific challenges associated with zero-emission systems are then addressed respectively in section 5.6 and section 5.7.



Figure 5.1: Systems involved in the different scenarios

5.1. SYSTEMS IN THE DIFFERENT SCENARIOS

The thesis will center its focus on Power Rooms and scenarios for an average Feadship yacht which length, gross tonnage and power characteristics are reported in Table 5.1:

Table 5.1: Average Feadship characteristics

Average Feadship characteristics			
Length Overall	Gross Tonnage	Propulsion Power	Hotel Load
$LOA[m]$	$GT[GT]$	$P_P[kW]$	$P_H[kW]$
80	2250	3000	1800

Besides the main Power Generation Systems described in Figure 5.1, the different scenarios involve many other systems which are responsible for the proper working of the power generating ones and for guaranteeing safety during the Power Room operations. These systems have been described in section 2.2 for what concerns the systems in a current PR such the one of Scenario 0, while the new systems required when switching to alternative fuels have been covered in section 2.6.

As shown in Table 5.2, the presence or absences of the different systems depends on the scenario. The systems presented in the table will be later treated as Building Blocks (BBs) that will constitute the starting point for the layout concepts and model application in a later stage.

Table 5.2: Subsystems involved in the different scenarios

Location	Systems	Scenario 0 Diesel ICEs + batteries	Scenario 1 Diesel ICEs + FCs + Batteries	Scenario 2 DF ICEs + FCs + Batteries	Scenario 3 FCs + Batteries
Power room	Diesel gensets	✓	✓	✗	✗
	DF gensets	✗	✗	✓	✗
	Fuel cells	✗	✓	✓	✓
	Ventilation	✓	✓	✓	✓
	Oil Lubrication	✓	✓	✓	✗
	Fresh water system	✓	✓	✓	✓
	Seawater cooling system	✓	✓	✓	✓/ ✗
	LT cooling system	✓	✓	✓	✓/ ✗
	HT cooling system	✓	✓	✓	✓/ ✗
	WHRS	✓	✓	✓	✓
	Diesel Bunkering station	✓	✗	✗	✗
	Diesel supply	✓	✓	✓	✗
	Diesel transfer	✓	✓	✓	✗
	SCR+DPF	✓	✓	✓/ ✗	✗
	Oxicat	✗	✗	✓/ ✗	✗
	Nitrogen system	✗	✓	✓	✓
	ARAFF system	✗	✓	✓	✓
	MeOH Safety system	✗	✓	✓	✓
	DF Bunkering station	✗	✓	✓	✓
	MEoH bilge system	✗	✓	✓	✓
Battery room	Battery racks	✓	✓	✓	✓
	Ventilation	✓	✓	✓	✓
Switchboard room	DC-DC converters	✓	✓	✓	✓
	AC-DC converter	✓	✓	✓	✓
	Ventilation	✓	✓	✓	✓

5.1.1. Building Blocks dimensions and other data

There is a main distinction that can be made while analyzing the different building blocks:

- Power Generation Systems (PGSs)
- Energy Storage Systems (ESSs)
- Auxiliary Systems

The PGSs are the systems responsible for generating electric power and thus, for the purpose of this thesis, are generators (both Diesel and Dual Fuel ones) and Fuel Cells, while ESSs are devices responsible for storing energy and later supply it to consumers: as described in subsection 2.2.2, in this thesis Batteries are the only ESS considered. On the other hand the auxiliary systems are responsible for three main tasks:

1. Guarantee a efficient operation for the PGSs and the ESSs
2. Guarantee safe operation in the different spaces
3. Transfer and convert the electric energy generated by the PGSs

Given the different relevance between PGSs and ESSs and the Auxiliary Systems while determining their Building Blocks dimensions they have been treated differently. The generators and FC's dimensions and main characteristics have been determined by analyzing different specifications of different suppliers has reported below.

Generators

Table 5.3 reports for different ranges of power outputs the main dimensions, and relevant characteristics for cooling and ventilation. All the data are presented as function of the power outputs and has been retrieved by considering 25 different generator sets for marine application from MTU and CAT.

Table 5.3: Main data for generators

	Diesel Generators			
	Power Range [kW]	0-500	501-1000	1001-2240
Total Radiation and Conv. Heat at 2 m/s [kW/kW]		11.2	25.6	32.0
Combustion air volume flow [m^3/MWh]		4641	5277	5086
Exhaust volume flow [m^3/MWh]		10266	11094	11708
Heat rejection to HT Cooling System (Jacket water) [kW/kW]		1.9	1.6	1.3
Heat rejection to LT Cooling System (Aftercooler) [kW/kW]		5.0	6.8	3.9
Area [kW/m ²]		75	73	200
Volume [kW/m ³]		42	35	88
Weight [kW/t]		100	90	121

The table above reports data for Diesel generators, such data are not yet available for DF ICE, however experts believe that the DF generators coming in the next years will have the same characteristic as current Diesel ones both in terms of dimensions and in terms of ventilation and cooling requirements.

Fuel Cells

As for generators, also for FCs not only the data related to footprint and weight have been considered but also those inherent to cooling and ventilation. In this case, the data in Table 5.4 are the most reliable one available between Feadship's suppliers, but it is worth noting that they will probably change given the room for improvement for FCs.

Table 5.4: Main data for Fuel Cells

	Fuel Cells			
	FC type	LT PEM FC	HT PEM FC	SOFC
Air in [m^3/MWh]		9500	8500	19400
Air out [m^3/MWh]		9500	8500	20900
Water cooling flow [m^3/MWh]		23	32	-
Heat rejection water cooling [kW/kW]		5.1	1.6	-
Heat recovery rate [kW/kW]		-	-	2.2
Area [kW/m ²]		22	22	33
Volume [kW/m ³]		12	13	18
Weight [kW/t]		69	87	35

Auxiliary Systems

On the other hand, the main dimensions of the different BBs for the auxiliary systems, which represent a key aspect in the development of PR layouts have been determined considering the dimensions of existing or similar BBs onboard current Feadship yachts. Even if the dimensions can differ from yacht to yacht depending on the vessel dimensions and power requirement, Table 5.5 presents the dimensions for systems onboard an average Feadship. The data have been retrieved by analyzing previous similar Feadship projects and from Feadship suppliers info for what concerns methanol dealing systems.

Table 5.5: Auxiliary systems BBs dimensions

Location	Systems	Dimensions					
		Length [m]	Width [m]	Height [m]	Area [m ²]	Volume [m ³]	Weight [t]
Power room	Oil Lubrication	0.5	0.5	1.0	0.3	0.3	0.2
	Fresh water system	2.0	1.5	1.0	3.0	3.0	1.0
	Seawater cooling system	1.1	2.9	1.0	3.2	3.2	1.0
	LT cooling system	1.8	4.3	1.0	7.6	7.6	1.5
	HT cooling system	2.0	1.5	1.0	3.0	3.0	1.0
	WHRS	1.6	0.4	2.0	0.6	1.3	1.0
	Diesel bunkering station	1.2	1.0	1.0	1.2	2.4	0.3
	Diesel supply	0.6	0.8	1.0	0.5	0.5	1.0
	Diesel transfer	2.5	1.0	1.5	2.5	3.8	1.0
	SCR+DPF	4.0	0.9	1.5	3.7	5.5	0.6
	Oxicat	0.4	0.9	0.7	0.4	0.3	0.2
	Nitrogen system	2.5	0.7	2.0	1.8	3.5	1.0
	ARAFF system	0.6	1.3	1.5	0.8	1.2	1.0
	Safety system	0.8	0.6	1.5	0.5	0.8	0.5
	DF bunkering station	1.2	1.0	1.0	1.2	1.2	0.3
	MEoH bilge system	1.5	1.0	1.0	1.5	1.5	1.0
	MeOH transfer	1.0	2.0	1.0	2.0	2.0	1.0
MeOH supply	1.0	2.0	1.0	2.0	2.0	1.0	
MeOH manifold	1.5	1.0	1.0	1.5	1.5	1.0	
Switchboard room	DC-DC switchboard	0.6	0.8	2	0.5	1.5	0.7
	AC-DC switchboard	0.6	0.9	2.0	0.6	1.2	0.7

5.2. SCENARIO 0

Scenario 0, featuring a Diesel-Batteries power plant, represents the baseline for the future-proofed designs that will be explored in subsequent sections. As already described in subsection 2.2.1, to allow such systems working properly and to distribute the energy to all the consumers, there are many other auxiliary systems required. A flow diagram depicting the various systems, their physical locations (rooms) onboard and their connections within Scenario 0 is shown in Figure 5.2. The arrows in the figure represent the different types of connections that exist between the various systems: grey arrows represent ducts, blue ones pipes and yellow arrows electric cables.

The flow diagram reveals the interactions between various PR systems and their connections. In this scenario the diesel generators are the primary source of power generation. They convert diesel fuel into AC current which is then converted, in AC-DC switchboards, into DC current to be used for propulsion and hotel loads or to charge batteries. The battery bank can then supply power when the diesel generators are not running, or supplement the generators during peak loads. Moreover the auxiliary systems such as cooling, oil lubrication and ventilation ensure smooth and safe operations.

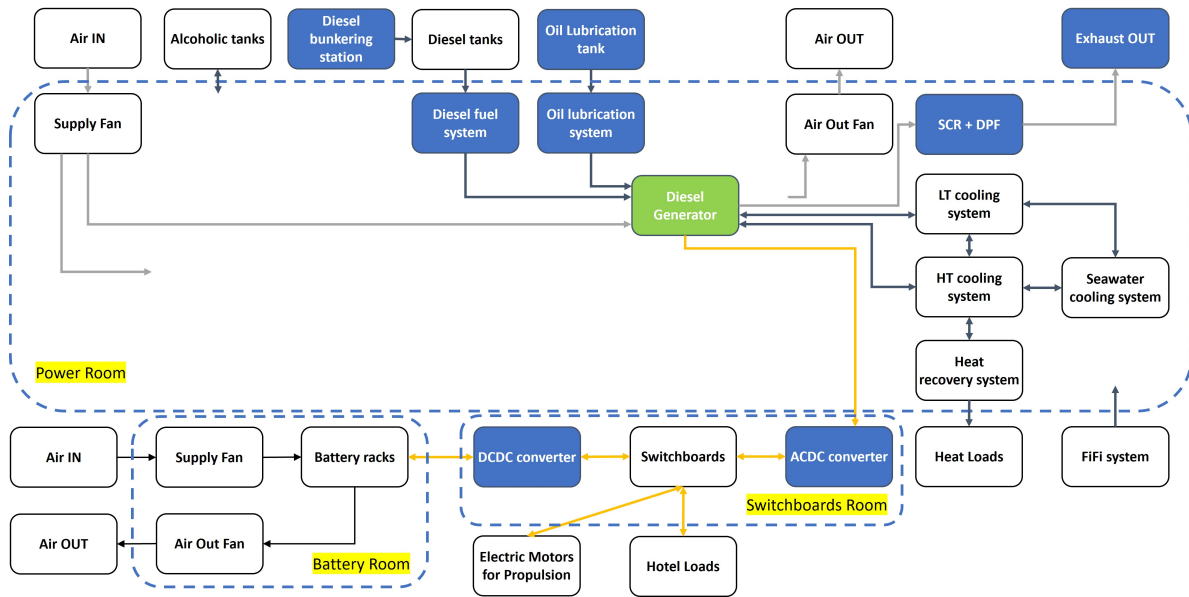


Figure 5.2: Flow diagram for Scenario 0

The flow diagram above, while providing a clear picture of the current system’s complexity, also highlights challenges for future-proofing the power room. These challenges arise from the intricate network of connections (pipes, ducts, and cables) between various systems. Retrofitting the power room to accommodate future zero-emission systems, such as fuel cells, will likely require modifications to these connections. New systems may have different space requirements and necessitate adding new connections, while potentially removing existing ones.

The flow diagrams serve for efficiently comparing future scenarios with Scenario 0. By comparing the flow diagrams, it will be identified which systems and connections need to be modified or replaced entirely. This information will be crucial for the design method to evaluate different layouts and identify the most logical and cost-effective configurations, in terms of Connection Costs, for future-proof PRs.

5.3. SCENARIO 1

Scenario 1 introduces the first future-proof design step for the vessel’s power room. It incorporates fuel cells alongside the existing Diesel-Batteries system from Scenario 0, with the purpose of using FCs for hotel loads allowing for zero-emission and silent operation while at anchor or for short transits.

The layout for Scenario 1 maintains the core components from Scenario 0, including the diesel generators, battery bank, and various auxiliary systems like cooling, lubrication, and ventilation. New additions required for fuel cell, and the fuel cell block itself, are highlighted with a red border in the flow diagram in Figure 5.3. These new additions include:

- **Fuel Cell Stack:** the fuel cell stack converts chemical energy from the alcoholic fuel into electricity. Inside the stack besides the proper fuel cells there are other systems such as an exhaust cooler and a reformer (in PEM FC case), however in the flow diagram and in this thesis Fuel Cell represents the whole block with the different subsystems already included in it.
- **Alcoholic Fuel System:** this system supplies fuel to the fuel cell. The diagram depicts a separate room around it which is the Fuel Preparation Space (FPS), which as described in section 2.6 hosts all the alcoholic fuel-dealing systems.

- Dedicated outtake ventilation systems for the FPS: this dedicated air outtake system is responsible for guaranteeing safety conditions in the FPS.
- Nitrogen system: it is needed to keep alcoholic tanks blanketed and inerted.
- ARAFFF systems: it is a fire suppression system specifically required when dealing with alcoholic fuels.

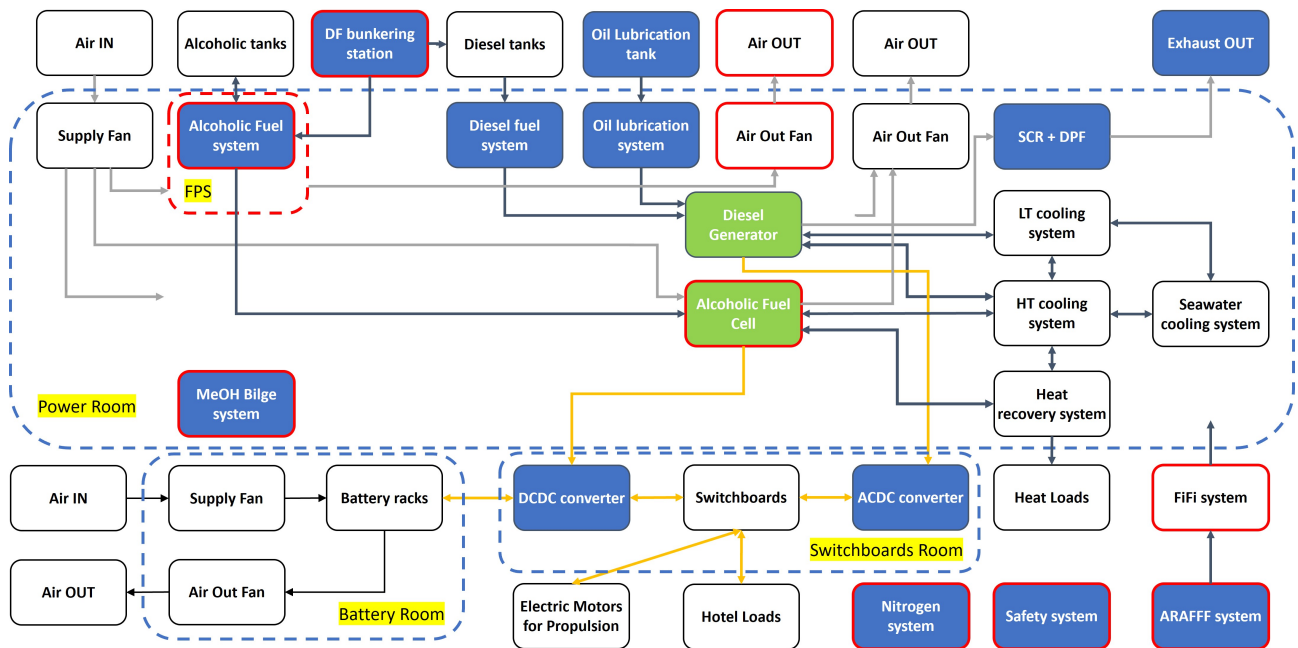


Figure 5.3: Flow diagram for Scenario 1

While the flow diagram offers a valuable scheme for Scenario 1, it also reveals design challenges that need to be addressed for successful implementation. First of all the red-bordered additions in the flow diagram highlight that many new components will be added in this scenario, requiring for new footprint. Moreover, Figure 5.3 depicts the increased number of connections required for the fuel cell system. This highlights the potential for increased connection costs, suggesting to keep connections well into consideration in the design method.

5.4. SCENARIO 2

Scenario 2 introduces a further step towards a zero-emission power room design by incorporating Dual Fuel generators. The layout for Scenario 2 retains many of the core components from Scenario 1, including the fuel cell system, battery bank, and various auxiliary systems (cooling, lubrication, ventilation). However, the most significant change involves replacing the existing diesel generators with Dual Fuel ones that are highlighted with a red border in the flow diagram in Figure 5.4. Besides DF generators the flow diagram illustrates the presence of another new system: the Oxicat which is an oxidation catalyst needed to significantly reduce the emissions given by the unburnt alcoholic fuels (Wei et al., 2017).

In Figure 5.4, the SCR+DPF and the Oxicat blocks are lightly shaded to indicate that these systems might not be required for all applications, such as SI ICE, as described in subsection 2.5.1.

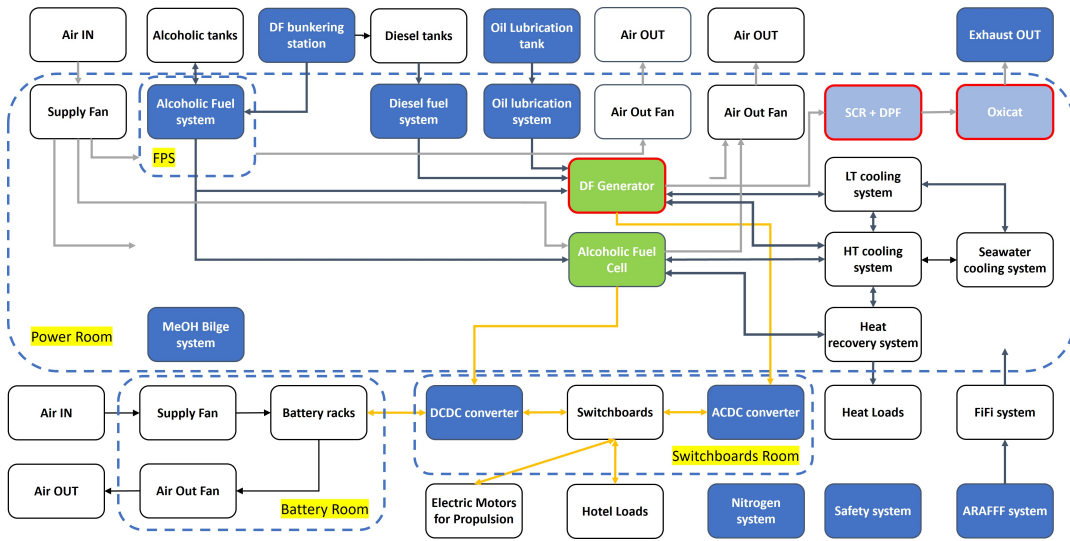


Figure 5.4: Flow diagram for Scenario 2

While Scenario 2 offers environmental benefits through the use of Dual Fuel generators, the flow diagram also highlights design the presence of new connections that can complicate the integration of such systems onboard. Particularly in addition to Scenario 1, in this case there exist a new connection between the alcoholic fuel system and the DF generator. Once again complexity of connections underscores the critical role they play on the design layout, suggesting for careful consideration later in the future design method development.

5.5. SCENARIO 3

Scenario 3 depicts a complete zero-emission power room design that exclusively relies on fuel cells for power generation by removing generators and all their related auxiliary systems, as shown in Figure 5.5. The remaining core components from Scenario 1 and 2 are maintained . These include the fuel cell systems and all its auxiliary components, switchboards and batteries that in this scenario will be particularly relevant during the fuel cell startup and to supplement peak loads.

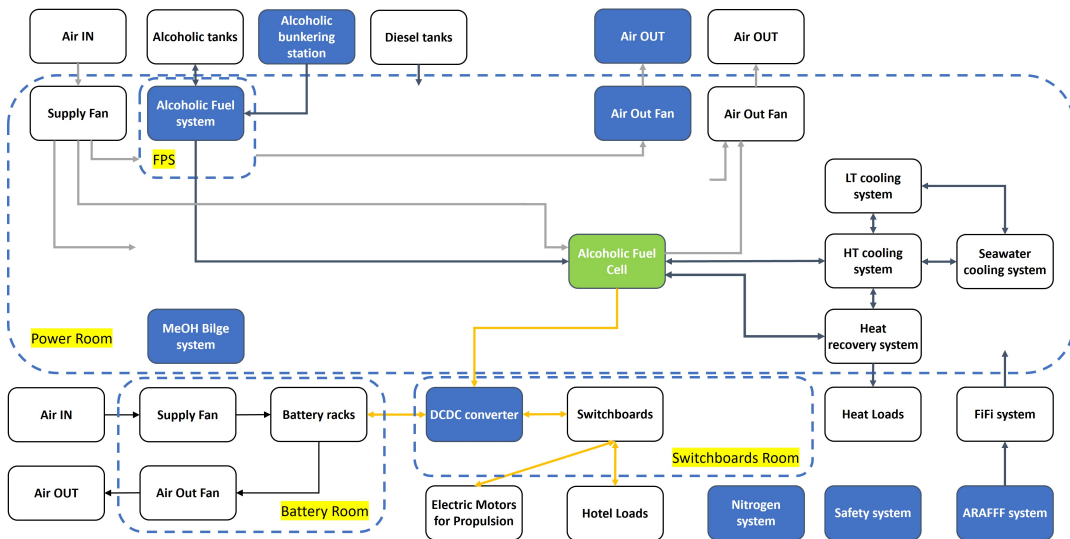


Figure 5.5: Flow diagram for Scenario 3

The flow diagram shows that this scenario has simpler connections compared to scenarios 1 and 2, due to relying on a single type of PGS and requiring fewer auxiliary systems. Despite the simpler appearance in terms of connection this scenario presents a critical challenge in terms of power density. Indeed, current FC energy density does not allow having a FC only PR in the same area and volume of a current PR. As will be detailed in subsection 6.1.1, since the design method considered in this thesis specifically addresses PRs that maintain fixed dimensions throughout different scenarios, this scenario will become relevant only when FCs will have an energy density comparable to the ones of generators. As detailed in subsection 6.1.3 this is expected around 2040, but since the designed method presented in this thesis is a future-proof one, this advancement in FCs technology is already taken into consideration, and this scenario is studied as the last step of the future-proof road-map.

5.6. CONNECTIONS

As explained in section 2.3, connections among different systems are crucial in the layout arrangement. Throughout the scenarios considered, specific connections are modified to accommodate changes in system configurations. Methanol pipes, nitrogen pipes, and DC electric cables are added for FCs, while additional ducts and methanol and nitrogen pipes are needed for DF generators. Conversely, removing diesel generators eliminates diesel pipes and cooling system water piping and AC electric cables.

Table 5.6 presents an overview of the various connections within the power room, highlighting inputs and outputs between different systems. Each row represents a specific system, detailing the inputs received from other systems (in column “Inputs from”) and the outputs provided to others (in column “Outputs to”). The “Inputs” and “Outputs” columns specify the type of connection used between systems, such as fuel pipes, electrical cables, or air ducts.

Location	Systems	Inputs	Inputs from	Outputs	Outputs to
Power room	Diesel gensets	AC electric cable	AC switchboards	AC electric cable	AC switchboards
		Diesel piping	Diesel supply	Water piping	HT system
		Water piping	HT system	Water piping	LT system
		Water piping	LT system	Exhaust ducts	SCR+DPF
		Oil piping	Oil lubrication		
	DF gensets	MeOH piping	MeOH supply	AC electric cable	AC switchboards
		Diesel piping	Diesel supply	Exhaust ducts	SCR+DPF
		Water piping	HT system	Water piping	HT system
		Water piping	LT system	Water piping	LT system
		Oil piping	Oil lubrication	Exhaust ducts	Oxicat
	Fuel cells	DC electric cable	DC switchboards	DC electric cable	DC switchboards
		MeOH piping	MeOH supply	Water piping	HT system
		Water piping	HT system		
	Ventilation	Ventilation ducts	Casing In	Ventilation ducts	Casing out
		AC electric cable	AC switchboards		
	Oil	Oil piping	Oil tanks	Oil piping	Diesel gensets
	Lubrication	AC electric cable	AC switchboards	Oil piping	DF gensets
	Fresh water system	Water piping	Sea chests	Water piping	Users
		AC electric cable	AC switchboards		
	Seawater system	Water piping	Sea chests	Water piping	LT system
AC electric cable		AC switchboards	Water piping	HT system	
LT cooling system	Water piping	HT system	Water piping	HT system	
	Water piping	Seawater system	Water piping	Seawater system	
	AC electric cable	AC switchboards	Water piping	Diesel gensets	
			Water piping	DF gensets	

Continued on next page

Location	Systems	Inputs	Inputs from	Outputs	Outputs to
Power room	HT cooling system	Water piping	LT system	Water piping	LT system
		Water piping	Seawater system	Water piping	Seawater system
		Water piping	WHRS	Water piping	WHRS
		AC electric cable	AC switchboards	Water piping	Diesel gensets
		Water piping		Water piping	DF gensets
		Water piping		Water piping	Fuel cells
	WHRS	Water piping	HT system	Water piping	HT system
		AC electric cable	AC switchboards	Water piping	Heat loads
				Water piping	Fuel cells
	Diesel Bunkering station	Diesel piping	from shore	Diesel piping	Diesel tanks
	Diesel supply	Diesel piping	Diesel tanks	Diesel piping	Diesel gensets
		AC electric cable	AC switchboards	MeOH piping	DF gensets
	Diesel transfer	Diesel piping	Diesel tanks	Diesel piping	Diesel tanks
		AC electric cable	AC switchboards		
	SCR+DPF	Exhaust ducts	Diesel gensets	Exhaust ducts	Outside
		Exhaust ducts	DF gensets	Exhaust ducts	Oxicat
	Oxicat	Exhaust ducts	SCR+DPF	Exhaust ducts	Casing out
	Nitrogen system	Nitrogen piping	Nitrogen tank	Nitrogen piping	MeOH tanks
		AC electric cable	AC switchboards	Nitrogen piping	DF gensets
				Nitrogen piping	Fuel cells
	ARAFFF system	Water piping	Fresh water system	AFFF piping	Bunker station
		AC electric cable	AC switchboards	AFFF piping	FPS
	Safety system	AC electric cable	AC switchboards		
	DF Bunkering station	MeOH piping	from shore	MeOH piping	MeOH transfer
	MEoH bilge system	MeOH piping	DF gensets	MeOH piping	MeOH tanks
		MeOH piping	Fuel cells		
		AC electric cable	AC switchboards		
	MeOH transfer	MeOH piping	MeOH tanks	MeOH piping	MeOH supply
		MeOH piping	MeOH bunkering station	MeOH piping	MeOH tanks
		AC electric cable	AC switchboards		
MeOH supply	MeOH piping	MeOH transfer	MeOH piping	DF gensets	
	AC electric cable	AC switchboards	MeOH piping	Fuel cells	
MeOH manifold	MeOH piping	MeOH tanks	MeOH piping	MeOH transfer	
Battery room	Battery racks	DC electric cable	DC switchboards	DC electric cable	DC switchboards
	Ventilation	Ventilation ducts	outside air	Ventilation ducts	outside air
		AC electric cable	AC switchboards		
Switch-board room	DC-DC switchboards	DC electric cable	Battery racks	DC electric cable	electric motors
		DC electric cable	Fuel cells	DC electric cable	AC-DC converters
	DC electric cable	AC-DC converters	DC electric cable	Hotel loads	
	AC-DC switchboards	AC electric cable	Diesel gensets	AC electric cable	DC switchboards
AC electric cable		DF gensets	DC electric cable	Hotel loads	
Ventilation	Ventilation ducts	outside air	Ventilation ducts	outside air	
	AC electric cable	AC switchboards			

Table 5.6: Interfaces between the different systems

Once known the weight factor for the connections between the different systems, to use the formula in Equation 4.20, the interfaces positions of the different BBs still have to be determined. These are the input and output positions and are described in the following Table 5.8:

Table 5.8: Input and output position referred to the different BBs

Location	Building Block	X	Y	Z	X	Y	Z
		Input	Input	Input	Output	Output	Output
Power room	Diesel gensets	0.5	0	0.25	-0.5	0	0.75
	DF gensets	0.5	0	0.25	-0.5	0	0.75
	Fuel cells	0	-0.5	0.25	0	-0.5	0.75
	Oil Lubrication	0	-0.5	0.5	0	-0.5	0.5
	Fresh water system	-0.5	0	0.25	-0.5	0	0.75
	Seawater cooling system	-0.5	0	0.25	0.25	0	0.5
	LT cooling system	0	-0.5	0.25	-0.5	0	0.5
	HT cooling system	0	-0.5	0.25	-0.5	0	0.5
	WHRS	0	0.5	0.25	-0.5	0	5
	Diesel Bunkering station	0	0.5	0.5	0	-0.5	0.5
	Diesel supply	0	-0.5	0.5	0	0.5	0.5
	Diesel transfer	0.25	-0.5	0.5	-0.25	-0.5	0.5
	SCR+DPF	-0.5	0	0	0.5	0	0.75
	Oxicat	-0.5	0	0.75	0.5	0	0.75
	Nitrogen system	0	-0.5	0.25	-0.5	0	0.5
	ARAFFF system	0	-0.5	0.25	-0.5	0	0.5
	Safety system	0	-0.5	0.25	-0.5	0	0.5
	MeOH Bunkering station	0	-0.5	0.25	-0.5	0	0.5
	MEoH bilge system	0	-0.5	0.25	-0.5	0	0.5
	MeOH transfer	0	-0.5	0.25	-0.5	0	0.5
MeOH supply	0	-0.5	0.25	-0.5	0	0.5	
MeOH manifold	0	-0.5	0.25	-0.5	0	0.5	
Switchboard room	DC-DC converters	0	0	0.5	0	0	0.5
	AC-DC converter	0	0	0.5	0	0	0.5

5.7. PECULIARITIES OF LAYOUT DESIGN WITH ZERO-EMISSION SYSTEMS

The integration of zero-emission systems, particularly those fueled by alcoholic fuels, poses unique challenges and considerations for maritime engineering layout design.

5.7.1. Safety Measures and Regulatory Compliance

One of the primary concerns in designing layouts with zero-emission systems revolves around safety measures and regulatory compliance. Alcoholic PGs, both internal combustion engines and fuel cells, require specific auxiliary systems to ensure their safe operation. These systems, described in section 2.6, include Nitrogen Systems, ARAFFF systems a dedicated safety cabinet and a dedicated fuel dealing system grouped in a FPS, including alcoholic bilge, transfer, supply and manifold systems.

While the Nitrogen System is mandatory for blanketing and inerting alcoholic fuel tanks, its placement within the power room does not have strict requirements, nor does the placement of other auxiliary systems like the ARAFFF system and the safety cabinet. However, the Fuel Preparation Space (FPS) presents unique challenges due to its stringent safety requirements. The FPS, where all alcoholic fuel-dealing systems are grouped, mandates features such as fire and gas detection systems, low oxygen level detection, firefighting equipment, and bilge equipment (Lloyd's Register, 2022). Consequently, careful consideration must be given to the integration

and location of the FPS to ensure compliance with safety regulations and efficient operation.

In the layout proposed in chapter 6, the FPS is allocated in a close but separate area from the Power Room. This choice, already applied in the literature (MAN ES, 2023d), was preferred for two main reasons:

- Safety: This approach allows the FPS to be completely segregated from the PR, with a dedicated ventilation system and in compliance with all IMO regulations, which state that “*Fuel preparation spaces should be located outside machinery spaces of category A*” (International Maritime Organization, 2020).
- Space: As shown in the next chapter, when retrofitting from one scenario to another, space becomes an issue. The layout developed aims to maintain or decrease the filling grade of the PR across different scenarios, which would not be feasible if the FPS were located within the PR.

In Scenario 0, the area where the FPS will be allocated will ideally be a luxurious space, which will be later sacrificed. This results in minimal lost value for the yacht given the relatively small size of the FPS. According to Feadship, its average yacht, described in Table 5.1, has an average luxurious area of $2900m^2$. Considering, according to Table 5.5, a FPS of $7m^2$, this results in a loss of just 0.2% of luxurious space.

5.7.2. Complexity of Connections

An important consideration in layout design with zero-emission systems is the complexity of connections and integration between various components. As illustrated in the flow diagrams of different scenarios in sections 5.2 - 5.5 and in Table 5.6, new specific connections, such as alcoholic fuel pipes, nitrogen pipes, and ARAFFF pipes, are installed with FCs and DF generators, along with additional connections like electrical cables and air ducts, all within the same confined spaces.

The layout design must account for these challenges and prioritize low connection costs in different scenarios, which translates into efficient routing. This is achieved by assigning weight factors in Table 5.7 to different connections, where complex connections like double-walled alcoholic fuel pipes or nitrogen piping are scored with higher values than simpler connections like electric cables.

In summary, layout design with zero-emission systems requires careful consideration of safety measures, space constraints, and system integration. The layout method explained earlier and applied in the following chapter addresses these peculiarities and challenges, serving as a starting point for evaluating the best layout solutions in different scenarios. These challenges are addressed by considering the additional safety systems that zero-emission PGSs require (Nitrogen, ARAFFF, and safety cabinet), by allocating the FPS outside of the PR in a segregated space, and by weighting the complexity of connections in the design method.

6. METHOD APPLICATION

This chapter focuses on the practical application of the design method proposed in this thesis, bridging the theoretical framework with real-world scenarios. It evaluates multiple power room layouts tailored to specific yacht configurations, addressing the research subquestion: “How can the proposed design method be practically applied to evaluate multiple power room layouts tailored to specific yacht scenarios?”

First, section 6.1 outlines the key assumptions underlying the design method, that ensure the method operates within well-defined boundaries. Next, section 6.2 explores various power room layouts considering ease of retrofit, practicality, and adaptability. and in section 6.3, insights from Feadship experts are incorporated using the Design Rationale method discussed in section 4.3. Finally, section 6.4 narrows down the layout options based on expert feedback and feasibility considerations, leaving a selection of filtered and refined designs for further analysis through the layout evaluation model.

6.1. KEY ASSUMPTIONS

By outlining key assumptions, this section establishes the foundation for applying the design method proposed in this thesis. These assumptions are necessary to ensure a comprehensive and coherent approach to evaluating the future-proofing of power rooms onboard yachts. By explicitly stating and discussing these key assumptions, the method can operate within a defined framework, providing clarity and context for the subsequent analysis and evaluation.

6.1.1. Power Room Dimensions

While previous studies, such as Souflis-Rigas et al., 2023, have analyzed layouts for methanol implementation in vessel power rooms focusing on total connection costs and power room length, this thesis diverges by prioritizing total retrofit costs, which is particularly relevant for future-proofing challenges. The decision to consider power room dimensions as fixed emerges from the necessity to establish a baseline for comparison across different layouts. Fixing power room dimensions provides a consistent baseline for comparing different layouts. For this analysis, the dimensions of an average Feadship PR, as detailed in Table 6.1, are used.

The fixed dimensions allow for standardized assessment of layout configurations and their impact on retrofit costs, facilitating direct comparisons between different layouts. Although the power room dimensions are fixed in this application, the model developed in section 4.4 can evaluate layouts regardless of their dimensions. This flexibility ensures the method can be applied to various power room configurations, allowing comprehensive assessment of future-proofing strategies in other research and applications

Table 6.1: Single vs Double layer PR main dimensions for an average Feadship

Layer	Length [m]	Width [m]	Height [m]	Floor Area [m ²]	Volume [m ³]
Single	14.7	13	3.2	191	611
Double	11	13	4.3	143	615

6.1.2. Filling Grade

The concept of filling grade, initially introduced by Coenen et al., 2015, serves as a fundamental parameter in the evaluation of power room layouts, offering a practical means to assess the realistic utilization of available space. The filling grade (FG) is formally defined as the ratio between the cumulative volumes of all building blocks (BB) within the power room and the total volume of the power room (PR) itself:

$$FG[-] = \frac{\sum_{i=1}^N V_{BB}}{V_{PR}} \quad (6.1)$$

In practical terms, assessing the detailed volume of every individual component within the power room, including pipes, cables, and minor systems, would be excessively complex and impractical. Instead, the filling grade provides a simplified yet effective measure to evaluate the overall occupancy of the power room space.

One of the primary purposes of considering the filling grade is to establish realistic constraints on the volume of new building blocks that can be installed within the power room. While two-dimensional plots of power room layouts, such the one in Figure 6.1, may suggest available space for additional systems such as FCs, it is essential to recognize that this apparent space is not necessarily vacant. As a result, the filling grade serves as a practical limitation on the capacity of the power room to accommodate additional systems during future retrofits. In this thesis, the layouts across different scenarios aims to maintain or decrease the FG of the baseline layout considered. This ensures proposed layout changes are feasible, considering the constraints of existing infrastructure. Incorporating the filling grade into the evaluation process acknowledges the interplay between available space and existing infrastructure, improving the realism and accuracy of the assessed layouts.

6.1.3. Advancements in Fuel Cell Technologies

As outlined in section 5.1, presently, diesel generators offer significantly higher volumetric power density compared to fuel cells ($42\text{-}88\text{ kW}/m^3$ for generators versus $12\text{-}18\text{ kW}/m^3$ for FCs). Consequently, replacing generators with fuel cells of comparable volume while maintaining the same filling grade in a power room could potentially result in reduced power output.

Although this may be acceptable when using one FC only for hotel load (Scenario 1 and 2), it is not when the whole propulsion power has to be covered by FCs (Scenario 3). However, the design method employed in this thesis aims to be future-proof, accounting for anticipated advancements in FC technologies. As shown in Figure 2.6, forecasts suggest a continual increase in fuel cell power density over time. As such, FCs will be integrated into PR layouts only when their power density matches or exceeds that of diesel generators, ensuring that the replacement does not compromise the overall power output.

By considering the evolving landscape of fuel cell technologies, the design method ensures that power room layouts remain adaptable to future advancements. This approach safeguards against premature integration of fuel cells, guaranteeing optimal power output while embracing sustainable energy solutions.

6.1.4. Exclusion of Batteries from the Design Method

Batteries are crucial for Diesel-Batteries yachts and future-proof scenarios, but they are intentionally excluded from the scope of this thesis. The primary focus of this research is on future-proofing the power room within a yacht and including batteries would divert from the central research question concerning the layout of the power room. Batteries are typically located outside the power room, in dedicated battery rooms for safety reasons, as shown in Figure 2.3. This placement complicates their integration into the power room layout and would require expanding the scope of this research, which could reduce the focus and effectiveness of the design method.

Battery technology is rapidly evolving, with significant advancements in energy density and safety, allowing more flexible placement options onboard yachts. These changes introduce complexities that warrant separate consideration. While battery advancements offer new opportunities, they also present integration challenges that go beyond the current study's focus. Moreover, at the present stage batteries are still too underdeveloped, leading to uncertainties regarding their placement and integration in future yachts.

Although batteries are excluded to maintain the clarity and focus of this research, their importance in future-proof yacht designs is acknowledged. Their exclusion is a deliberate choice to keep the study focused, but their relevance highlights the need for further research, as discussed in subsection 9.3.1.

6.1.5. Switchboards

As already detailed in subsection 2.2.1, current yacht configurations typically feature both DC-DC switchboards and AC-DC switchboards grouped within switchboard rooms. Diesel generators, produce alternating current (AC), which is converted into direct current (DC) in AC-DC switchboards. Conversely, batteries and fuel cells produce DC current, which is handled by DC-DC switchboards.

Considering the average Feadship, which presents four generators (two larger and two smaller), approximately six AC-DC switchboards are required to manage the load. However, the total number of switchboards on an average Diesel-Batteries Feadship typically comprises 12 AC-DC switchboards and 28 DC-DC switchboards, all usually grouped in three separate switchboard rooms. The huge number of switchboards is due to the fact that these systems are responsible for the whole electric distribution onboard, not only for propulsion but also for all the hotel systems.

In the design method, when a generator is removed and replaced by fuel cells, an AC-DC switchboard must be replaced with a DC-DC one. Fortunately, as shown in Table 6.2, the dimensions of DC-DC and AC-DC switchboards dealing with similar power loads are comparable, mitigating potential installation challenges.

It is important to acknowledge that future electric distribution systems may evolve beyond this conventional setup. For example, when all diesel generators are replaced by fuel cells, the necessity for AC-DC switchboards may diminish, potentially allowing for a vessel-wide DC-DC network. However, such a transition is complex and requires further investigation. Presently, most hotel loads onboard, from HVAC systems to domestic appliances, operate on AC current. Transitioning to a DC-only network would necessitate developing alternatives for these systems to function on DC power. While advancements in technology may facilitate this shift, it remains uncertain whether suppliers will produce DC-compatible systems for smaller domestic components. As will be detailed in subsection 9.3.2, further research and exploration into alternative electric distribution systems onboard yachts are recommended.

Table 6.2: Switchboards dimension on average Feadship (adapted from ABB, 2020 and ABB, 2011)

Switchboards	Length [m]	Width [m]	Height [m]	Volume [m ³]	P Max [kW]
DC-DC	0.644	0.8	2	1.03	800
AC-DC	0.644	0.9	2	1.16	900

6.2. LAYOUTS CONCEPTS

While theoretically, the method could proceed without this step, relying solely on existing layouts for evaluation, the inclusion of layout concepts enhances the efficacy and robustness of the approach. By addressing multiple power room layouts based on the current state of the art and considerations of ease of retrofit, this step provides a diverse pool of options for evaluation. Through this approach, the method aims to identify and prioritize layouts that exhibit the highest potential for future-proofing power rooms, thereby ensuring the selection of the most suitable and resilient designs.

The novelty of this design method lies in designing power layout adaptable across different scenarios. Thus, in this section, the layout concepts will be developed in such a way to be used across the different scenarios. But first, the layout of the current power room onboard a yacht is presented in Figure 6.1. As mentioned in subsection 2.2.1, currently a power room onboard a yacht can be on one layer or divided over two layer. A double layer engine room usually looks like the layout in Figure 6.1 while a single layer one resemble the layout in Figure C.11. Besides the number of decks they occupy which have impact on the interior design of the yacht, the main difference between the single and double layer layouts lies in the amount of connections they have which are way higher for PR spreading over two different decks (Feadship, 2023b). This is why this thesis will then on the double layer layouts, but the design method can be applied to whatever PR, with no distinction if they are single or double layer.

It is worth noting that the different systems have been categorized with specific colors to make layouts easier to understand. Table 6.3 reports the various colors chosen.

Table 6.3: Building blocks color legend

Building Blocks color legend								
Generators	Fuel Cells	Water	Diesel	Oil	EGATS	MeOH	Safety	Switchboards
Red	Light green	Blue	Orange	Purple	Grey	Dark green	Yellow	Light grey

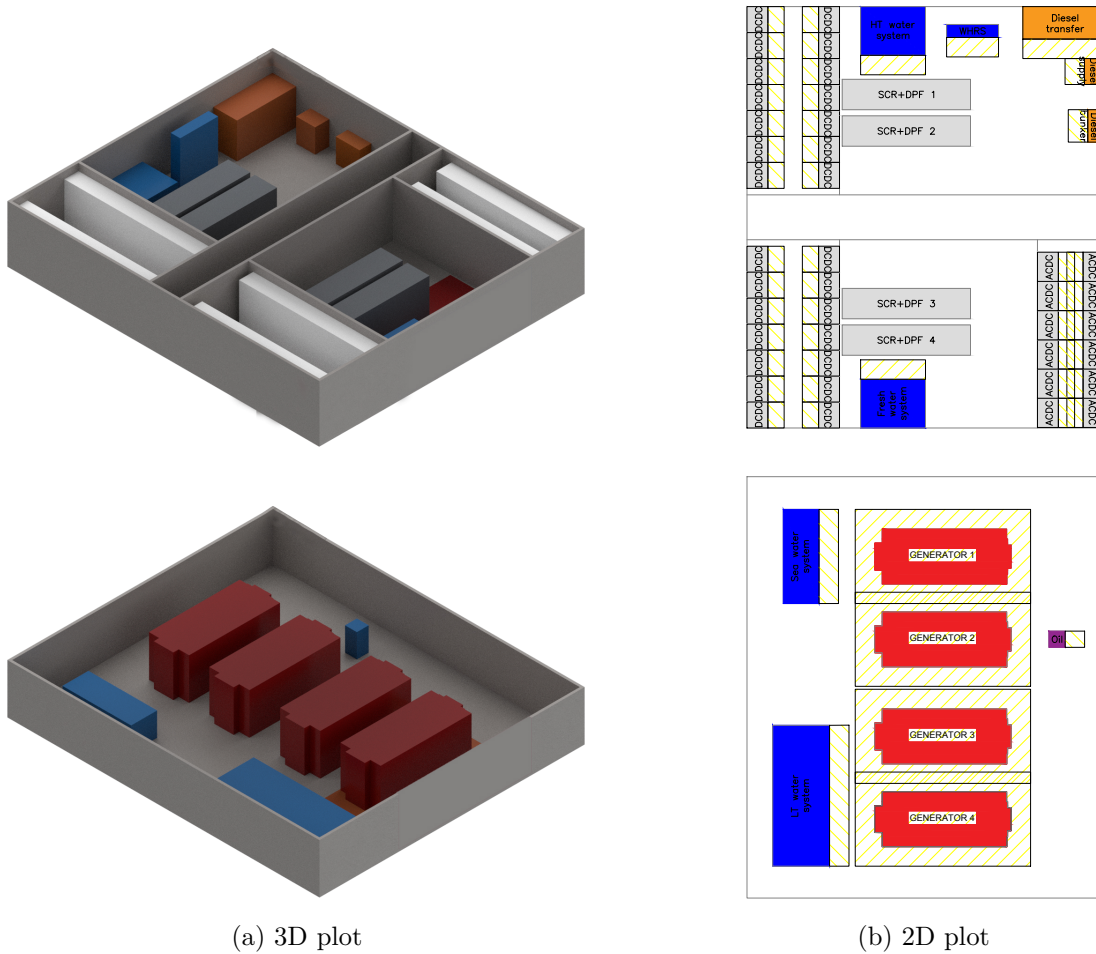


Figure 6.1: Current double layer PR - Layout 0.1

Considering the different requirements of the different scenarios, described in chapter 5, a first pool of layouts was developed with the main ideas of having layouts easy to be retrofitted. Moreover, peculiarities regarding layout design with zero-emission systems, presented in section 5.7 were taken into consideration. Specifically, the FPS hosting alcoholic fuel dealing system was located close to PR but in a separate area and connections among zero-emissions PGSs and their auxiliary systems (Nitrogen, ARAFFF and safety cabinet) were prioritized by trying to allocate these systems close to the PGS they deal with.

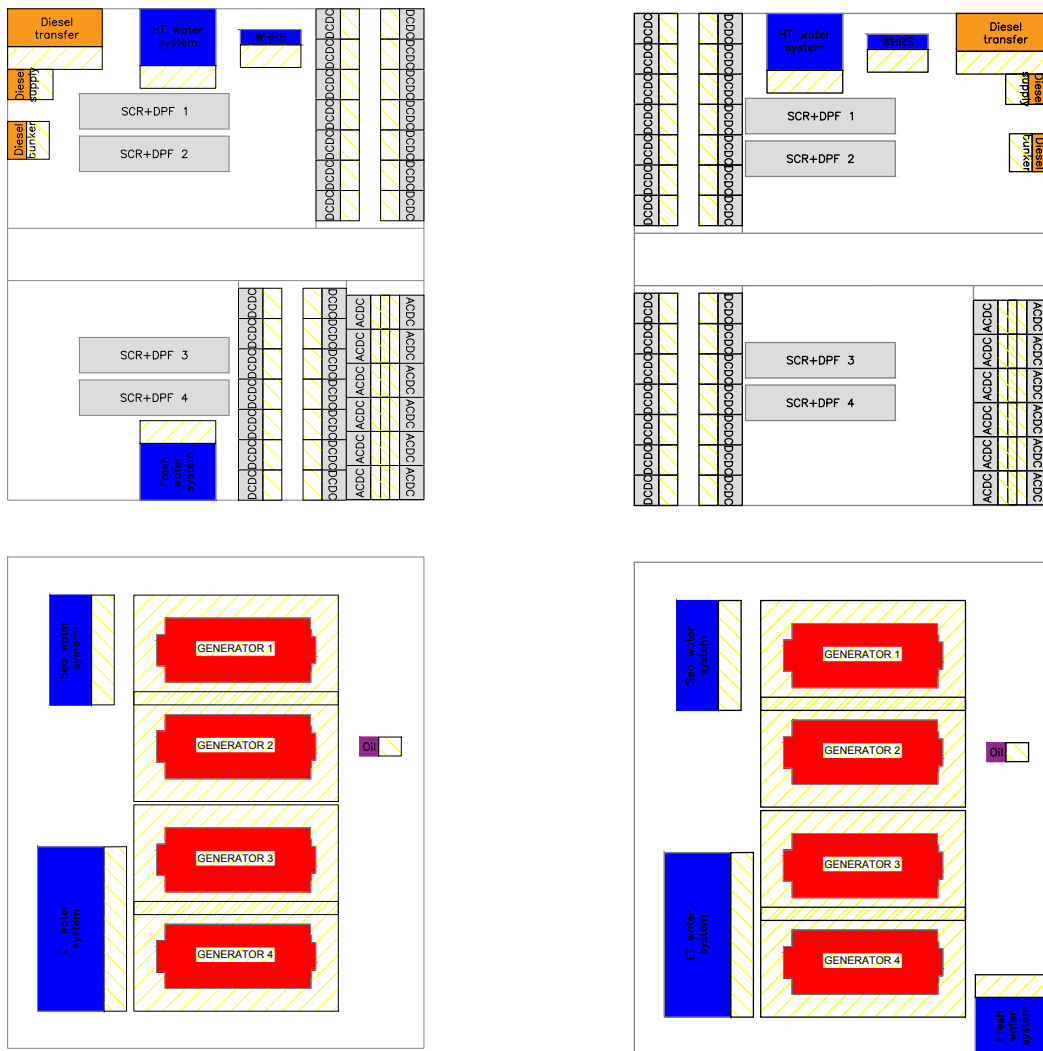
With the aim to keep the same Filling Grade (FG) across the different scenarios, as described in subsection 6.1.2, it was observed that the auxiliary systems required by zero-emissions PGSs, can fit on the place of a superfluous EGATS, causing no trouble on maintaining or reducing the FG across the various scenarios.

The layouts developed have been categorized with a two-digit code (*X.Y*) where *X* stands for the scenario at which the layout belongs and *Y* for the concept that driven that layout. Even if the different scenarios led to different layouts, there exist some driven concepts that were considered in this first layout development:

- No switchboard room on one side of the power room: this would facilitate the access from the power room to other closer spaces such as the tender garage - Layouts X.2.
- No system on one side of the power room: this would facilitate the creation of an access opening on that side of the room and to have a direct path to it - Layouts X.3.
- Wider corridor: this would allow to be able to easily transport in/out the different systems without the need for creating additional openings, if the corridor lead to a tender garage or a another room with a direct outboard access - Layouts X.4.

- Corridor exactly above one PGS: in a two layer PR this would allow creating an hatch on the corridor floor an hoisting the generator or the FC and easily remove it through the corridor - Layouts X.5.
- Power room split in two to be directly accessible via the tender garage: this would facilitate the movement in/out of the systems given the direct access to the tender garage where both moving equipment and access points are already present - Layouts X.6 and X.7.
- PGSs disposed in transverse direction: this would help in having smaller access opening the yacht’s side - Layouts X.8.
- PGSs on an upper layer of the power room: in a double layer power room this would facilitate the removal/installation of these big components that would not need to be hoisted vertically.

Below the different concept layouts generated at this stage of the method for Scenario 0 are reported. These layouts will be later refined, adjusted and filtered according to experts’ opinions. The same concept ideas apply for the other scenarios. An example of a layout with a zero-emissions PGS is shown in Figure 6.5 while the other layouts for scenario 1, 2 and 3 are presented in Appendix C showing how layouts based on the same concepts change across various scenarios.



(a) Layout 0.2 - No switchboards on the aft of the PR (b) Layout 0.3 - No systems on one side of the PR

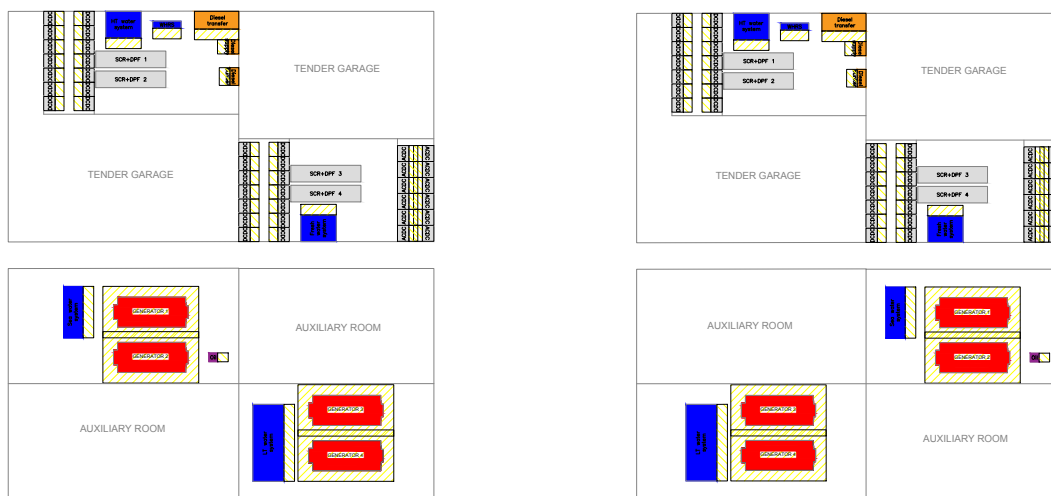
Figure 6.2: Layouts with no components on one side of the PR



(a) Layout 0.4 - Central wider corridor

(b) Layout 0.5 - Wider corridor above one generator

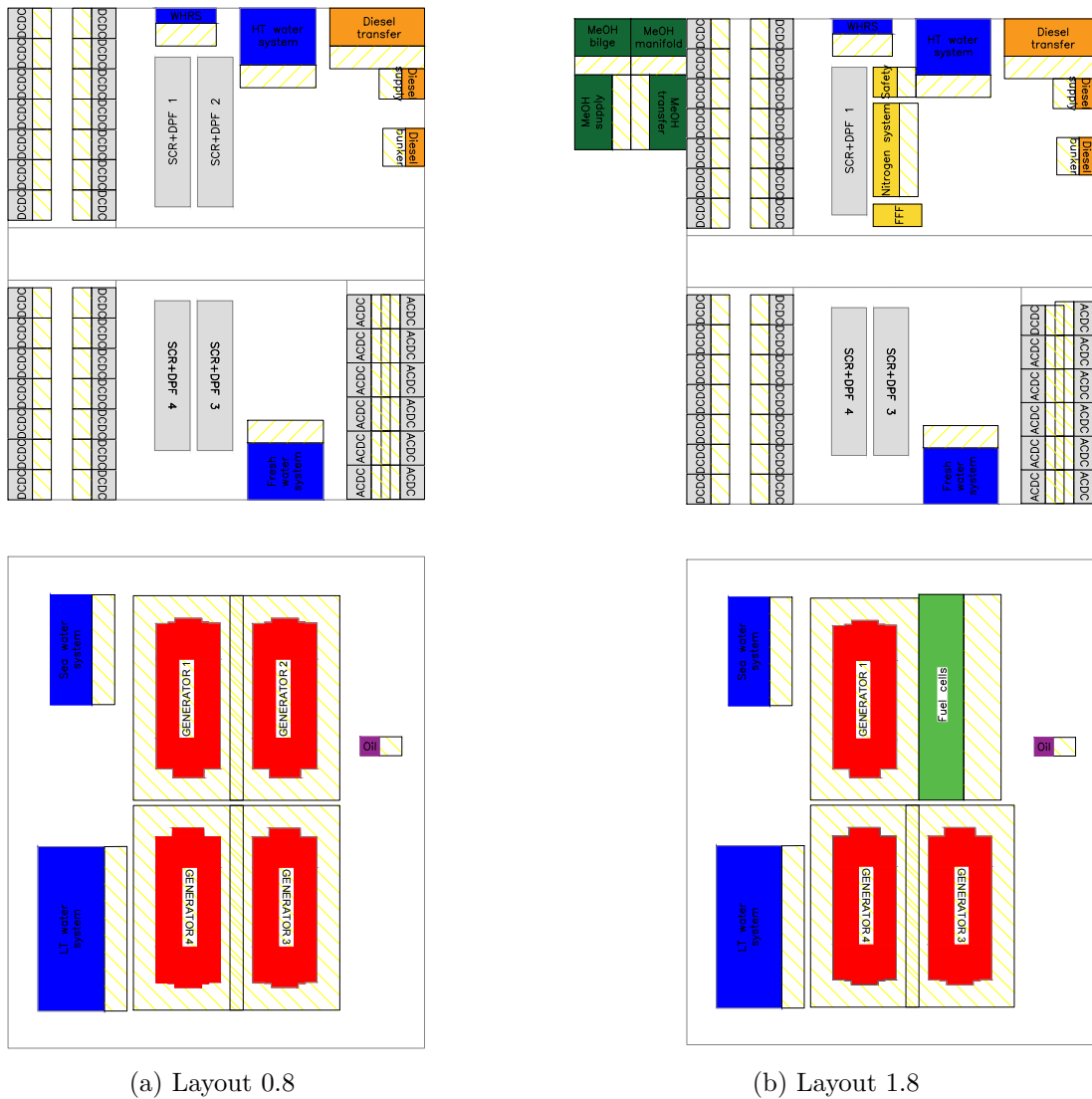
Figure 6.3: Layouts with wider corridors



(a) Layout 0.6 - TG close to the PR

(b) Layout 0.7 - TG above the PR

Figure 6.4: Layouts with the PR directly accessible via the TG



(a) Layout 0.8

(b) Layout 1.8

Figure 6.5: Layouts X.8 - PGSs rotated in transversal direction

6.3. INTEGRATING THE EXPERTS' OPINIONS

Following the development of the power room layouts, as detailed in method, the following step regards the Design Rationale, particularly capturing the Design Rationale behind the layout concepts and utilize the experts' feedback based on the rationale to filter and refine the layouts concepts.

The Design Rationale in this case can be considered capture by looking at the different ideas presented in section 6.2 that drove the development of the layouts concepts. Thus, considering that rationale, a round of interviews with experts in Feadship power room arrangements was conducted to evaluate the layouts. In alphabetic order the experts consulted are:

- Research at Feadship R&D Department - 5 years of experience
- Senior Specialist at Studio De Voogt - 30 years of experience
- Technical Manager at Feadship Refit & Service - 24 years of experience
- Project Manager at de Vries Shipyard - 20 years of experience

The interviews have been conducted in such a way to address the design rationale behind each layout concept and address all the different ideas that drove the development of the layouts in the previous section 6.2. Here is a summary of the key considerations emerged from these interviews, categorized based on the various arguments treated:

6.3.1. Switchboard Position

The initial discussion focused on the possibility of having all switchboards located in the front part of the Power Room for easier access from the Tender Garage or other closer spaces (as in layouts X.2 - Figure 6.2a). Even though the logic behind this reasoning is understandable, there exists a major drawback that makes it impractical. The DC electric cables running from the pod thrusters to the propulsion switchboards (DC-DC grids) and then to the power generation systems (PGSs) are massive and very difficult to model and install. Therefore, the most suitable solution is to have the switchboards located between the pod thrusters and the power generation systems, placing the DC switchboards at the aft of the Power Room.

6.3.2. Empty Side in the Power Room

The possibility of having a Power Room layout with no systems on one side (as in layouts X.3 - Figure 6.2b) to facilitate the creation of an access opening and passage was explored. While feasible, critical considerations regard the presence of ducts, cables, and pipes. It appears challenging to eliminate them entirely from one side, as room sides are often where most cables and pipes are routed due to their structure, which would not allow for any other system to fit. However, experts suggested the possibility of designing the path of pipes and cables to leave a designated area on one side of the PR with minimal pipe and cable concentration, facilitating the creation of an access opening and passage through that side.

6.3.3. Corridor Design

The third topic discussed was the corridor and the possibility of having it wider (as in layouts X.4 - Figure 6.3a) and/or located directly above a generator or fuel cell (as in layouts X.5 Figure 6.3b). Regarding a wider corridor, it appears as a feasible option due to the minimal additional width ($< 0.5m$) needed to allow for easy passage of bulky systems. However, the maximum width of watertight doors (currently set at $2m$) needs to be respected. As for locating the corridor directly above a power generation system, the experts highlighted the challenge of SCR+DPF block placement with generators. If the corridor is positioned directly above a generator, the Exhaust Gas After Treatment System (EGATS) cannot be located there, as is typical in most current arrangements. Nevertheless, alternative locations exist for the SCR+DPF block, such as in front of the generators (as sometimes seen in single-layer power rooms) or on an upper level slightly to the side and not directly above the generator. The critical consideration here is that the EGATS cannot be situated too far from the generators because the ducts connecting these two components are particularly large, and the SCR and DPF require the exhaust gases to be at a certain temperature to function adequately.

6.3.4. Power Room Directly Accessible via the Tender Garage

The concept of having a power room split in two with direct access from the tender garage (as in layouts X.6 and X.7 - Figure 6.4) was considered. While this offers a direct path out of the yacht with the presence of moving equipment (tender cranes) to facilitate moving systems in and out, the experts identified several disadvantages that render it an impractical solution:

1. Splitting the power room in two would result in complex connections between different systems, leading to high connection costs.
2. Such a configuration introduces stability issues that are complex to overcome, especially since generators are among the heaviest components onboard.
3. These layouts necessitate specific casing positions in certain fixed locations of the yacht, which is particularly undesirable for Feadship, where a key design philosophy is freedom of customization. In essence, the system location would dictate the design, whereas in the current design approach, where maximum customization is a priority, the design and arrangement of guest spaces dictate the systems' location onboard.

6.3.5. Generators in Transversal Direction

The idea of having generators arranged in a transversal direction (as in layouts X.8 - Figure 6.5a), instead of the longitudinal direction used in most power room layouts today, originated from the need for limited dimensions of the access opening and a more direct path to it. However, a major drawback highlighted by the experts is the potential loss of oil pressure in the generators due to yacht heeling (tilting to one side). While specific oil pumps can address this issue, they are quite expensive, making this solution impractical. However, it appears feasible to incorporate sufficient space around the generators to enable their rotation during future retrofit operations.

This layout will not be taken into account for the purpose of this application, it is however suggested to further analyze the maximum heeling angle of yachts, as given the present and future improvement in stability this might not represent an issue anymore (Nicholls, 2022).

6.3.6. Structural Issues

Regarding structural considerations related to facilitating future retrofits onboard yachts, the interviews focused on two main aspects:

1. Removing a Power Generation System from Below the Hull: this is a viable solution, but the bottom structure of the yacht would need to be designed to accommodate it, with girders design in such a way to be easily cut out and later reinstalled. Basically, the part immediately below the Power Generation System has to be designed as a “Soft Patch” (as defined in subsection 3.2.2). This would necessitate some changes to the bottom structure of the hull, increasing its complexity, but still represents a realistic solution.
2. Placing a Power Generation System on the Upper Layer of the PR: this solution doesn't present any major challenges. The upper deck will need to be designed for it, but without any significant complications. Stability has to be further studied but does not present an issue as the position is still low compared to the whole yacht.

By integrating these expert considerations into the design rationale for each layout, it was possible to evaluate their suitability for future-proof power room design. Layouts that demonstrate a strong rationale for accommodating future zero-emission technology integration and address the expert concerns will be prioritized for further analysis using the model described in section 4.4.

One of the significant benefits of design rationale is the potential for knowledge reuse, specifically the valuable insights captured from Feadship power room arrangement experts. Particularly, in this case the experts' knowledge have been summarized in tabular form as seen in Table 6.4.

Table 6.4: Design Rationale

Design Consideration	Layout Feature	Expert Feedback	Rationale	Alternative Solutions
Switchboard Placement	All switchboards in front for Tender Garage access	Impractical due to large DC cables, locate switchboards aft	Easier cable routing for pod thrusters, minimizes cable length	Strategically design pipe/cable paths for access point to switchboards
Access within Power Room	No systems on one side for access opening creation	Difficult to eliminate pipes/cables entirely	Room sides are often where most cables and pipes are routed	Design path for pipes and cables to minimize concentration on one side for access point creation
Corridor Design (Width)	Wider corridor for passage of bulky systems	Feasible with minimal additional width needed	Maximum watertight door width needs to be respected	N/A

Continued on next page

Design Consideration	Layout Feature	Expert Feedback	Rationale	Alternative Solutions
Corridor Design (Location)	Corridor directly above generator or fuel cell	Challenge with SCR+DPF block placement with generators. EGATS cannot be located above.	SCR+DPF block needs to be close to generators due to large ducts and temperature requirements.	Alternative locations for SCR+DPF block exist (e.g., in front of generators or on upper level but not far from PGS)
Power Room split in two	Direct access from Tender Garage	Complex connections between systems, high connection costs. Stability issues due to generator weight. Limits design customization.	Not recommended due to impracticalities.	N/A
Generator Orientation	Generators in transversal direction for smaller access opening	Potential loss of oil pressure due to yacht heeling. Expensive oil pumps required.	Not recommended due to impracticalities.	Include sufficient space around generators to enable future rotation for potential longitudinal placement.
Structural Issues (Removing PGS)	Removing PGS from below hull	Bottom structure needs design to accommodate, with no girders below PGS. Increases complexity.	Realistic solution, but requires significant changes to hull structure.	N/A
Structural Issues (Placing PGS on Upper Layer)	Placing PGS on upper layer of Power Room	No major challenges, upper deck needs to be design for it.	Feasible solution with minimal complications.	N/A

6.4. FILTERED AND REFINED LAYOUTS

According to the expert's opinions there are some layouts that are unfeasible for multiple reasons and that will be discarded and no longer considered in the thesis. These layouts are the ones based on the following rationale concepts:

- Switchboards at the front of the PR - Layouts X.2
- PR divided in two to be directly accessible via TG - Layouts X.6 and X.7
- PGS disposed in transverse direction - Layouts X.8

Thus, based on the experts' feedback, the filtered layouts are the ones based on these other rationale concepts:

- No systems on one side of the PR - Layouts X.3
- Wider corridor - Layouts X.4
- Wider corridor above one PGS - Layouts X.5

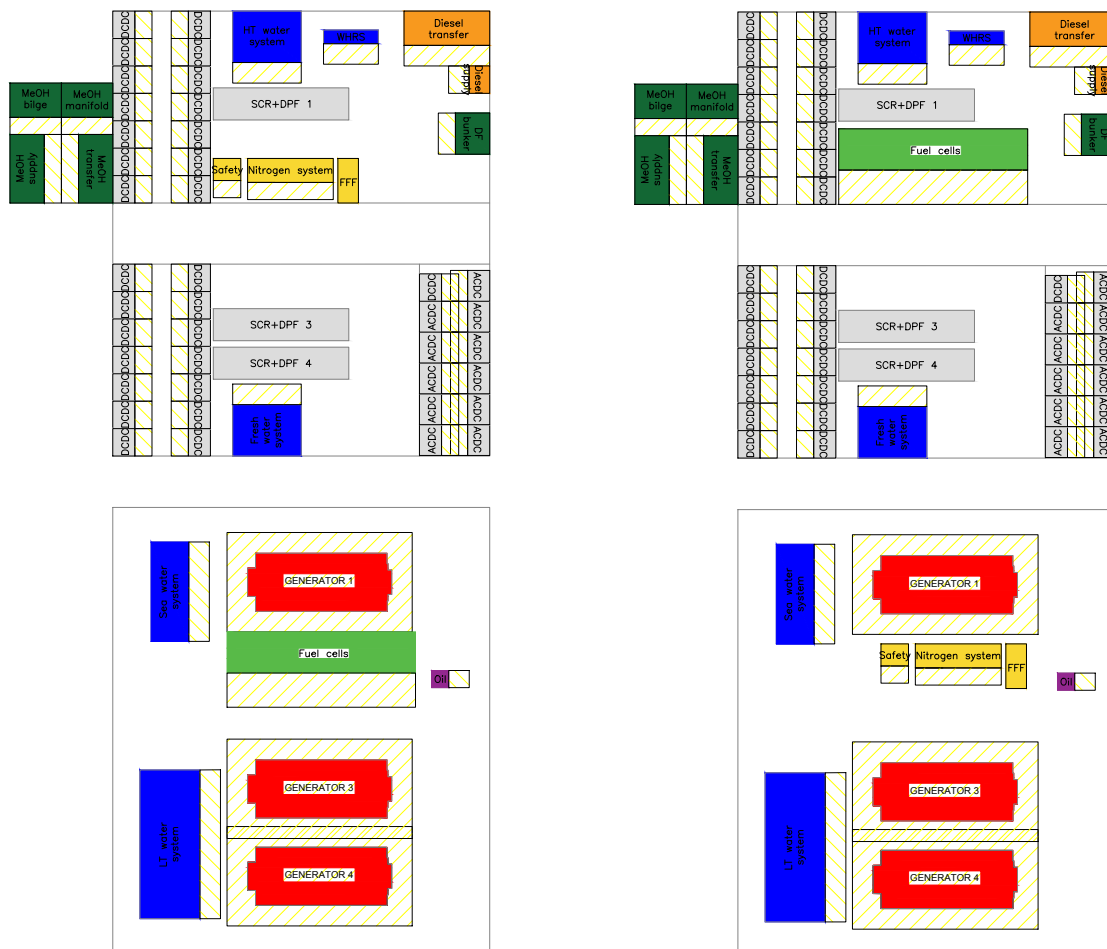
Furthermore, as described in subsection 6.3.6, it is possible to place PGSs on the upper level of the PR. While this arrangement may pose challenges for generators, particularly regarding the placement of EGATS,

it can be advantageous for fuel cells. Placing FCs on the upper level reduces the distance they need to be transported into the PR, leading to lower retrofit costs. Consequently, a variation of layouts X.3 and X.4 will also be evaluated in the model for scenario 1, 2 and 3. This variation, presented in Figure 6.6, is designated by the letter B after the identification code (*X.Y.B*) and involves placing the fuel cells on the upper deck of the PR and the auxiliary systems (Safety, Nitrogen, and ARAFFF) on the lower deck.

This variation was not found relevant for layouts X.5 because this would lead to two big access openings, one on the floor of the corridor and one on its wall, while putting the FC on the lower layer will lead only to one access opening on the corridor floor since the other components that need to be installed are smaller and can fit through the door or through a smaller opening.

In this chapter, the foundational assumptions were established and a series of power room layouts to address the future-proofing of yacht power systems were developed. These layouts were filtered and refined based on expert feedback and feasibility considerations. The analysis conducted here sets the stage for the application of the layout evaluation model described in section 4.4.

In chapter 7, the refined and filtered layouts from this chapter will be used in the model that will assess the effectiveness of each layout in terms of retrofit costs and connection costs. By applying the model to the selected layouts, it will be possible to identify the best configurations and practices for future-proofing power rooms, providing insights for yacht design and retrofitting.



(a) Layout 1.4 - FC on the lower layer

(b) Layout 1.4.B - FC on the upper layer

Figure 6.6: Layouts 1.4 vs 1.4.B - No systems on one side of the PR

7. RESULTS

This chapter aims at answering the research subquestion “*What insights and conclusions can be drawn from the analysis of the evaluated power room layouts in terms of their feasibility, effectiveness in accommodating zero-emission systems, and potential implications for the future design and retrofitting of superyachts?*”. Therefore, it reports the results that were obtained by submitting the filtered and refined layouts described in section 6.4 to the layout evaluation model presented in section 4.4. Furthermore, besides the filtered and refined layouts, the current PR layout (layout X.1) has also been evaluated and considered as a baseline.

First, the connection costs resulting for the different layouts are presented in section 7.1, then the AO configurations considered for the distinct layouts are presented in section 7.3 and the best option among the various transport equipment is discussed in section 7.2. In the end, the results for retrofit costs from one scenario to another and an overall discussion on the results are provided respectively in section 7.4 and section 7.6.

7.1. TOTAL CONNECTION COSTS

Based on the method explained in section 4.6 and according to the weight matrices presented in Figure 5.6, the Total Connection Costs (TCC) for the various layouts selected in section 6.4 were calculated for every scenario. The TCC results are presented in Figure 7.1 showing the Total Connection Costs of the layouts while in the table it is shown the percentage variation from layout X.1 (considered as baseline) for every scenario.

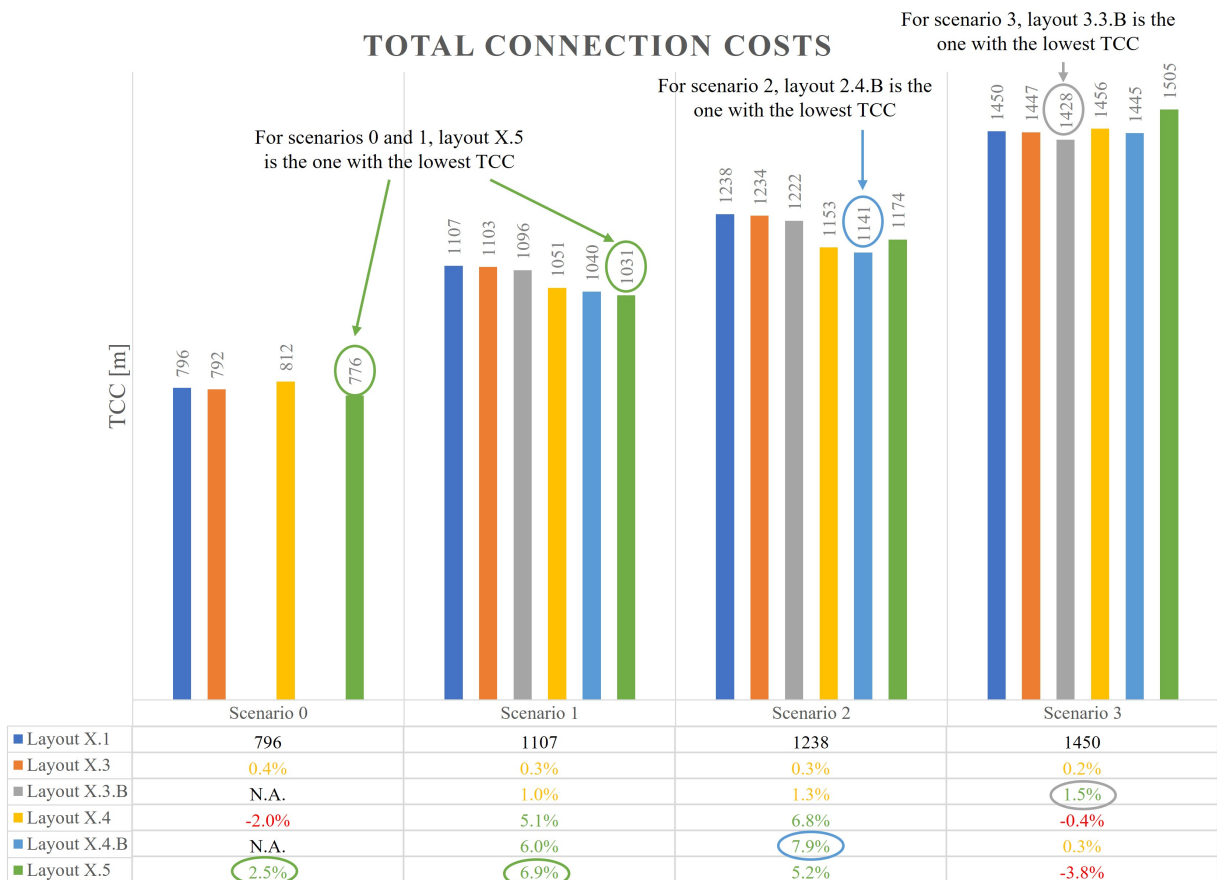


Figure 7.1: Total Connection Costs results

What can be noticed from the figure above is that in Scenario 0 layout 0.4 has higher TCC compared to the baseline considered (layout 0.1). This is due to the EGATS disposition which in this layout is located further from the generators with the ducts connecting these two systems having a high connection weight. On the other hand, layouts 0.3 and 0.5 perform better, with layout 0.5 leading up to 2.5% gain in the TCC compared to layout 0.1. This is because of the position of the HT cooling system which was located closer to the generators it has to deal with, to create space on the upper deck.

For Scenario 1 and 2 it can be noticed that all layouts perform better than the baseline ones, with layouts X.4, X.4.B and X.5 having important gains in the TCC, particularly layout 1.5 results as the best option in scenario 1 with 6.9% lower TCC compared to layout 1.1. While for scenario 2 the best layout is 2.4.B that has 7.9% lower TCC compared to layout 2.1. All these gains can be addressed to the close allocation of FC to its safety systems (yellow in the layouts in Appendix C).

For scenario 3, it can be noticed that in this case the differences among the layouts are way lower with layout 3.3.B having the lowest TCC with 1.5% saving compared to layout 3.1. While layouts 3.4 and 3.5 performs slightly worse than the baseline layout.

For what concerns the TCC analysis it can be concluded that starting from scenario 0, layout 0.5 is identified as the most suitable option when transitioning to scenarios 1 or 2, whereas layout 0.3.B is preferred when moving towards scenario 3. For pathways starting from scenarios 1 or 2 and moving towards scenarios 2 or 3, layouts X.4 and X.4.B emerge as the most effective choices. These considerations will be particularly relevant in section 7.5 when analyzing the best layout for each future-proof pathway considering both TCC and TRC which results will be presented in section 7.4, after an analysis on the preferred moving equipment in section 7.2.

7.2. MOVING EQUIPMENT

In subsection 3.2.3, three different transport means were introduced and later considered in the equations to calculate the Total Retrofit Costs in section 4.5. Moving systems just with hands was an option discarded due to the limited weight operators can carry, thus the considered options were rails and chain and tackle (C&T), both considered in two ways: whether they are already pre-arranged and installed onboard before the retrofit or if they have to be installed specifically for the retrofit. The results for the moving equipment change from scenario to scenario and from layout to layout, however analyzing the averages of all the results gained was possible to establish some trends shown in Figure 7.2.

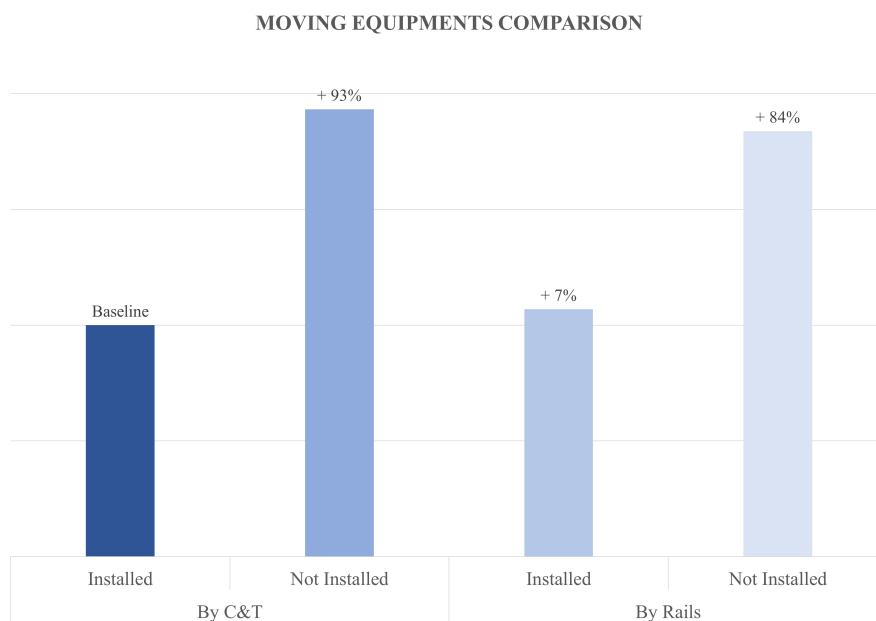


Figure 7.2: TRC comparison between the different moving equipment options

The figure above shows that the option with chain and tackle already prearranged and installed into the PR is the one that brings the lowest transport costs and was taken as baseline. Slightly higher (+7%) are the average transport costs for the option with rails already installed. While the options with C&T and rails to be installed are the ones that result with the higher transport costs. However, it is interesting to see that among moving equipments not installed rails perform better than C&T (+84% vs +93%). This may seem counter-intuitive at first sight but it is not. Indeed, C&T are way more complex than rails to be installed into a PR as they may also require arranging additional beams on which to be mounted, leading to higher transport costs. What explained finds confirmations also in the equations presented in section 4.5 where even if C&T was considered the fastest transport mean (Equation 4.10) it was also judged as the most complex one to be installed and it is exactly the complexity installation factor k described in Equation 4.9 that brings C&T to have higher transport costs compared to rails if none of them are already installed.

Overall it can be concluded that the preferred option is to have C&T already pre-arranged and installed onboard, if that is not the case it is preferred to use rails which are easier to install.

7.3. ACCESS OPENING CONFIGURATIONS

The different layouts considered can have different access opening location and configurations which lead to different retrofit costs. Before delving into the results for retrofitting a power room from one scenario to another, the possible access opening configurations for the various layouts are described in this section.

7.3.1. Current Power Room Layout - X.0

First of all, the possible access opening configurations for the current PR layout, presented in Figure 6.1, were analyzed. To transport in and out systems four main AO configurations can be considered, those are visualized with different colors in Figure 7.3 and their description is provided in table Table 7.1. It is worth noting that in Figure 7.3 the two PR layers are shown on the same level but they have to be intended on top of each other.

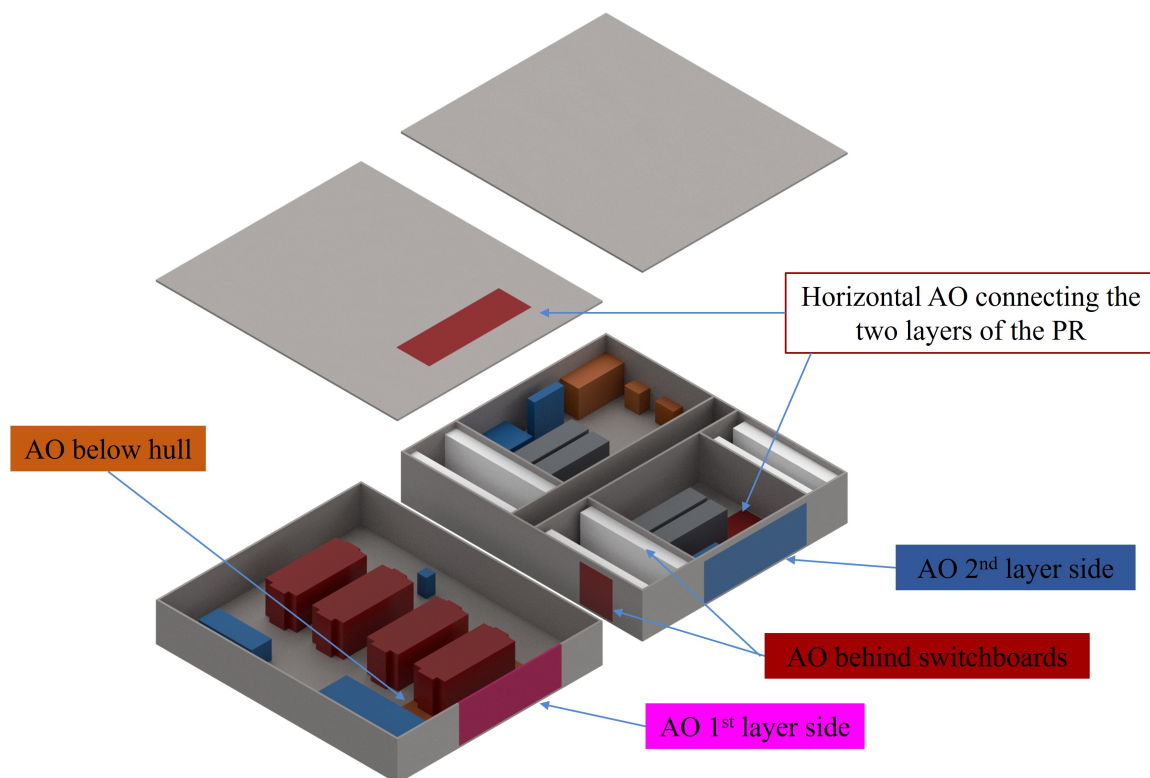


Figure 7.3: Layout 0.1 with possible AO configurations

Table 7.1: Possible AO configurations for layouts X.1

	Color	Configuration	Description	Types
Below hull	Orange	<ul style="list-style-type: none"> • 2 horizontal on the floor of each PR deck 	One AO serves to connect the two different layers of the PR while the other is the AO that effectively connects the PR to the outside	<ul style="list-style-type: none"> • No Pipes/Cables • To be created
Behind switchboards	Red	<ul style="list-style-type: none"> • 1 horizontal on the 2nd layer floor • 2 verticals on the switchboard rooms walls 	The horizontal AO serves to connect the two different layers of the PR while the vertical ones connect the PR to the space located aft of it (i.e. TG)	<ul style="list-style-type: none"> • Present • No Pipes/Cables • To be created
1st layer side	Pink	<ul style="list-style-type: none"> • 1 horizontal on the 2nd layer floor • 1 vertical on the 1st layer side 	The horizontal AO serves to connect the two different layers of the PR while the vertical one connects the PR to the outside	<ul style="list-style-type: none"> • No Pipes/Cables • To be created
2nd layer side	Blue	<ul style="list-style-type: none"> • 1 horizontal on the 2nd layer floor • 1 vertical on the 2nd layer side 	The horizontal AO serves to connect the two different layers of the PR while the vertical one connects the PR to the outside	<ul style="list-style-type: none"> • Present • No Pipes/Cables • To be created

It must be noticed that the horizontal AO that connects the first and second layer of the PR is visualized only in red in Figure 7.3, but, as described in Table 7.1, it is always present when there is the need to carry in/out systems located on a layer diverse from the one where the AO is.

Furthermore, it is important to point out that in the AO configurations described in the table as “*Below Hull*” and “*1st layer side*” openings are below the water line. This is the reason why in this case the AO can not be already present. Moreover, this also mean that when retrofitting with such a configuration the vessel must be in dry-dock and can not just be docked to a shipyard berth as instead the other configuration allow. The need for the vessel to be in dry-dock during the PR refit would bring higher costs due to shipyard rates, which have not been considered in the method. However, when presenting the results at the end of this chapter they will be divided into “*Vessel in dry-dock*” and “*Vessel not in dry-dock*”.

7.3.2. No systems on one side of the Power Room- X.3 and X.3.B

This configuration consists in having no systems on one side of the PR on the 2nd layer and having two access opening, a vertical one on the side and an horizontal one on the floor of the 2nd layer to connect the two layers of the PR among each other. This is exactly the same access opening presented in blue in and described as “*2nd layer side*” in Table 7.1.

7.3.3. Wider corridor - X.4 and X.4.B

As explained earlier the rationale behind a wider corridor, is the possibility to use it to easily carry in and out the systems. It is particularly useful if at the aft of the PR there is the Tender Garage and the corridor leads directly to it so that the systems can then be carried in/out using the moving equipment and the void space present in that area.

As shown in Figure 7.4 and detailed in Table 7.2, with a wider corridor there will always be a vertical AO that leads to the aft of the PR, and one horizontal AO. There is a distinction that can be made regarding the position of this horizontal AO, indeed it can either be located exactly in the corridor (green in the layout and in the Figure 7.4) and be already present or pre-arranged in order to be opened easily or it can be located into the PR exactly above one PGS (yellow in the layout and in the Figure 7.4). In this case it cannot be pre-arranged as it will serve as basement for other systems.

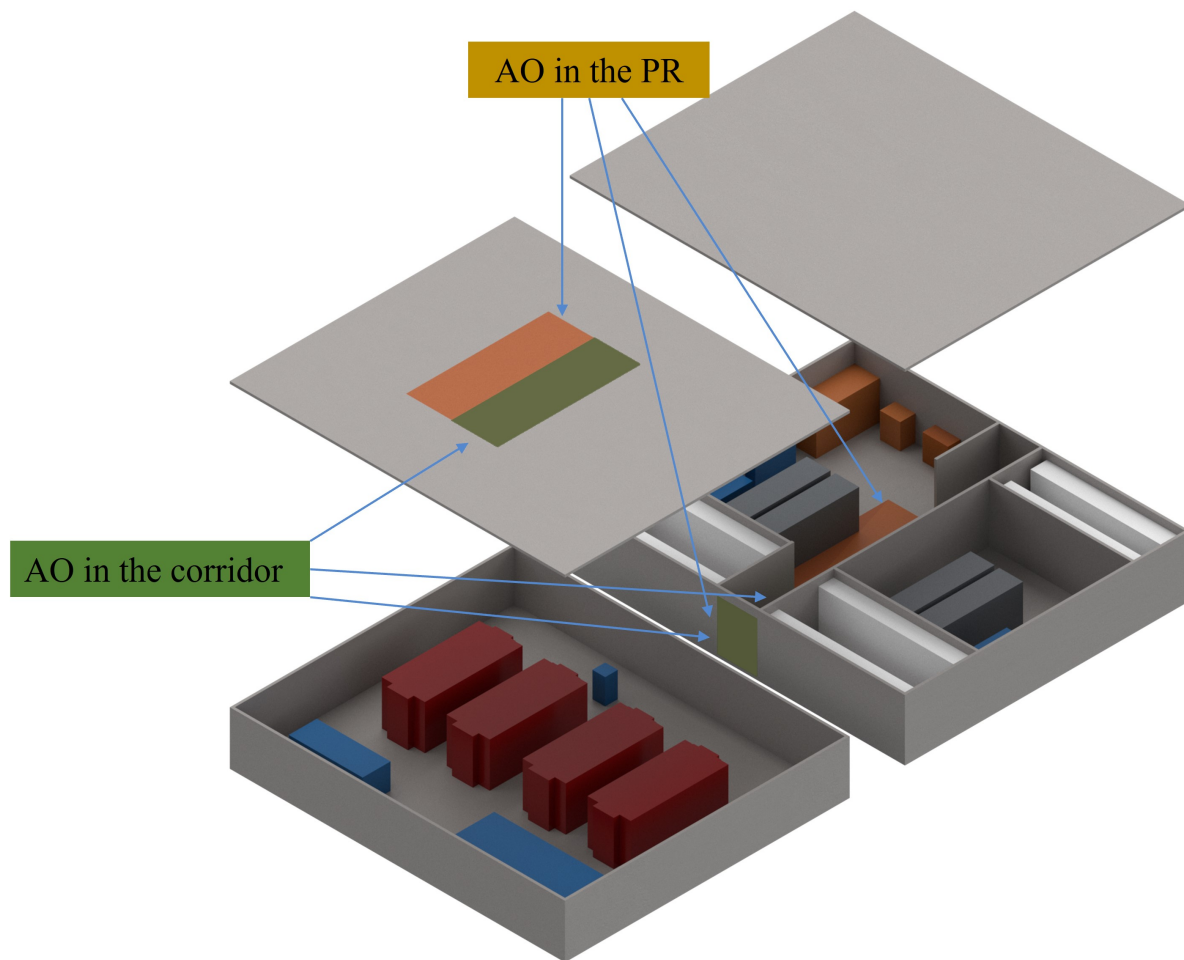


Figure 7.4: Layout 0.4 with possible AO configurations

Table 7.2: Possible AO configurations for layouts X.4 and X.4.B

	Color	Configuration	Description	Types
In the corridor	Green	<ul style="list-style-type: none"> • 1 horizontal on the 2nd layer floor in the corridor • 1 vertical on the corridor wall 	The horizontal AO serves to connect the two different layers of the PR while the vertical one connects the corridor to the space located aft of it (i.e. TG)	<ul style="list-style-type: none"> • Present • No Pipes/Cables • To be created
In the PR	Yellow	<ul style="list-style-type: none"> • 1 horizontal on the 2nd layer floor in the PR • 1 vertical on the corridor wall 	The horizontal AO serves to connect the two different layers of the PR while the vertical one connects the corridor to the space located aft of it (i.e. TG)	<ul style="list-style-type: none"> • Present • No Pipes/Cables • To be created

7.3.4. Wider corridor above one Power Generation System - X.5

As explained earlier, this configuration is really similar to the previous ones (X.4 and X.4.B), however in this case the corridor is decentralized and located exactly above one PGS, thus as AO configuration is considered only the case called “*AO in the corridor*” in Table 7.2 and not as earlier also the one with the AO located into the PR.

7.4. TOTAL RETROFIT COSTS

The previous section analyzed the possible AO configurations for the different layout considered, this section will detail the Total Retrofit Costs for converting a Power Room from one scenario to another, considering all the possible options in terms of layouts, AO configurations and moving equipment.

7.4.1. From Scenario 0 to Scenario 1

The retrofit from scenario 0 to 1 mainly involves the replacement of one generator and its relative EGATS with a fuel cell block and the installation of alcoholic fuel and safety related systems.

It is worth mentioning that considering all the possible combinations of transport means, layouts and AO configurations, a total of 116 results were analyzed, leading to an intricate graph shown in Figure 7.5. To make it more understandable different colors have been used for the AO position, type and for the transport mean, as explained below:

- AO position: the same color in which the AO has been represented in the previous 3D plots and detailed in Table 7.1 and 7.2 was used as background for the AO position text and as dominant color for the bars.
- AO type: to distinguish whether the AO is “Present”, a soft patch (called in the graphs as “No Pipes/Cables”) or “To be created” these words have been given a background of different colors (green for “Present”, yellow for “No Pipes/Cables” and red for or “To be created”)
- Transport Mean: the different possibilities in terms of transport mean were presented in the graph by using different transparency for the bars. As described in the chart legend, the highest transparency was assigned to “Rails not installed”, slightly lower to “Rails installed”, even lower to “C&T not installed” and no transparency to “C&T installed”.

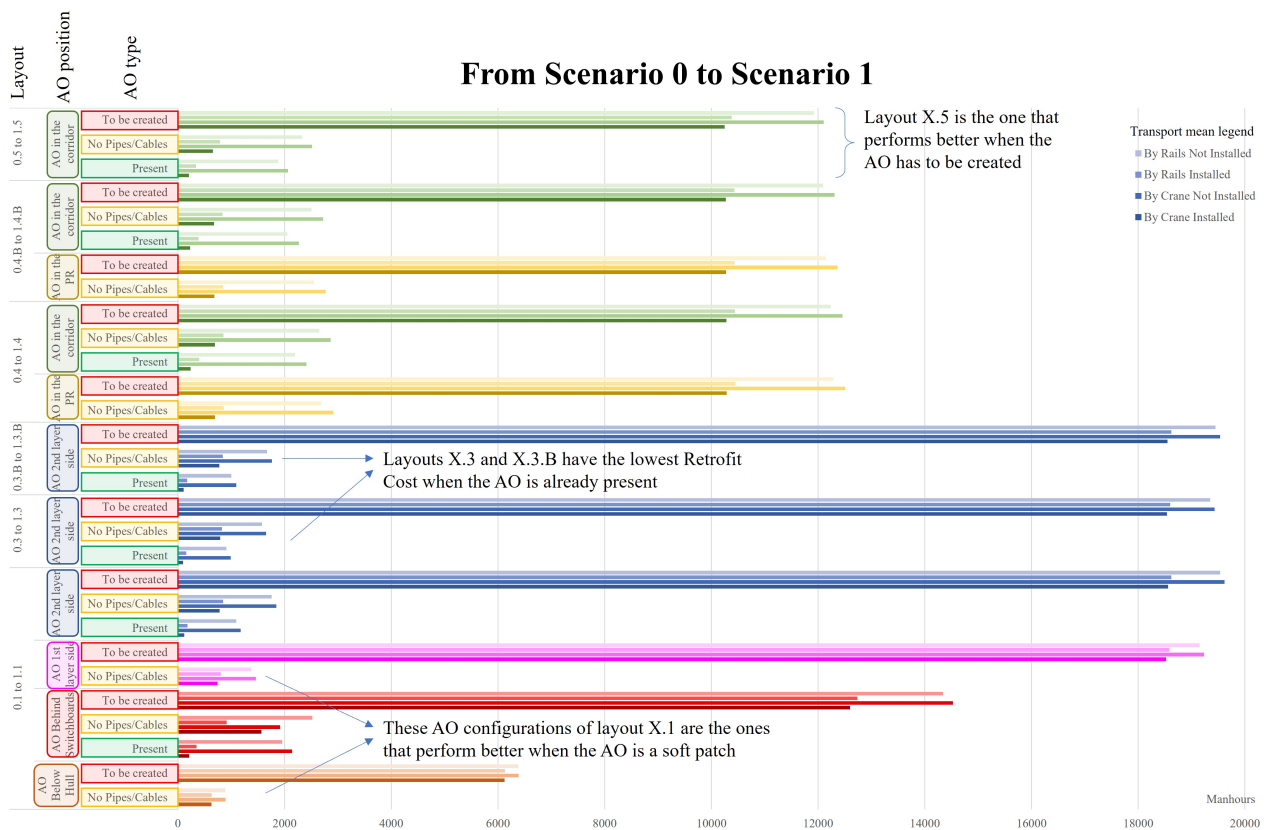


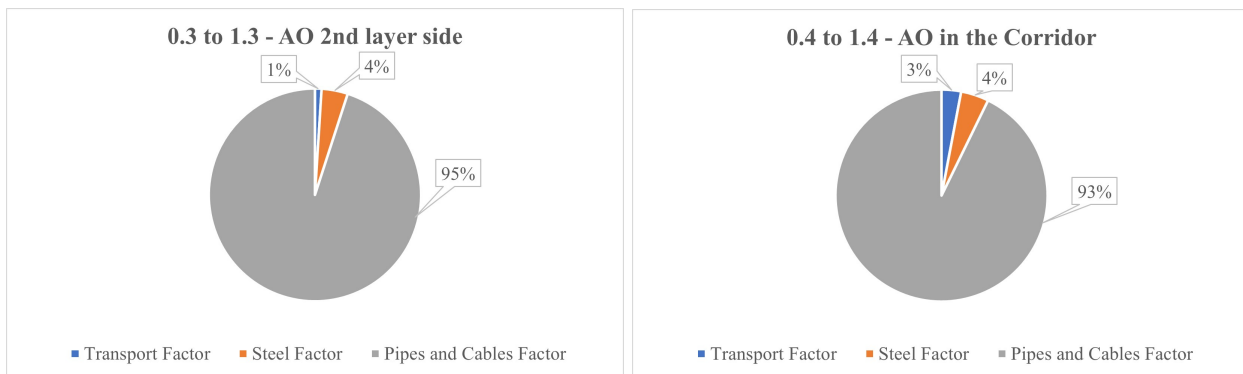
Figure 7.5: Total Retrofit Costs from Scenario 0 to Scenario 1

From this intricate graphs much information can be retrieved which regards mainly three topics: the transport equipment, the AO configuration and type and the layout.

For what concerns the transport mean, as outlined in section 7.2, the Chain and Tackle already installed is the one that always performs better, followed by the rails already installed. When there is no moving equipment installed the trend is opposite with rails leading to lower retrofit costs than C&T.

Considering the different layouts and their Total Retrofit Costs (TRC) it is worth distinguishing between the AO type. Indeed, if the AO is already present the layout X.3 is the one with the lowest TRC, while if the AO is a soft patch (No Pipes/Cables) or has to be created, layout X.1 with the AO configuration below hull is the one that performs better. However, as mentioned in subsection 7.3.1, this AO configuration would require the vessel to be in dry-dock. Without putting the yacht in dry-dock, layout X.5 is the one with the lowest TRC both for AO to be created and in the no pipes/cables type.

As can be seen from Figure 7.5 as well as from the following figures 7.7, 7.9, 7.10, 7.11 and 7.12 reporting the TRC for the other future-proof pathways, there is a huge difference between the various AO types, especially between the *“To be created”* and the soft patch (*“No Pipes/Cables”*) one. This is mainly due to the huge impact that dismantling cables and pipes have, as can be seen from Figure 7.6, the cables and pipes factor accounts for more than 90% of the TRC. This percentage can vary depending on the layout and the AO configurations. Two examples are presented: Figure 7.6a reports the different factors of the TRC for layout X.3 with the AO to be created on the 2nd layer side while Figure 7.6b report the same but for layout X.4 where the transport factor is a bit higher and thus the pipes and cables factor has a slight lower impact. Given the important cost of removing and reinstalling pipes and cables when creating an AO, these results suggest when it is not possible to have a present AO to opt for soft patch which is way cheaper in terms of TRC compared to an AO *“To be created”*.



(a) Impact of retrofit factors on layout X.3

(b) Impact of retrofit factors on layout X.4

Figure 7.6: Impact of the different retrofit factors from Scenario 0 to 1

7.4.2. From Scenario 0 to Scenario 2

As detailed in section 7.2, the C&T installed is the moving equipment that always lead to the lowest retrofit costs. Thus, to have less intricate graphs easier to read, in this subsection and in the following ones, the bar charts will show only the result for this moving equipment. The complex charts showing all the possible combinations of transport means and AOs are presented in Appendix D

Figure 7.7 shows the results for retrofitting from Scenario 0 to Scenario 2. In this case the retrofit involves the replacement of one generator and one EGATS with a fuel cell block, the conversion of the other generators to dual fuel, the installation of alcoholic fuel and safety related systems, and the installation of Oxicat system.

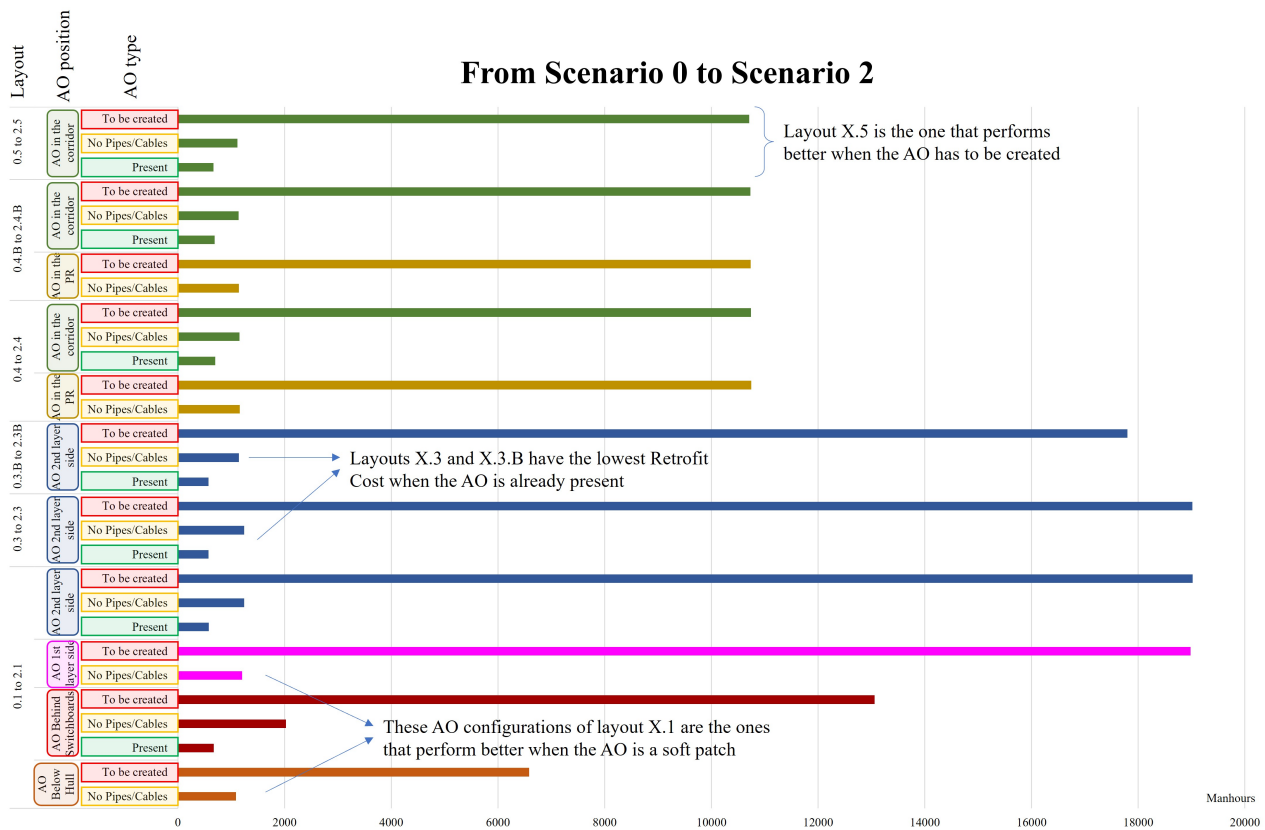
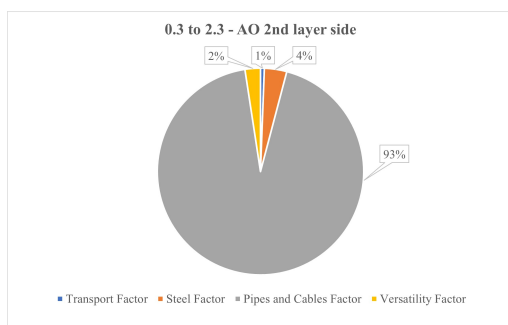


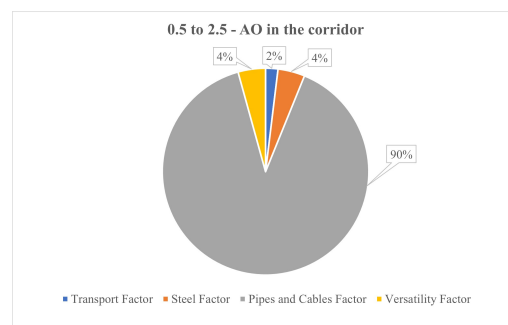
Figure 7.7: Total Retrofit Costs from Scenario 0 to Scenario 2 showing only C&T installed

As in the pathway from Scenario 0 to 1, if the AO is already present layout X.3 is the one with the lowest TRC, while if the AO is a soft patch (No Pipes/Cables) or has to be created layout X.1 with the AO configuration below hull is the one that performs better, followed by layout X.5 that does not require the yacht to be in dry-dock and still have good TRC both for AO to be created and in the no pipes/cables type.

Given the conversion of generators to dual fuel, compared to the previous pathway, this one has also a versatility factor. However, as can be seen from Figure 7.8, the impact of cables and pipes is still higher than 90%, with the versatility costs accounting between 2% and 4% of the TRC depending on the layout and on the AO configuration considered. Two examples are presented: Figure 7.8a reports the different factors of the TRC for layout X.3 with the AO to be created on the 2nd layer side while Figure 7.8b reports the same but for layout X.5 where the transport factor is a bit higher and creating an AO is a bit easier, leading to slightly higher impact of the versatility factor.



(a) Impact of retrofit factors on layout X.3



(b) Impact of retrofit factors on layout X.5

Figure 7.8: Impact of the different retrofit factors from Scenario 0 to 2

7.4.3. From Scenario 0 to Scenario 3

Figure 7.9 shows the results for the TRC when retrofitting from Scenario 0 to Scenario 3. This involves the replacements of all the generators and the diesel-dealing systems with fuel cells and alcoholic fuel and safety related systems.

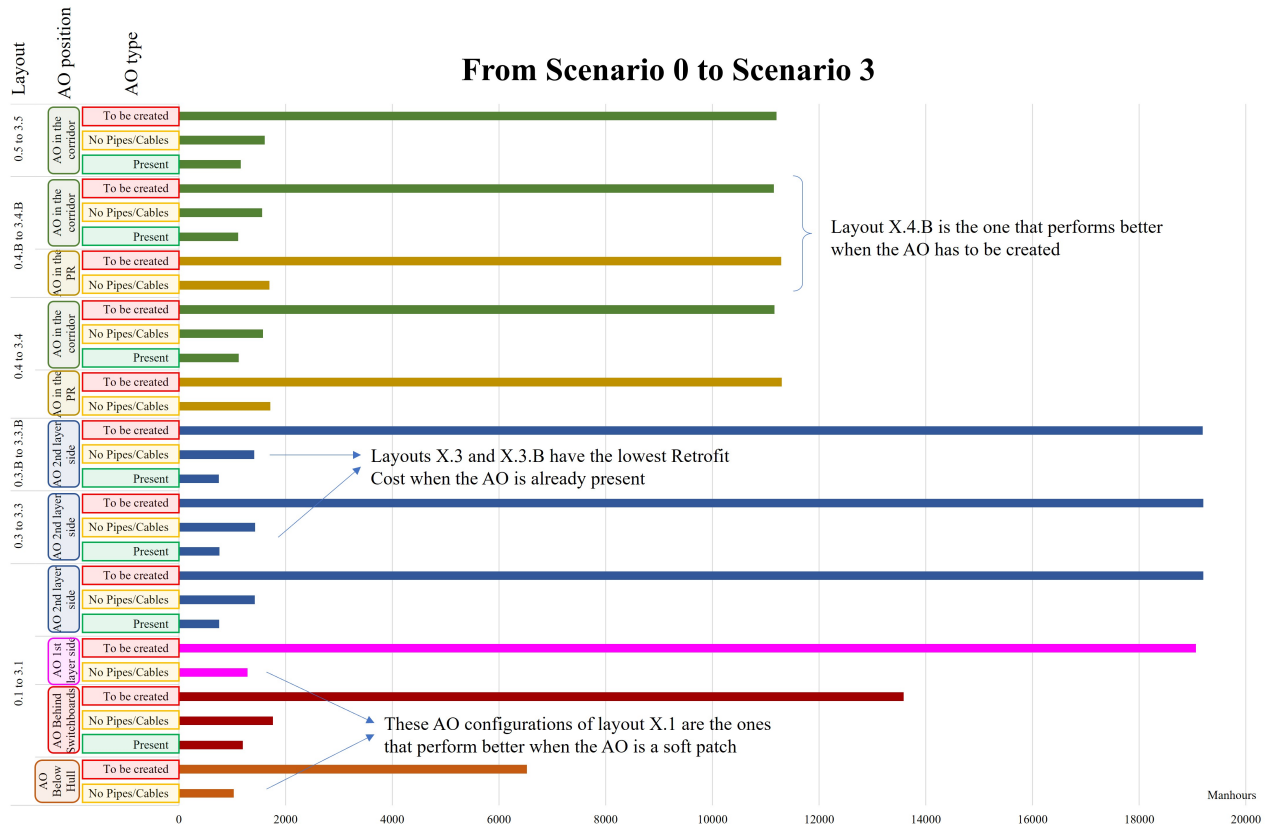


Figure 7.9: Total Retrofit Costs from Scenario 0 to Scenario 3 showing only C&T installed

Also in this case if the AO is already present layout X.3 is the one with the lowest TRC, while if the AO is a soft patch (No Pipes/Cables) or has to be created layout X.1 with the AO configuration below hull is the one that performs better. Differing from the previous pathways, in this case, when considering the option in which the yacht is not forced to go to dry-dock thus discarding the below hull and 1st layer side configuration of layout X.1, the layout with the lowest TRC with a soft patch AO is X.3.B while if the AO has to be created the layout that performs better is layout X.4.B with the AO in the corridor.

7.4.4. From Scenario 1 to Scenario 3

This retrofit pathways is very similar to the previous one but instead of replacing all the generators it is considered that one has already been replaced and that the alcoholic fuel and safety related systems are already installed. As shown in Figure 7.10 this leads to lower TRC compared to the previous pathway (Scenario 0 to 3).

Even if the TRC are lower, the best layouts for the different AO types are unchanged from the previous scenario. Layout X.3.B is the one with the lowest TRC when the AO is already present. Layout X.1 with the AO below hull configuration is the one that performs better if the AO is a soft patch or if it has to be created, while considering the non dry-dock option it is followed for the former type by layout X.3.B and in the latter by layout X.4.B with the AO in the corridor.

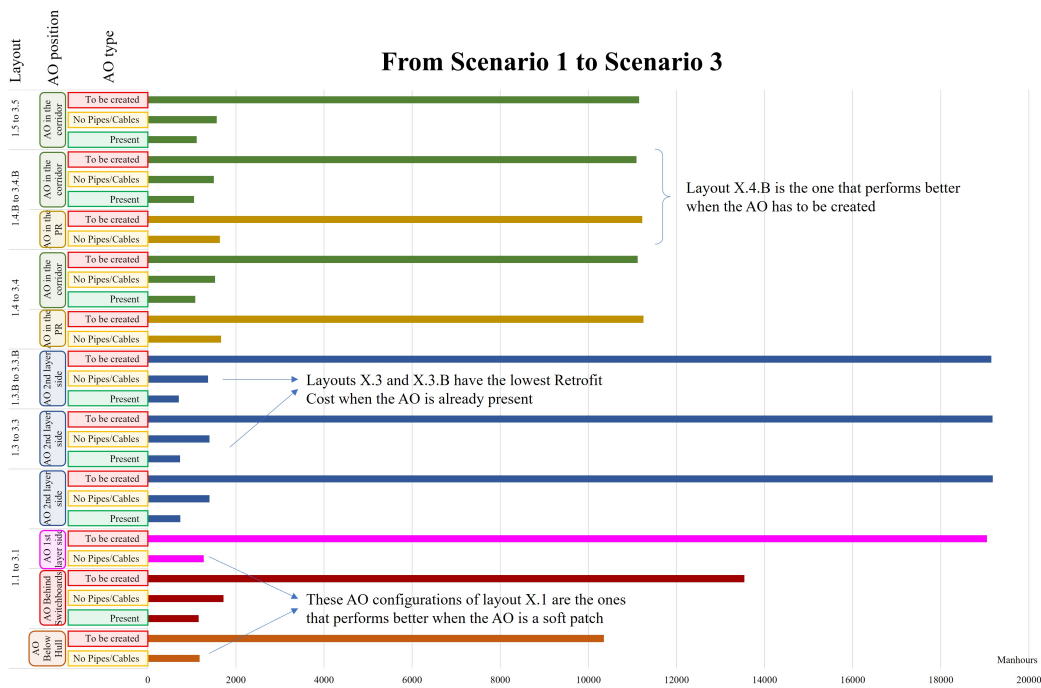


Figure 7.10: Total Retrofit Costs from Scenario 1 to Scenario 3 showing only C&T installed

7.4.5. From Scenario 2 to Scenario 3

This pathway is particularly similar to the previous one despite the fact that the generators to be replaced are DF and not diesel only and that there is the need to remove also the Oxicat system. However, the Oxicat system is relatively small and light and does not have a huge impact on the results which are present in Figure 7.11 while for the description it is possible to refer to the previous subsection.

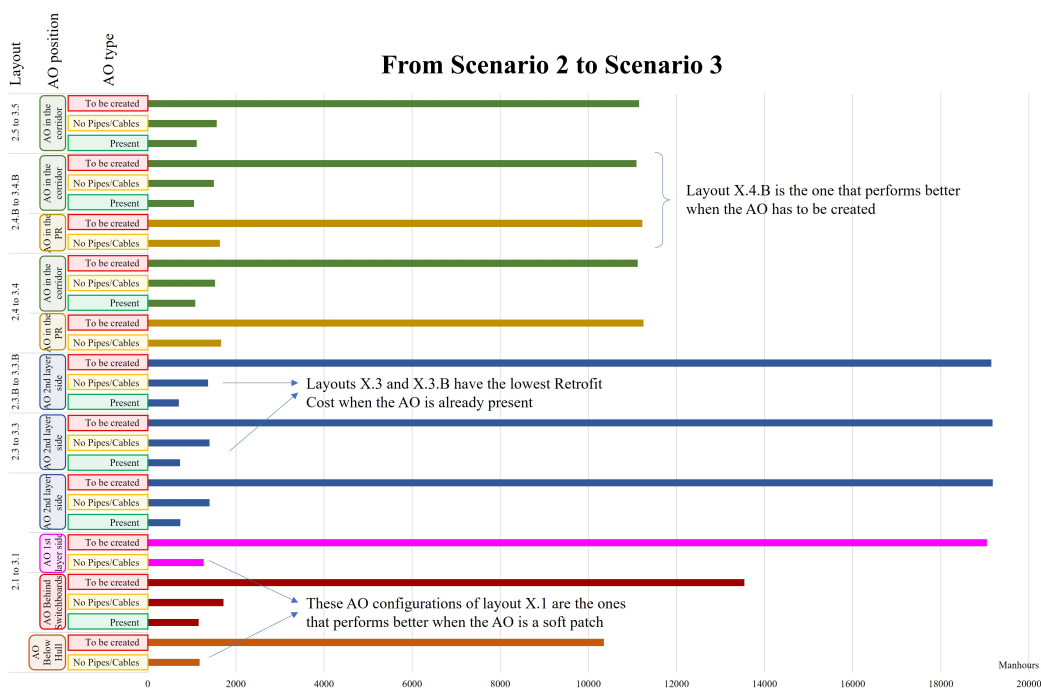


Figure 7.11: Total Retrofit Costs from Scenario 2 to Scenario 3 showing only C&T installed

7.4.6. From Scenario 1 to Scenario 2

This pathway is the one that present the smallest changes among its two scenarios and thus, as shown in Figure 7.12 also the lowest Total Retrofit Costs which are given just by the generators conversion to dual fuel and by the installation costs for the Oxicat system, as shown in Table 5.2 and Figure 5.4. It is worth mentioning that given the small size of the Oxicat system the AOs considered in this case are way smaller than the ones for the previous pathways, leading to low CAF and to smaller differences in the results for the AO types.

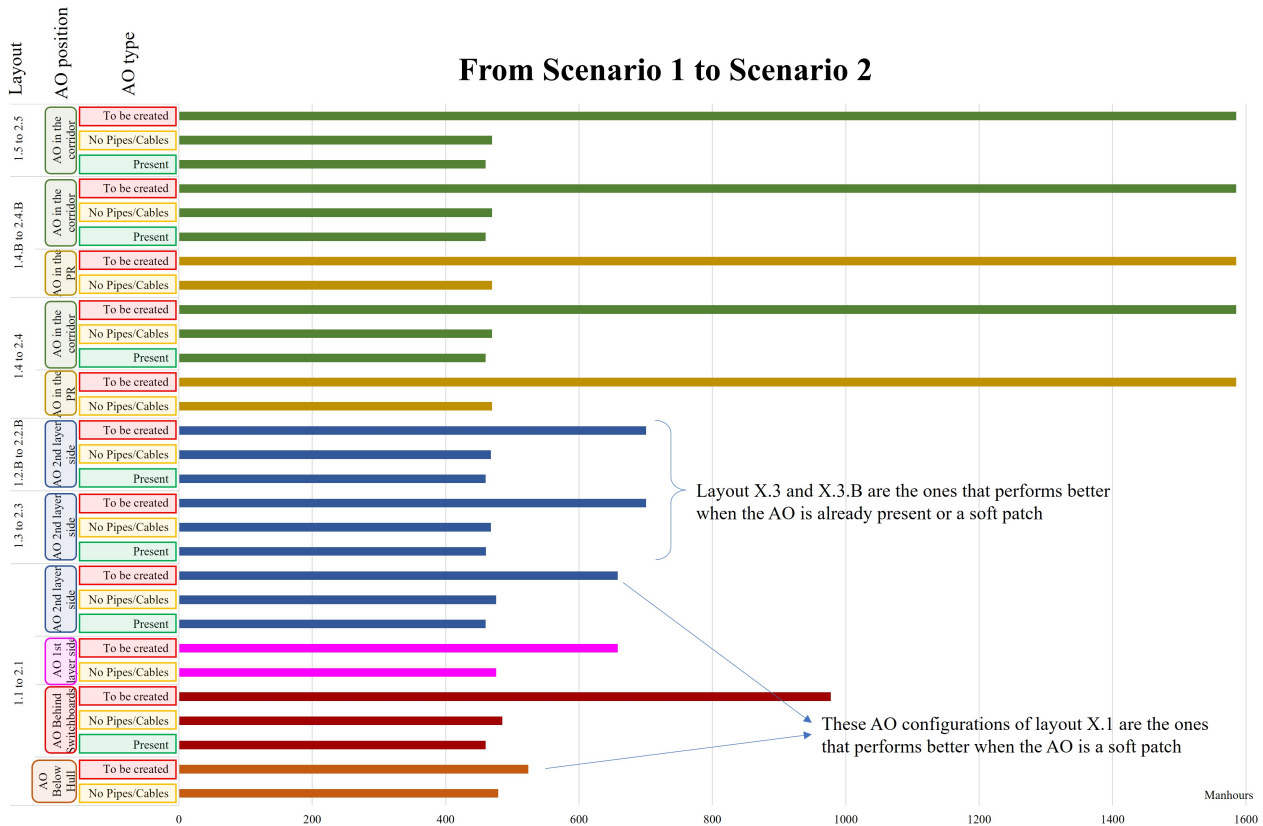


Figure 7.12: Total Retrofit Costs from Scenario 1 to Scenario 2 showing only C&T installed

As shown from the figure above, the layout with the lowest TRC if the AO is already present or is a soft patch is layout X.3. While in case of AO to be created the best solution is still layout X.1 with the AO below hull followed, as option not to force the yacht to go to dry-dock, by layout X.1 with the AO on the 2nd layer side.

As can be seen from Figure 7.12, compared to the previous future proof-pathways results the order of magnitude of the TRC is way lower and there is a less significant difference between the various AO types considered. This is due to the fact that in this pathway the only systems to be installed are Oxicat which are relatively small, thus also the AO are small. Furthermore, in this case given the low cost of transport and creating access opening, the TRC are dominated by the versatility costs of retrofitting the diesel generators to dual fuel. As can be seen from Figure 7.13, the versatility factor accounts for more than 60% of the TRC with the pipes and cables factor limited even to less than 10%. This percentage can vary depending on the layout and on the AO configurations. Two examples are presented: Figure 7.13a reports the different factors of the TRC for layout X.1 with the AO to be created on the 2nd layer side, while Figure 7.13b report the same but for layout X.3.

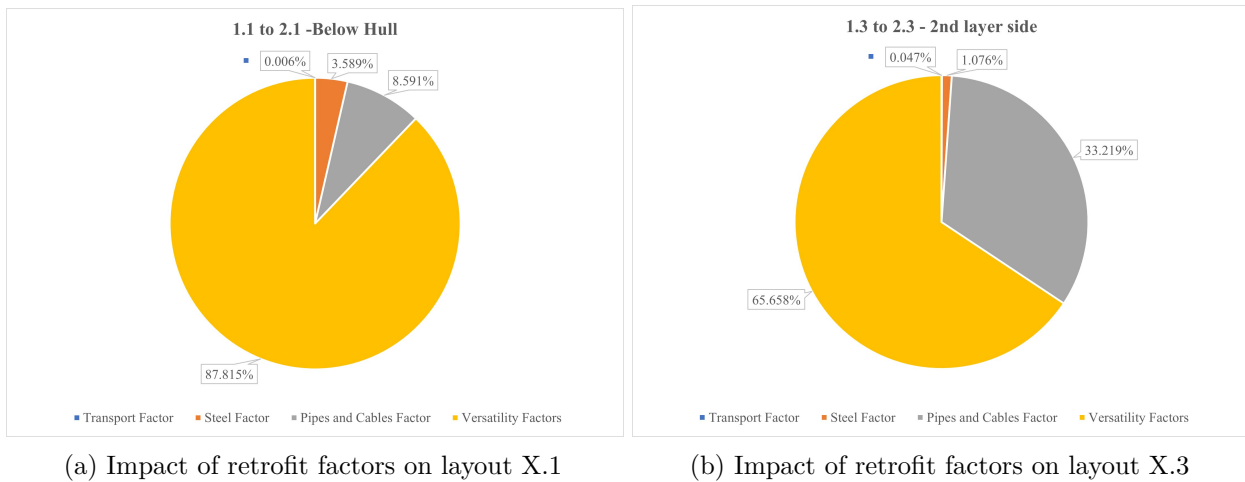


Figure 7.13: Impact of the different retrofit factors from Scenario 1 to 2

7.5. RESULTS SUMMARY

The previous subsections analyzed the Total Retrofit Cost (TRC) for the various future-proof pathways considering different layouts and the possible Access Openings configurations they can have. As mentioned, there exist important differences whether the yacht is willing to perform the retrofit in dry-dock or not. As outlined earlier, performing the retrofit with the yacht in dry-dock is often the best solution in terms of TRC however this would translate in higher costs due to the rates of dry-dock at shipyards which are way higher than just simple berths. For this reason, in this section a summary of the results related to the TRC is presented in two different tables: Table 7.4 shows the best solutions in terms of TRC when the yacht is just berth in a shipyard while Table 7.3 shows the best solution for a yacht that performs its retrofit in dry-dock.

Table 7.3: Best layouts and AO configurations and relative TRC for the different future-proof pathways - without the need to bring the vessel to dry-dock

Future-Proof pathways	Present Best Layout	TRC [manh]	Vessel not in dry-dock		To be created Best Layout	TRC [manh]
			No Pipes/Cables Best Layout	TRC [manh]		
Scenario 0 to 1	X.3	99	X.5	658	X.5	10249
	AO 2 nd layer side		AO in the corridor		AO in the corridor	
Scenario 0 to 2	X.3	573	X.5	1119	X.5	10709
	AO 2 nd layer side		AO in the corridor		AO in the corridor	
Scenario 0 to 3	X.3.B	748	X.3.B	1415	X.4.B	11152
	AO 2 nd layer side		AO 2 nd layer side		AO in the corridor	
Scenario 1 to 3	X.3.B	704	X.3.B	1371	X.4.B	11093
	AO 2 nd layer side		AO 2 nd layer side		AO in the corridor	
Scenario 2 to 3	X.3.B	705	X.3.B	1372	X.4.B	11094
	AO 2 nd layer side		AO 2 nd layer side		AO in the corridor	
Scenario 1 to 2	X.3	460	X.3	468	X.1	658
	AO 2 nd layer side		AO 2 nd layer side		AO 2 nd layer side	

Table 7.4: Best layouts and AO configurations and relative TRC for the different future-proof pathways - accepting the vessel to go to dry-dock

Future-Proof pathways	Vessel in dry-dock					
	No Pipes/Cables			To be created		
	Best Layout	TRC [manh]	% w.r.t. no drydock	Best Layout	TRC [manh]	% w.r.t. no drydock
Scenario 0 to 1	X.1 AO below hull	630	-4 %	X.1 AO below hull	6124	-67 %
Scenario 0 to 2	X.1 AO below hull	1090	-3 %	X.1 AO below hull	6584	-63 %
Scenario 0 to 3	X.1 AO below hull	1030	-37 %	X.1 AO below hull	6524	-71 %
Scenario 1 to 3	X.1 AO below hull	1180	-16 %	X.1 AO below hull	10353	-7 %
Scenario 2 to 3	X.1 AO below hull	1181	-16 %	X.1 AO below hull	10354	-7 %
Scenario 1 to 2	X.3 AO 2 nd layer side	468	0 %	X.1 AO below hull	524	-26 %

As can be noticed from Table 7.3, and as was outlined in the bar-charts, when the Access Opening (AO) is already present the best solution is always represented by layout X.3 or X.3.B with the AO on the 2nd layer side. While when the AO is a soft patch (No Pipes/Cables) and the yacht is not in dry-dock, the best solution is layout X.5 when going from scenario 0 to 1 or 2, thus when there are few systems to be removed and installed, or again layout X.3 and X.3.B in the other future-proof pathways. When the AO has to be created, when going from 0 to 1 or 2 the best layout is still X.5, when going from 1 to 2 the best option is layout X.1 with the AO on the 2nd layer side and in the other cases, layout X.4.B is the one that performs better.

In the case in which the yacht is willing to go to dry-dock, the best option is always represented by layout X.1 with the AO below hull except for having a soft patch when going from scenario 1 to 2 that has as best solution layout X.3. As can be seen from Table 7.3, the percentage differences of TRC when going to dry-dock or not vary a lot depending on the future-proof scenario and on the AO type. Overall it can be stated that when having a soft patch the difference in TRC is quite small for all the pathways, except for 0 to 3, making not convenient to go to dry-dock as it will cost more than just performing the retrofit with the solutions presented in Table 7.4. On the other hand, when the AO has to be created if starting from scenario 0 the difference in TRC compare to the non dry-dock solution are significant and thus it would be convenient to go to dry-dock for the retrofit. In the other pathways the differences are way less important and it is better just to berth the yacht at a shipyard and opt for the non dry-dock solution.

To check the best layouts in terms of TRC against the TCC and evaluate if they also have logical consistency, it is possible to visualize the two outputs in the same graph as in Figure 7.14, which reports the TRC on the Y-axis and the TCC on the X-axis. Figure 7.14 presents the results for the AO present type for all the possible pathways. As can be noticed, in certain future-proof pathways such as from 0 to 3, the layout with the lowest TRC (layout X.3.B in this case) is also the one with the lowest TCC while in other pathways, such as from scenario 0 to 1, the layout with the lowest TRC (X.3 in this case) is not the one with the lowest TCC but there exist other layouts that have lower connection costs (presented with yellow labels). However, for the purpose of this thesis the primary focus is on minimizing retrofit costs, as they are crucial for future-proofing. TCC is used to check the logical consistency of the layouts. As long as the layout with the lowest TRC does not have higher TCC than the baseline layout X.1 (indicated in red on the graph), it is preferred because it minimizes TRC while keeping TCC at an acceptable level. The only exception is the pathway from scenario 1 to 2: in this case given the huge impact of the versatility factor (as described in Figure 7.13, the TRC variation for the various layouts is minimum, thus it is suggested to opt for the option with the lowest TCC, which is highlighted in the figure.

TCC vs TRC – Vessel not in dry dock – AO present

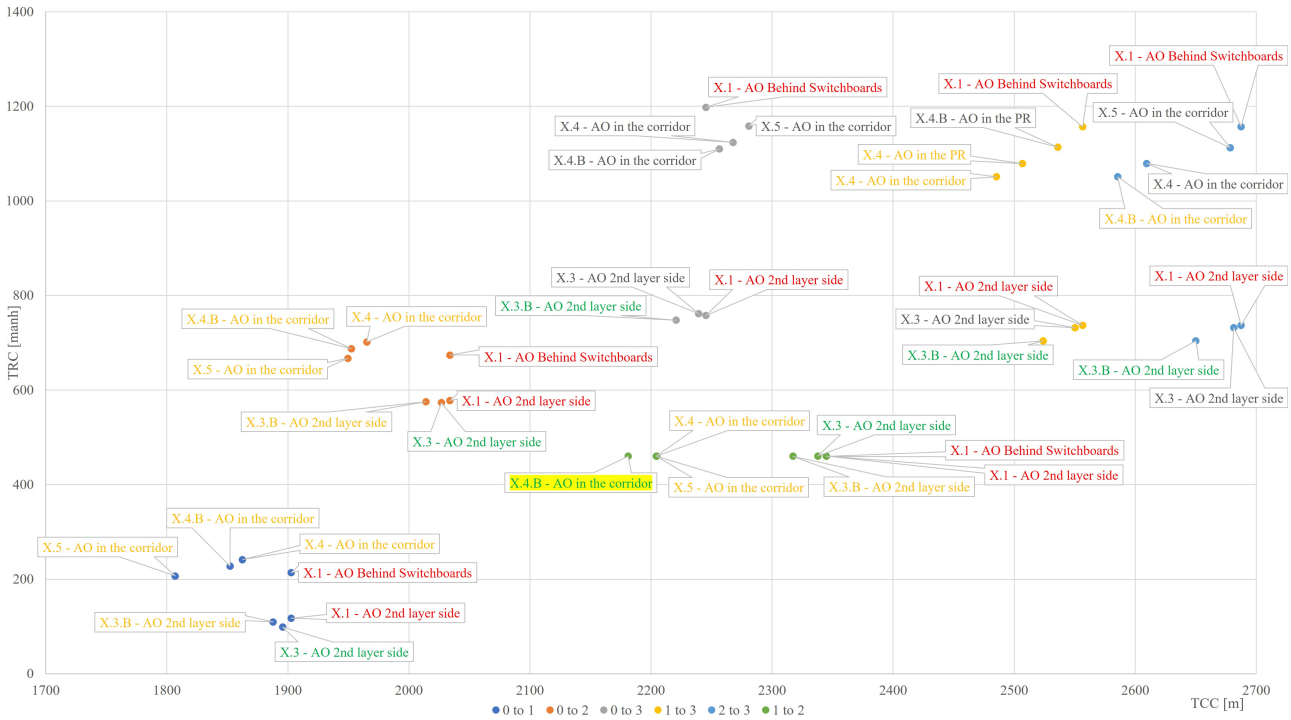


Figure 7.14: TCC vs TRC for vessel not in dry-dock with AO already present

The same reasoning applies also for the cases in which the vessel is not in dry-dock and the AO is of the type “No Pipes/Cables” and “To be created”, presented respectively in Figure D.7 and D.8. On the other hand, when the yacht is willing to go to dry-dock in almost all the cases the baseline layout X.1 is the best solution and this does not bring any higher TCC.

In the end, it is worth noting that all the final results considerations in section 7.5 are based on the key assumption that berthing a yacht in a shipyard is less expensive than bringing it to a dry-dock. However, yachts typically must go to dry-dock every five years for specific surveys. Combining these surveys with retrofit operations could be the best solution, as the yacht would already be paying for the dry-dock. Then when design with future-proof consideration into account it is suggested to keep future surveys and inspections by classification societies into account as they can be easily scheduled and they can be combined with a retrofit to a newer scenario with the yacht in dry-dock.

7.6. DISCUSSION ON THE RESULTS

The results presented in this chapter not only highlight the best layout options in terms of Total Connection Costs (TCC) and Total Retrofit Costs (TRC), but also offer valuable insights on the optimal transport means and Access Opening (AO) configurations and types.

Overall it was concluded that Chain and Tackle already pre-arranged and installed in the Power Room is always the preferred option among the transport mean proposed, this can be addressed to the equations and factors described in section 4.5 (specifically in equations 4.8 - 4.11) which have been discussed with Feadship’s experts, refined and later validated and verified as will be shown in the following chapter 8.

Among the various Access Openings types (“Present”, soft patch called “No Pipes/Cables” and “To be created”), as was expected the “Present” type is the one that has always the lower TRC followed by the soft patch and then by “To be created” type. Also in this case the results are driven by the factors and equations presented in section 4.5. Specifically, equations 4.12 - 4.17 played a primary role in results obtained alongside

the values in Table 4.2 - 4.4. Even if some assumptions have been made such as the cables and pipes densities on the different PR walls and their complexity factor, these assumptions can be considered realistic as referred to previous Feadship's projects. However, to get better estimations on the TRC of a specific project, in a later design stage, it is suggested to determine more accurately the amount of pipes and cables to be removed and re-installed when creating an Access Opening.

The method and its application aimed to be as realistic as possible, considering a maximum of 29 building blocks (BBs) depending on the scenarios. The connections between these BBs and their possible removal and/or installation were analyzed. However, real vessel power rooms are far more complex and include additional systems and subsystems not covered in this thesis, such as grey and black water systems or bilge systems. These would increase the Total Connection Costs and complicate retrofit operations. Nonetheless, all major systems and subsystems were considered, and their connections and possible removal and installation were analyzed and calculated. Thanks to the design rationale in section 4.3 and experts' opinions, it is safe to assume that the filtered and refined layouts are realistic and provide valuable insights for designing future-proof power rooms.

Moreover, as described in section 4.5, assumptions were made regarding transport means and access openings. Despite their realistic nature, the model does not produce detailed retrofit costs but rather estimations useful for determining the best layout arrangements and good practices for future-proof Power Room design.

Another consideration pertains to connection costs, which were implemented and calculated using 3D modeling compared to previous works. However, the calculated TCC are not detailed connection costs, as actual interfaces are more complex than those presented in this thesis. Therefore, the TCC results should be seen as indicators for evaluating layout dispositions and good practices in the early design phases.

7.6.1. Accuracy of the results

The primary goal of the results presented in this chapter is to offer insights into the best layout configurations and future-proof design strategies during the early stages of yacht design. Despite the assumptions and simplifications, these results serve as valuable indicators for making informed decisions.

It is crucial to understand that these findings should not be taken as precise financial predictions but rather as strategic guidelines. The results presented are the outcome of analytical equations that give realistic but not real costs that the yard will incur in. The equations and the results do not account for many factors that contribute to financial costs for shipyards during retrofit. The results serve as valuable indicator for layout and choice comparison in the early stage design but they are not useful to effectively predict the yard costs, due to the high number of assumptions and parameters adopted.

All assumptions made during this thesis were uniformly applied across different layouts and scenarios, ensuring consistency in the comparative analysis. The auxiliary building blocks were disposed in different positions depending on the scenarios and the layouts. These positions have been chosen with an accuracy of 0.1 to 0.2 meters, ensuring a high level of detail but at the same time leading to minor inaccuracies in the results. Given this accuracy range, the maximum potential inaccuracy in the TRC and TCC results was calculated to be between 0.01% and 0.2%. This means that these costs are not accurate financial predictions but quite accurate indicators for layout comparison.

Figure 7.15 reports the plot of TCC against TRC for a vessel not in dry-dock with the access opening present (as Figure 7.14) with a zoom only on the scenario from 0 to 1, with the error bars for the TCC and TRC results. As can be noticed from Figure 7.15, despite the minor inaccuracies, the diversity in results for different layout concepts is significant enough to confidently state which layouts perform better than others in various future-proof pathways. The only exception regards the variation in results between layout X.3 and X.3.B and the one between X.4 and X.4.B. As it is highlighted in Figure 7.15, but as can also be noticed from Figure 7.14, D.7 and D.8, the results for layout X.3 and X.4 and their B variations are particularly close to each other, meaning no safe statement can be made regarding which option has the lowest TRC and TCC. However, it is important to note that the concept behind the normal layout and their B variations is the same, with the only change being the FC deck position. This suggests that the FC deck position does not significantly impact the results, and whether the best layout is X.3 or X.3.B, or X.4 or X.4.B, does not change the overall layout concept.

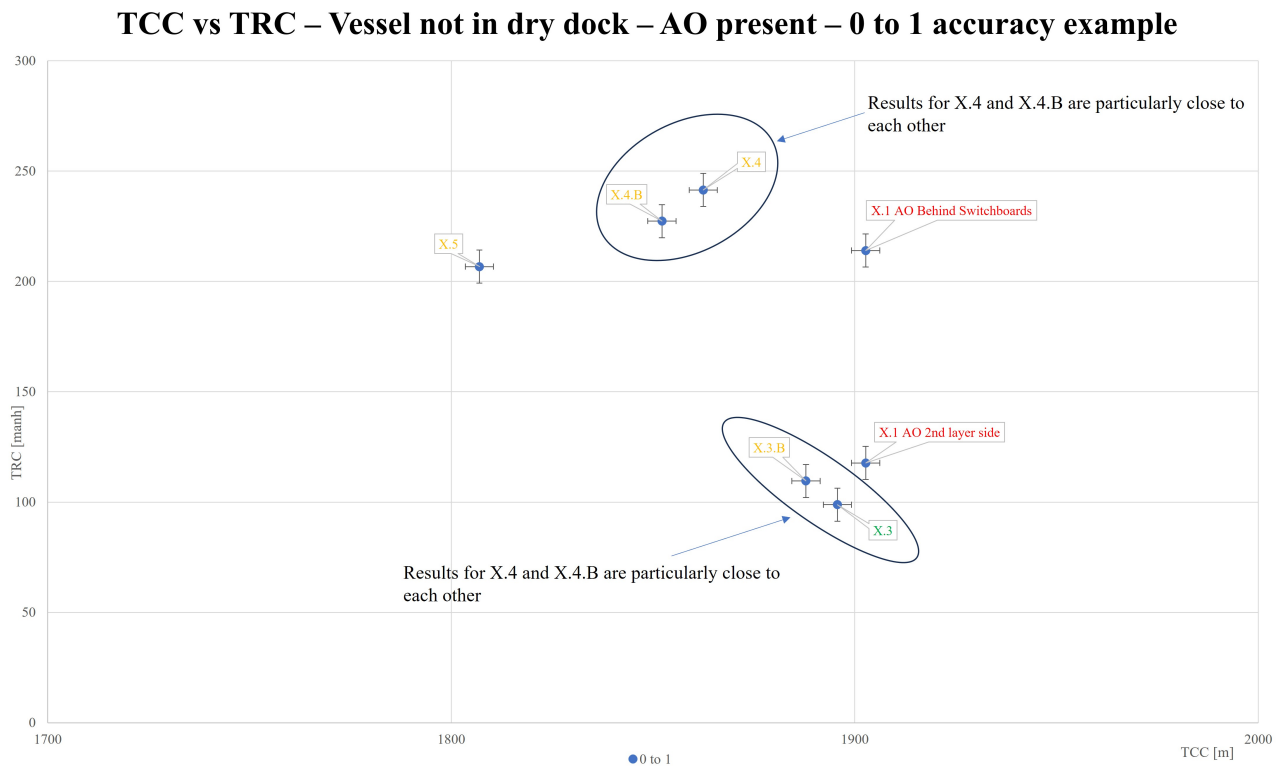


Figure 7.15: TCC vs TRC for vessel not in dry-dock with AO already present for Scenario from 0 to 1 with error bars

In conclusion, while the results of this thesis provide crucial insights into the best practices for future-proofing yacht power rooms, they should be interpreted with an understanding of their inherent limitations. The insights drawn are robust for early-stage design decisions but should be supplemented with detailed analyses during later design phases to account for the complexities of actual retrofit and connection processes.

8. VALIDATION AND VERIFICATION

This chapter outlines a validation process for the design method developed in this thesis. The method, as described in chapter 4, aims to effectively and efficiently evaluate multiple Power Room layouts and sort out the best ones for future-proof intend. Validation ensures the method is well-founded, internally consistent, and generates useful outcomes for the intended purpose.

This validation process adheres to the framework proposed by Pedersen et al., 2000 shown in Figure 8.1. It is divided into two main parts: structural validation and performance validation. Each part consists of three steps, resulting in a six-step validation process.

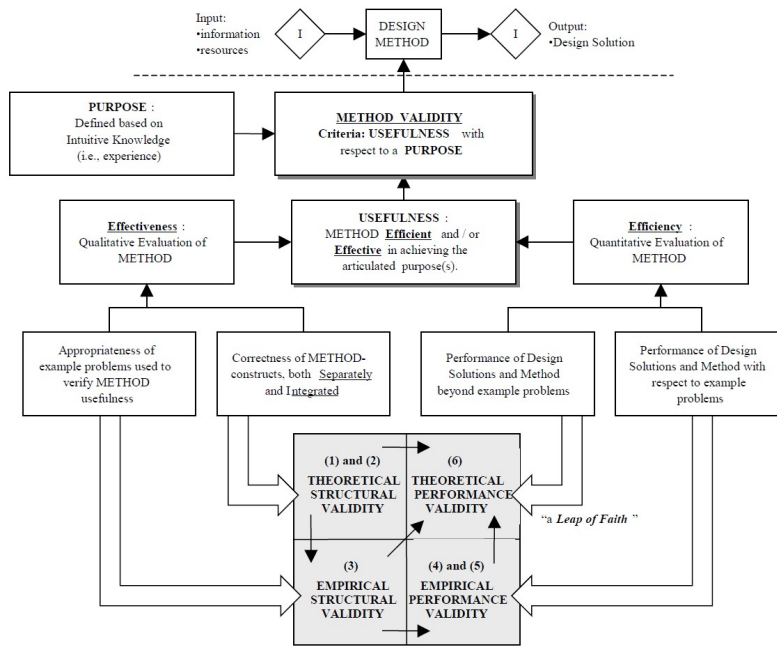


Figure 8.1: Design method validation by using the Validation Square (Pedersen et al., 2000)

8.1. STRUCTURAL VALIDATION

Structural validation focuses on the internal structure and logic of the design method. This ensures the method is built upon sound principles and its components work together coherently.

Step 1: accepting the individual constructs constituting the method and thereby accepting its validity

In validating the design method outlined in the thesis, it is crucial to thoroughly examine the individual constructs forming the method. These constructs serve as the foundational elements upon which the entire methodology is built. The three key constructs are shown in Figure 4.1 and confidence in their validity is built upon literature, as suggested by Pedersen et al., 2000:

- **Layouts concepts based on current State of the art and easiness of retrofit:** The concept of generating layouts based on the current state of the art and considering ease of retrofitting is well-established in engineering and design literature especially when it comes to civil engineering and architecture (Rosso et al., 2020). Retrofitting challenges and the importance of adaptable layouts in these sectors have been extensively discussed in various studies as demonstrated by Jagarajan et al., 2017. Even though in the

maritime domain future-proofing is gaining relevance only in recent years (Lateral Naval Architects, 2023) there were some studies that took into consideration the relevance of future-proofing vessels (Pruijn, 2023) and even more specifically retrofit of PR (Coenen et al., 2015). This construct is essential as it sets the initial groundwork for designing future-proof engine rooms. By considering current technological capabilities and retrofitting constraints, the method ensures that generated layouts are practical and adaptable to evolving needs.

- **Layouts filtering based on experts' opinions:** expert opinion and design rationale play a crucial role in design decision-making, particularly in complex engineering projects such as conceptual ship design (Garcia et al., 2020) and ship layout design (le Poole et al., 2022). Filtering layouts based on expert feedback ensures that practical considerations and industry insights are incorporated into the design process (Ahmad et al., 2008). By leveraging experts' opinions, the method ensures that only feasible and relevant layouts are considered for further evaluation. This construct enhances the validity and applicability of the generated layouts by tapping into the collective wisdom of industry professionals.
- **Layouts evaluation based on future-proof evaluation model:** the model provided aims to facilitate PR layouts evaluation by assessing the bests layouts in terms of connection costs and retrofit costs. The first ones are calculated based on equations and matrices already extensively used by Drira et al., 2007, van der Bles, 2019 and Poullis, 2022. On the other hand, the methodology to evaluate the retrofit costs is mainly based on the formulas by Coenen et al., 2015 and on the values by Butler, 2013, even tough the equations and the values presented in these two papers have sometimes been refined according to experts' insights to better fit the challenge of future-proofing a PR. The evaluation of layouts using such a methodology ensures that selected designs are robust and adaptable to emerging trends and technologies.

By critically assessing these key constructs, it was possible to establish the theoretical foundation and validity of the design method. Each construct is rooted in established principles and practices within the fields of engineering design, sustainability, and future-proofing strategies. Together, these elements form a comprehensive method for designing future-proof power rooms, integrating expert insights, practical considerations, and forward-thinking approaches.

Step 2: accepting the internal consistency of the way the constructs are put together in the method

To validate the internal consistency of the design method, it is imperative to examine how the three chosen constructs described in the previous subsection are logically integrated and work together cohesively throughout the design process. This step ensures that the method follows a consistent flow, with each construct contributing to the overall effectiveness and efficiency of the design process.

The design method follows a structured and systematic approach, consisting of several interconnected steps aimed at generating, filtering, and evaluating layouts for future-proof engine rooms of superyachts. Initially, layouts are generated based on the current state of the art and considerations for ease of retrofitting (section 6.2). Expert opinions are then solicited to filter these layouts, ensuring practicality and relevance (section 4.3). Then, the retained layouts undergo evaluation using a future-proof methodology, that evaluates total connection costs to prove layouts' relevance and total retrofit costs to estimate layouts' future retrofit costs.

As illustrated in Figure 4.1, the method's steps are logically connected and follow a consistent flow, with each stage building upon the previous one. Layouts generated in the first step serve as the foundation for subsequent filtering and evaluation processes. Expert feedback informs the selection and refinement of layouts, ensuring that only viable options are considered for further evaluation.

Step 3: accepting the appropriateness of the example problem that will be used to verify the performance of the method

To verify the performance of the method, it is crucial to choose an example problem that aligns with the intended purpose and scope of the method. While some constructs of the method are well-established in the literature such as the Design Rationale use in layout evaluation problems (le Poole et al., 2022 and le Poole et al., 2023) as well as the formula to calculate the TCC (van der Bles, 2019 and Poullis, 2022), the TRC calculation represents

a novel contribution to the maritime landscape, especially as in section 4.5 new and modified equations and parameters were established. Given the significance of TRC calculation and its potential as a weak link, it's crucial to verify its accuracy. The chosen example problem will exclusively assess TRC calculations by comparing model outputs against actual retrofit costs from a documented retrofit project.

The selected example problem should closely resemble the real-world scenarios for which the method is designed to be applicable. In this case, the example problem chosen for verification is a retrofit that took place at Feadship's Kaag shipyard involving the motor yacht Sport, a 46m yacht built in 2007, which underwent refit from October 2023 until April 2024 (Jusufi, 2024).

The example problem shares key similarities with the purpose problem addressed by the method. While the method focuses on designing future-proof engine rooms to accommodate zero-emission systems during retrofits, the example retrofit of yacht Sport also involved significant modifications to the engine room, including the replacement of generators and removal and re-installation after overhaul of main engines, for which cutting a bulkhead was needed to create an AO. Although the example retrofit did not specifically involve the integration of zero-emission systems, it presents an opportunity to verify whether the model's outputs align with the retrofit cost outcomes observed during the yacht Sport refit.

The example retrofit effectively represents the defined problem for which the method is intended to be used. While the focus of the retrofit was on upgrading existing systems rather than integrating zero-emission technologies, the underlying challenges and objectives remain relevant to the method's scope. By comparing the effective retrofit costs incurred by the Sport yacht to the costs estimated by the model for the same retrofit, it is possible to verify whether the model effectively represents the retrofit costs incurred during engine room retrofits. The example retrofit provides a real-world case study that allows for a practical assessment of the method's performance and applicability in other retrofit scenarios.

In summary, while the example retrofit at Feadship did not involve the integration of zero-emission systems, it serves as a suitable example problem for verifying the performance of the method. By examining the similarities between the example and the purpose problem, as well as demonstrating how the example represents the defined problem, it is possible to build confidence in the appropriateness of the example for evaluating the method's effectiveness and accuracy.

8.2. PERFORMANCE VALIDATION

Performance validation evaluates the effectiveness and usefulness of the design method in achieving its intended goals.

Step 4: accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem

Once the appropriateness of the example problem is accepted, the method usefulness and efficacy are evaluated focusing on its ability to evaluate the effective retrofit costs of a Power Room. By applying the method to the engine room retrofit of yacht Sport and comparing the Total Retrofit Costs (TRC) calculated by the model with the actual costs incurred during the refit, the effectiveness of the method can be assessed.

Figure 8.2 reports a block layout of the Engine Room of yacht Sport. During the refit an AO in the bulkhead was opened (shown in red in Figure 8.2 and Figure 8.3), the main engines were taken out first and then the generators, while during the re-installation the generators were installed first followed by the main engine. To do such operations no transport mean was already pre-arranged or installed and among the ones proposed in subsection 3.2.3 the yard used C&T. Furthermore, the door leading to the TG, which as can be seen from Figure 8.2 is located close to the ER, was not big enough and the bulkhead dividing these two areas was cut opened and thus it can be considered that the AO was of the type "To be created" among the ones described in subsection 3.2.2. Moreover, it is worth noting that since Sport yacht in the Tender Garage does not have cranes but the tender is moved via a hook, the yard personnel once moved the systems out of the ER in the TG had to carry them still with C&T for 7 meters before they could have been handled by the shipyard cranes. This was considered while using the model for this specific yacht Sport case, while generally the model accounts

just for transporting the systems out of the PR. To provide a better understanding, Figure 8.3 shows the yacht's TG (that when at anchor is converted into a gym) in reality highlighting the area of the bulkhead that was cut open and the way out of the TG via the foldable swim platform.

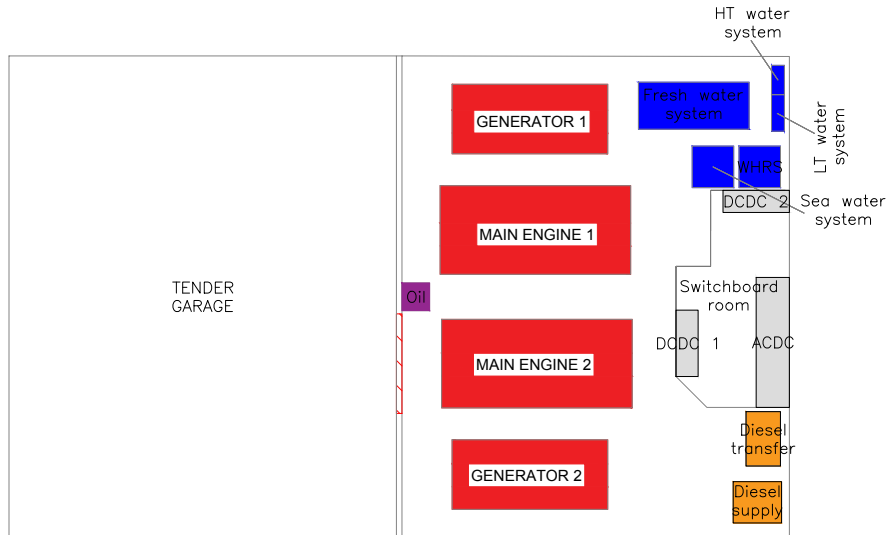


Figure 8.2: Yacht Sport ER block layout (adapted from Feadship's project 796)



Figure 8.3: Sport's TG showing the bulkheads AO and the way out (adapted from Edmiston, 2024)

Excluding all the other retrofit costs that the yard incurred with which are not relevant for the model such as interior modification to the yacht but also main engine alignment (not relevant since the method focus on diesel-electric only yacht thus the costs to perform shaftlines alignment is not applicable), the focus was just on the relevant retrofit works for the model such as generators and main engine remove and replacement and bulkheads cut. Comparing the model outcome with the yard actual costs, it was possible to establish that the model overestimated the Total Retrofit Costs by just 3%.

The close correspondence between the calculated and actual TRC demonstrates the practical utility of the method in supporting decision-making for power room future-proofing. By providing reliable cost estimates, the method enables stakeholders to make informed decisions that can potentially reduce costs and improve efficiency in future retrofit projects.

Overall, the findings validate the usefulness of the method's outcome in achieving the initial purpose of cost evaluation in engine room retrofits, thereby enhancing confidence in its applicability and effectiveness.

Step 5: accepting that the achieved usefulness is linked to applying the method

To ensure that the usefulness of the resulting solutions from the design method is directly attributed to the method itself, a systematic evaluation of the contributions from each construct is warranted. This involves comparing the solutions obtained with and without the incorporation of each construct, allowing for a quantitative assessment of their individual impacts on the method's effectiveness. Furthermore, in evaluating the achieved usefulness, it is imperative to compare the solutions obtained from the method with those derived from existing design approaches. This comparative analysis enables a comprehensive assessment of the method's efficacy relative to established practices and methodologies. By benchmarking against rival theories or alternative explanations, the method's unique contributions and advantages can be clearly delineated and validated.

The first step in evaluating the method's usefulness is to isolate the effects of each construct on the outcomes generated by the method. By systematically removing or modifying each construct and observing its impact on the solutions, it becomes possible to discern their specific roles in enhancing the method's effectiveness. For example, by removing the Layout Filtering construct and evaluating layouts without expert feedback, it is possible to assess the importance of expert opinion in filtering out impractical or non-feasible layouts, as not all the relevant aspects for which some layouts have been discarded according to experts' opinions would have been caught just with the layout evaluation model.

Next, it's crucial to compare the solutions obtained from the method with those derived from existing design approaches. From the literature review it emerged that currently there exists no design method that account for evaluating and comparing various layouts across different future-proof scenarios. Thus, it can be hard to compare the whole method to existing approaches. However, it is possible to compare the model's TRC outcome with the design approach proposed by Coenen et al., 2015, which focused on Total Retrofit Costs as well but did not specifically address future-proof power rooms, thus overlooking factors such as versatility costs as well as not considering the retrofit from one scenario to another but just a simple ER retrofit. Moreover, Coenen et al., 2015's approach considered both a Create Access Factor and a Transport Factor, but it did not meaningfully account for their interaction. By comparing the solutions obtained from the method with those derived from Coenen et al., 2015's approach, it is possible to assess the method's ability to identify layouts that not only minimize retrofit costs but also prioritize future-proofing considerations.

Overall, this step serves as a critical component of the validation process, elucidating the causal link between the method's application and the achieved usefulness of its outcomes. By systematically evaluating the contributions of each construct and comparing solutions with existing approaches, this step enhances confidence in the method's applicability and effectiveness in real-world design scenarios.

Step 6: accepting that the usefulness of the method is beyond the case studies

The preceding five steps have provided a comprehensive validation process for the design method, encompassing structural and performance aspects, and demonstrating its effectiveness in achieving the intended purpose. Now, the evaluation is extended to consider the broader applicability and usefulness of the method beyond the specific example problem examined in previous steps.

Since the effectiveness and applicability of the method through the validation process have been established it is now possible to assert that the method is useful beyond the tested example problems. With proper adaptation, thus considering proper PR and BBs characteristics it is believed that the method can be applied not only to average Feadships or yacht power rooms but more generally to various types of vessel power rooms. By leveraging the method's structured approach and incorporating domain-specific knowledge, stakeholders can design power rooms that meet evolving industry requirements and standards.

In conclusion, the method's generality and usefulness transcend the specific case studies presented in this validation process and in this thesis, offering a robust framework for designing future-proof power rooms across the maritime industry.

9. CONCLUSION AND DISCUSSION

This final chapter focuses on conclusions and discussion of the overall thesis. First the conclusions are presented both as summary of the findings of the thesis and then as design guidelines that can be used by yacht builders as well as by the academic world for the purpose of future-proofing.

Then the limitations of the design method developed are highlighted and future research suggestions are provided to further implement the method and to cover more in detail aspects that were left out of the scope of this thesis. In the end, the author's personal opinion on how this thesis can help in the challenge of yacht future-proofing is given.

9.1. CONCLUSIONS

9.1.1. Summary

This thesis was originated to fill the lack of a design method able to account for future-proof considerations and to provide designers and engineers with indicators in the early design phases pointing out the best layouts and practices to design a future-proof power room.

Chapter 2 focused on the current state-of-the-art of yachts' engine rooms setting the Diesel-Batteries power plant as baseline. This chapter outlined that current state-of-the-art power rooms are far from being zero-emission and investigated several sustainable options both in terms of fuels and power generation systems. Findings highlighted alcoholic ICEs and FCs as the most promising solutions for zero-emission yachts. The requirements for current PR as well as for the new PGSs have been investigated, particularly in terms of auxiliary systems needed to operate efficiently and safely and the auxiliary systems to allow PGSs to work properly were outlined alongside their location onboard.

Afterwards, chapter 3 provided considerations regarding retrofit techniques, transport means and current AO configurations. Moreover, the concept of future-proofing was introduced alongside different theories to achieve it, with a mixture of robustness, versatility and design for retrofit, identified as the preferred choice for power room onboard yachts.

In chapter 4, the design method was introduced in three major steps: layout concepts, design rationale and layout evaluation model. The equations for the model were set up and a small-scale example to understand the functioning of the model was provided. The model provides results in terms of Connection Costs and Retrofit Costs. These two indicators have been later used to evaluate the best layout arrangements and good practices in future-proof designs.

Chapter 5 delved into the four scenarios constituting the future-proof road-map, the systems in these scenarios were described with a specific focus on the requirements that integrating zero-emission PGSs in a PR brings. In chapter 6, the method was applied to the scenarios considered. Various layout concepts were developed and later filtered and refined according to experts' opinions.

The filtered layouts have then been evaluated through the model and the results were presented in chapter 7. The overall validity of the method was assessed in chapter 8, focusing especially on those that were considered the weakest parts. Results show both Connection Costs and Retrofit Costs and by analyzing these indicators it is possible to understand good practices for future-proofing power rooms.

9.1.2. Design Guidelines

The thesis was guided by the research question "*How can a future-proof engine room that facilitates the integration of zero-emission systems during future retrofit of superyachts be designed?*" leading to the above mentioned conclusions. The results obtained by answering this question can be translated into design guidelines to future-proof power rooms to be used specifically in the early stage design of a yacht:

- Prioritize proximity between zero-emission PGS and their auxiliary systems: zero-emission PGSs require specific auxiliary systems such as a dedicated fuel system and a nitrogen system. These zero-emissions systems are connected via peculiar pipes such as double walled pipes whose installation and routing prove to be complex. For this reason, as was demonstrated by comparing connections costs for different layouts, it must be prioritized close allocation between zero-emissions PGSs and their auxiliary systems.
- Pre-arrange and install transport equipment in the power room: to future-proof power rooms and allow them to easily transition across different scenario, current PGSs must be replaced with new sustainable ones. To do that the systems have to be moved into the PR and it was proven to be way easier if moving equipment are already pre-arranged and installed into the power room.
- Pre-arrange Access Openings and route to them: to carry in and out various systems access openings connecting the yacht to the outside are needed. When the access openings are already present or pre-arranged (soft patch), the retrofit operations are way easier and cheaper. It is then suggested when future-proofing power rooms to have easy opening doors or whether it is not possible to arrange pipes, cables and beams in a way to create a soft patch easy to be opened and then re-closed.
- Prioritize easy-retrofit layout configurations: the results shown that certain layout, specifically those with no systems on one side of the PR and those with wider corridor, prove to be particularly efficient in lowering the retrofit costs. To future-proof power rooms it is then suggested to adopt such layout configuration. Moreover, configurations allowing to retrofit the yacht without going to dry-dock are to be preferred as the no payment for dry-dock fees lead to overall lower retrofit costs.
- Identify yacht future scenarios: depending on when the yacht will be designed and built, it is possible to identify the starting scenario. Then, considering when the major classification inspections are expected and the anticipated advancements in PGS technologies, it is possible to predict to what future scenarios the yacht will be converted to. It is not suggested to retrofit the yacht across all the future-proof roadmap but rather to identify only one or two scenarios to be reached and design for them.

As was already mentioned, yacht configuration are client-driven and power room layouts may also differ from the ones examined in this thesis. However, the design method proposed in this thesis, or just the design guidelines presented above, used in the concept design phase, ensures that future-proof and easiness of retrofit considerations are taken into account allowing to design a yacht not only for its immediate needs but also with strategic considerations regarding future technological advancements.

9.2. DESIGN METHOD LIMITATIONS

The design method proposed in this thesis, while robust and comprehensive, does have some limitations that need to be acknowledged. These limitations have been categorized as follows:

Focus on superyachts

The primary focus of this research was on superyachts. While the design method is believed to have broader applicability, as mentioned in chapter 8, the specifics of other types of vessels were not explicitly tested. This limits the generalization of the findings to other maritime vessels, such as commercial or naval ships, which may have distinct design constraints and operational requirements.

Exclusion of certain technologies

As pointed out in section 6.1, certain technologies, like a detailed integration of batteries, were deliberately excluded from the scope of this thesis. Batteries were considered separately due to their unique safety, spatial, and operational considerations. Similarly, secondary DC grids, which could offer significant efficiency improvements, were acknowledged but not deeply explored. These exclusions entail that the design method does not fully encompass all potential future-proofing technologies.

Connection Costs irrelevant to Retrofit Costs

The analysis on retrofit costs focused on working costs of retrofitting a power room, specifically on removing and reinstalling certain systems, creating access openings and converting diesel generators to dual fuel. However, despite it was acknowledged that connections change across different scenarios, connection costs have been considered irrelevant for the retrofit costs but in reality there is a relation between these two voices which is the costs incurred when installing new pipes and cables required by new systems. This is mainly related to the concept design phase in which the method operates, indeed at this stage the accurate amount of pipes and cables in the power room is still hard to predict.

Client-Driven Design Method

This point is particularly relevant for Feadship's design process which, as noted, is strongly influenced by client preferences and requirements. This client-driven approach makes it unfeasible to standardize certain layout decisions purely for retrofit ease without considering client's specific needs and desires. Some insights for good practices have been drawn over this thesis, however the variability of Feadship's projects can limit applicability of the proposed design principles across different projects but using the method proposed in the thesis will ensure that future-proofing considerations are taken into account.

9.3. FURTHER RESEARCH

To address the limitations described earlier, future research recommendations are presented in this section.

9.3.1. Recommendations for Further Research on Batteries

While batteries are excluded from the current design method, their significance in future-proof yacht design cannot be overstated. Therefore, further research on the integration of batteries into power systems is strongly recommended. The following recommendations highlight key areas for exploration and development in battery technology and implementation:

- **Battery Technologies:** currently the batteries applied in the maritime field are mostly of the Li-ion type, however big advancements are expected in the future, which may lead to solid and maybe nonflammable batteries as well as to higher energy density. This will bring important changes into battery
- **Battery Placement:** Investigate the most efficient and safe locations for battery installation onboard yachts. Based on the new batteries technologies that will be available in the future, batteries may be allocated directly into the power room or decentralized on the yacht, without requiring a dedicated battery room.
- **Power Plant Integration:** Research methods for the effective integration of batteries into power plants, considering diverse energy sources such as fuel cells, diesel generators, and renewable energy sources. Explore possibilities for pre-charging batteries before long-haul transits to improve overall power system functionality.

Addressing these research recommendations can contribute to the advancement of efficient strategies for the incorporation of batteries into future-proof yacht designs.

9.3.2. Recommendations for Further Research on Switchboards and Electric Distribution Onboard

In this thesis, the focus was primarily on the replacement of switchboards dealing with power generation systems, specifically in the context of integrating fuel cells into existing Diesel-Batteries configurations. However, as the maritime industry progresses towards cleaner energy solutions, additional considerations arise for optimizing electric distribution onboard vessels.

One potential direction for further research is exploring the feasibility of transitioning to a predominantly DC-based electric distribution network. This could involve investigating the development of DC-compatible systems for hotel loads, such as HVAC, lighting, and appliances. Additionally, examining the potential for hybrid

AC-DC setups, where primary DC networks are supplemented by smaller AC-DC switchboards for specific components, warrants investigation.

However, the feasibility of such transitions is contingent upon technological advancements and market developments. It remains uncertain whether suppliers will produce DC-compatible systems for smaller domestic components, making further research and collaboration between industry stakeholders essential in exploring alternative electric distribution solutions for future-proofing yacht designs.

9.3.3. Recommendations for Further Economic Implementation of the Method

As mentioned, the method presented in this thesis focused only on certain costs incurred during a retrofit, a potential direction of further implementation of the method is to use it within broader calculations to illustrate the potential of future-proof power rooms. Alongside the method presented it is suggested to estimate costs for the following:

- Shipyard rates for berthing or putting vessel in dry-dock
- Connection costs impact on retrofit costs
- Capital expenses required to buy new power generation and auxiliary systems
- Operational expenses in the different scenarios for a certain yacht's lifetime

By implementing these voices alongside the method provided it would be possible to estimate the overall lifecycle costs of a future-proof yacht that will change power generation systems across its lifecycle until it reaches complete zero-emission operation. This can be particularly helpful to provide clients with estimations on the benefit of having future-proof yachts.

9.4. PERSONAL REFLECTION

This section reports the author's personal reflection on this thesis and his critical thoughts on how it can help the yachting and maritime industry to reach zero-emissions goals. Given that this section reflects the personal opinion of the author, it will be written in first-person.

Sustainability, zero-emissions, alternative fuels: these are just some of the many "green" words that have driven my studies in past years and that certainly will accompany me throughout my whole career as a marine engineer and my life as a world's citizen.

It is undoubted that the humankind needs to reduce its environmental footprint but at the same time there is a lack of green technologies ready to be used and economically suitable to replace their fossil counterparts. This holds true for all human activities from farming to building, from energy production to transportation, including maritime transportation and yachting.

For what concerns the maritime sector, as I hope that this thesis highlighted, major issues include costs and availabilities of zero-emissions fuels, as well as high price and low technology readiness level of the systems to use such fuels. However, sooner or later, the sector will reach a point in which alternative fuels will be convenient compared to fossil ones and available technologies will be as efficient and as cheap as diesel ones. These developments pertain mainly to fuels producers and distributors and to engine and fuel cells manufacturers; while, on their side, ship and yacht builders can push for these developments and most importantly they have to be ready to implement such technologies onboard.

In my opinion, the implementation of such technologies onboard should not be limited to the vessels to be built in the future, but there is the need to future-proof ships and yachts built today to host these technologies when they will be ready. Recognizing the harmful impact of fossil fuels, it is inconceivable to continue to design vessels whose lifecycle will last for more than 25 years without considering they will need to be powered by alternative fuels and new technologies at some point.

Alongside Feadship, almost all yacht builders nowadays recognize the need of sustainable yachts and have a carbon-neutrality roadmap that will eventually bring them to build zero-emission yachts in the future.

These roadmaps' departure point is a Diesel-Batteries yacht which, with one or two steps, reaches a complete zero-emission solution powered with fuel cells, exactly like the roadmap on four scenarios considered in this thesis.

However, there is a gap in the design methods currently employed, as no considerations are made on how to switch from one scenario to another without incurring in complex operations and major costs. Basically, a yacht is designed just for its need when launched and without considering the need to be converted to alternative fuels in the future.

During the development of this thesis, when speaking with project managers, engineers, designers and yard personnel the average opinion on the need to future-proof a yacht was "*It is complex, but there is always a way to do perform a retrofit and when it will be needed we will figure it out*". This testifies the general opinion on future-proofing that the yachting industry has: there is no need to future-proof because when the time will come a solution on how to install new systems onboard will be found.

My hope is that this thesis results and conclusions will make it clear that with minor adjustments in power room layout disposition, pre-arrangement and pre-engineering of moving equipment and access opening, retrofit costs get a lot lower, integrating green technologies onboard becomes way easier and the yacht becomes effectively future-proof.

In my personal opinion, the method developed and presented in this thesis can be used in the early stage design by every yacht builder without major complications, in order to effectively assess the future-proofing capabilities of certain decisions. I am aware that the usage of theoretical methods in an early stage design by yacht design offices is often unfeasible due to the limited amount of time constrains in this phase but my hope is that the results I have obtained in this thesis, specifically the design guidelines, will be used to take future-proof consideration in yacht designs.

Moreover, I think that this thesis has demonstrated that future-proofing a yacht today including just minor adjustments and considerations can bring great advantages tomorrow. To conclude, I hope that this thesis has shed a light on the fact that future-proofing yachts is not complex but it is needed and that future-proofing considerations will be taken into account in the yachts to be designed from today onwards.

This is just the personal opinion of a young marine engineer, today it is still hard to say if I am correct and as the great Italian writer Manzoni would say "*Ai posteri l'ardua sentenza*" (to posterity the arduous judgment).

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Appendices

A. ALTERNATIVE FUEL ENGINES

Engine Manufacturer	Engine Series	Speed	Fuels	Availability	Reference
WinGD	WinGD X-DF series	2 stroke	Diesel and LNG	In commerce	WinGD, 2023b
MAN ES	MAN B&W ME-GI	2 stroke	Diesel and LNG	In commerce	MAN ES, 2023b
Wärtsilä	Wärtsilä DF series	4 stroke	Diesel and LNG	In commerce	Wärtsilä, 2023a
MAN ES	MAN B&W DF series	4 stroke	Diesel and LNG	In commerce	MAN ES, 2023a
Rolls-Royce	MTU Series 4000	4 stroke	Diesel and LNG	In commerce	Rolls-Royce, 2023
MAN ES	MAN B&W ME-LGIM	2 stroke	Diesel and Methanol	In commerce	MAN ES, 2023c
WinGD	WinGD X-DF-M series	2 stroke	Diesel and Methanol	Expected in 2025	WinGD, 2023b
Wärtsilä	Wärtsilä 32 series	4 stroke	Diesel and Methanol	In commerce	Wärtsilä, 2023d
MAN ES	MAN Methanol Ready series	4 stroke	Diesel and Methanol	Future Retrofit	MAN ES, 2023e
Caterpillar	CAT 3500 E-Series	4 stroke	Diesel and Methanol	Future Retrofit	Pon Cat, 2022
Rolls-Royce	MTU Series 4000	4 stroke	Diesel and Methanol	Expected in 2026	Rolls-Royce, 2022
MAN ES	MAN B&W G60	2 stroke	Diesel and Ammonia	Expected in 2024	MAN ES, 2023f
WinGD	WinGD X-DF-A series	2 stroke	Diesel and Ammonia	Expected in 2025	WinGD, 2023b
MAN T&B	MAN D2862	4 stroke	Diesel and Hydrogen	In commerce	MAN T&B, 2023
Volvo Penta	Volvo Penta D13	4 stroke	Diesel and Hydrogen	In commerce	Volvo Penta, 2023
Rolls-Royce	MTU Series 500 and 4000	4 stroke	Diesel and Hydrogen	Future Retrofit	Rolls-Royce, 2021

Table A.1: Dual Fuel Engines

B. VENTILATION CALCULATIONS AND REQUIREMENTS

B.1. VENTILATION SYSTEM WITH GENERATORS

First of all the airflow for combustion has to be determined, and disregarding the boilers and not considering main propulsion engine (as they are not present in Diesel-Batteries yachts) it is only given by the airflow for the diesel generators as:

$$q_{dg}[m^3/s] = \frac{P_{dg} \cdot m_{ad}}{\rho} \quad (B.1)$$

where P_{dg} is the service standard power of the diesel generator engine(s) at maximum power output, in kilowatts while m_{ad} is the air requirement for diesel engine combustion, in kilograms per kilowatt second and ρ is the air density usually taken at +35 deg C, 70% RH and 101.3kPa meaning $\rho = 1.13kg/m^3$

Then the airflow for evacuation of heat emission has to be determined as:

$$q_h[m^3/s] = \frac{\phi_{dg} \cdot \phi_p \cdot \phi_{el} \cdot \phi_{ep} \cdot \phi_t \cdot \phi_o}{\rho \cdot c_p \cdot \Delta T} - 0.4 \left(\sum_{i=1}^N q_{dg}^i \right) \quad (B.2)$$

Where ϕ_{dg} stands for the heat emissions of diesel generators, ϕ_p for steam and condensate pipes, ϕ_{el} for electric equipment, ϕ_{ep} for exhaust pipes, ϕ_t for hot tanks and ϕ_o for other components. c_p is the specific heat capacity of the air, considered as $c_p = 1.01kJ/(kg \cdot K)$, ΔT is the increase of the air temperature in the engine room that for design conditions is taken as $\Delta T = 12.5K$. In the end, $\sum_{i=1}^N q_{dg}^i$ represents the combustion airflow for all the generators in the PR.

The heat emission from diesel generators (ϕ_{dg}) can be calculated as below

$$\phi_{dg}[kW] = P_{dg} \cdot \frac{\Delta h_d}{100} \quad (B.3)$$

where P_{dg} is the generator power while Δh_d is the heat loss from the generators that usually is given by the manufacturer but for the purpose of this thesis can be retrieved from Table 5.3. In the table it is also possible to find the exhaust volume flow ($q_{exhaust}$) which is relevant to determine the amount of exhaust gases that has to be carried out of the room.

While the heat emissions from steam and condensate pipes (ϕ_p) as well as the ones from hot tanks (ϕ_{dg}) can be discarded in a preliminary design stage, the heat emission from electrical components (ϕ_{el}) are calculated as the sum of the simultaneous heat emission according to components installed, their power and their load factors. In the end the heat emissions from exhaust pipes (ϕ_p) can be calculated with the following formula:

$$\phi_{ep}[kW] = h_c \cdot \Delta T \cdot A \cdot n = [4.7 + 0.0035 \cdot \Delta T] \cdot \frac{v^{0.61}}{D^{0.39}} \cdot \Delta T \cdot A \cdot n \quad (B.4)$$

where

- v is the air velocity,
- A is the area of each exhaust pipes,
- D is the pipe diameter,
- n the number of pipes
- ΔT is the difference between the temperature on the pipe surface and the maximum air temperature

For the purpose of this thesis that aims to give initial rough estimation of the ventilation requirements in the different scenarios, besides the one for generators, the other heat emission values will be taken from similar Feadship yachts where these values have already been accurately calculated in the design phase.

In the end, based on the previous formulas, it is possible to determine the total airflow in (Q_{in}) and out (Q_{out}) of the power room and the exhaust flow ($Q_{exhaust}$) that after passing through the EGATS will be carried out of the room:

$$\begin{cases} Q_{in} = \max(q_c + q_h; 1.5 \cdot q_c) \\ Q_{out} = q_h \\ Q_{exhaust} = \sum_{i=1}^N q_{exhaust}^i \end{cases} \quad (\text{B.5})$$

B.2. VENTILATION SYSTEM WITH FUEL CELLS

While the ventilation requirements for a power room with ICEs only are extensively covered by rules and regulations, the ventilation requirements for a PR with fuel cells in it is mostly based on the working air that the fuel cells need to generate electric current, on the exhaust flow of oxygen and water and on a fuel leakage scenario that has to be detected.

Depending on the FC type, these value can differ, however the values of “Air in” (q_{in}^{FC}) and “Air out” (q_{out}^{FC}) presented in Table 5.4 already accounts for the working air, the exhaust flow and a fuel leakage scenario, based on Feadship supplier.

Then for a Power room that hosts Fuel Cells the amount of air in and out of the room and of exhaust can be determined as

$$\begin{cases} Q_{in} = (\max(q_c + q_h; 1.5 \cdot q_c)) + q_{in}^{FC} \\ Q_{out} = q_h + q_{out}^{FC} \\ Q_{exhaust} = \sum_{i=1}^N q_{exhaust}^i \end{cases} \quad (\text{B.6})$$

B.3. VENTILATION RESULTS FOR THE DIFFERENT SCENARIOS

Applying the previous formulas and the generators and fuel cells data presented respectively in Table 5.3 and Table 5.4, it is then possible to calculate the ventilation requirements of the PR in the various scenarios considered. It is worth noting that the calculation has been done for an average Feadship which power demand was presented in Table 5.1 and its PR characteristics were listed in Table 6.1.

Moreover, it is important to mention that given the early stage of these calculations, the heat emissions of pipes, tanks, electric equipment and previous components have been estimated looking at previous Feadship projects. The results gained in terms of ventilation requirements in the different scenarios, considering various FC types are presented in Table B.1.

	Scenario 0	Scenario 1 and 2			Scenario 3		
	Generators	Generators + LT PEM	Generators + HT PEM	Generators +SOFC	LT PEM	HT PEM	SOFC
Q_{in}	65000	62000	61000	65000	55000	50000	70000
Q_{out}	40000	42000	41000	52000	55000	50000	108000
$Q_{exhaust}$	55000	45000	45000	45000	N.A.	N.A.	N.A.

Table B.1: Ventilation requirements in the different scenarios

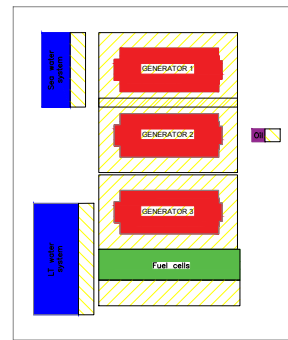
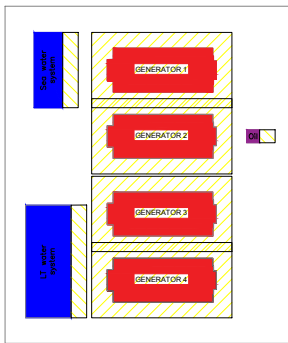
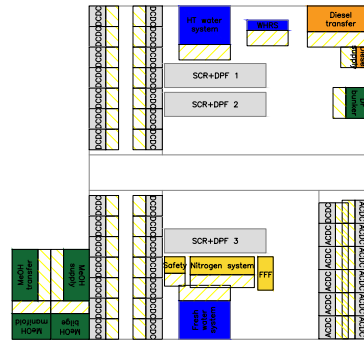
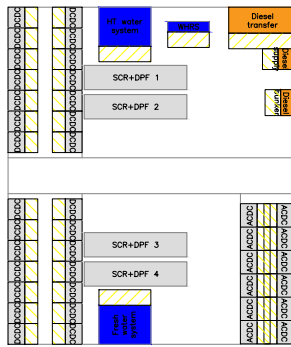
SOFCs require the highest air capacity. This is due to the high internal temperature of SOFCs which necessitates air cooling. The air cooling primarily dictates the required air capacity for these fuel cells.

Although more studies are needed to further detail the required air capacities of all components, a few conclusions can be drawn from this work:

- When replacing engines with LT- or HT PEM fuel cells, the amount of air exiting from ducts on the outlet side will remain the same. The amount of air on the inlet side will be even less.
- When replacing engines with SOFCs, the total amount of air on the outlet side will remain the same. However, it is necessary to route the exhaust piping from the engines to the canopy (and not underwater), which can later be used for the outlet air of the SOFCs. On the inlet side, an increase in air may be required, but this might not be necessary when re-using ventilation air as process air.

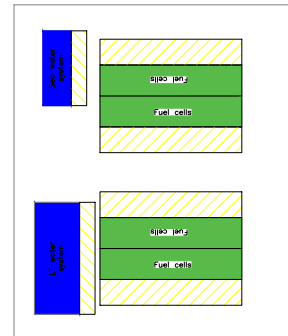
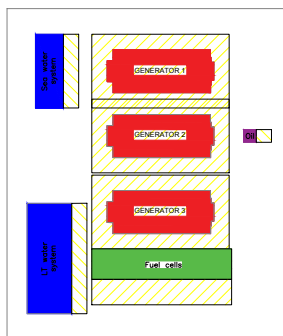
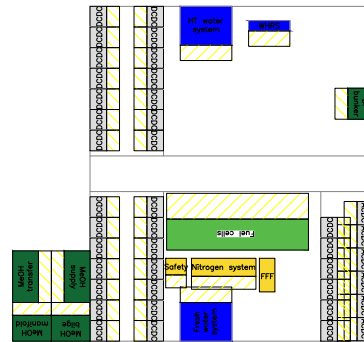
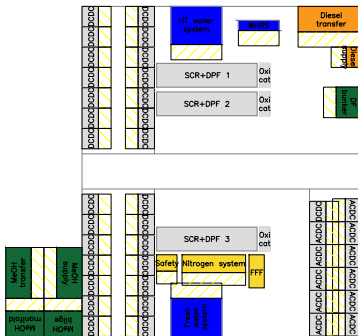
Overall, it can be concluded that the difference in various scenarios is not particularly high, thus the ventilation of a future-proof PR will not represent a major challenge. It is however suggested to perform more detailed calculation using more accurate suppliers' data.

C. POWER ROOM LAYOUTS IN ALL SCENARIOS



(a) Layout 0.1

(b) Layout 1.1



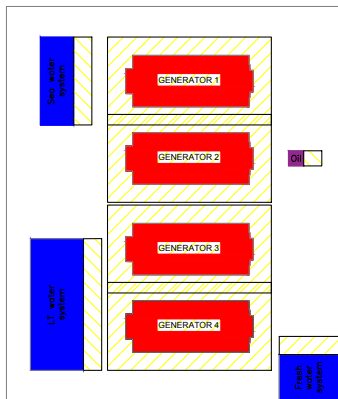
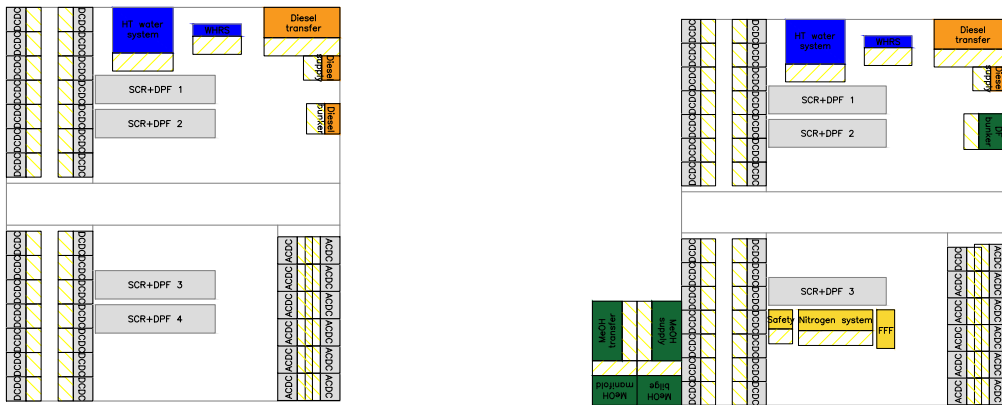
(c) Layout 2.1

(d) Layout 3.1

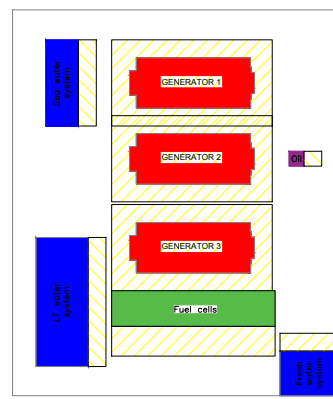
Figure C.1: Layout X.1 - Based on the current PR



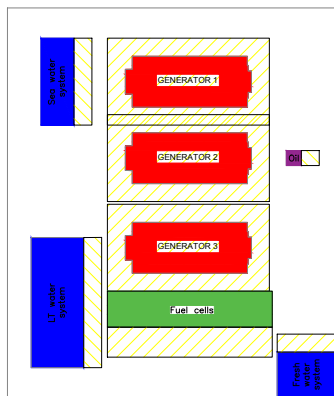
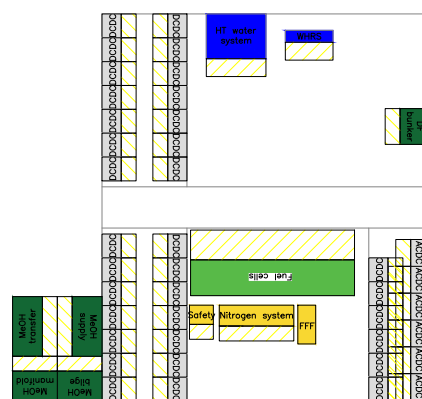
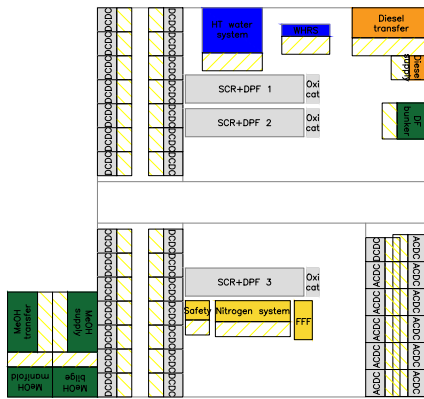
Figure C.2: Layout X.2 - No switchboard on the aft of the PR



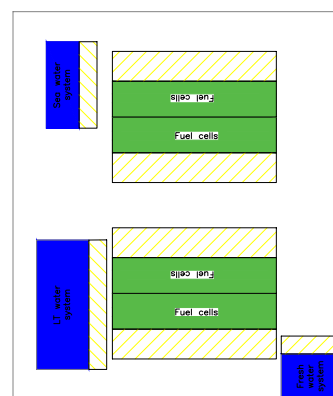
(a) Layout 0.3



(b) Layout 1.3



(c) Layout 2.3

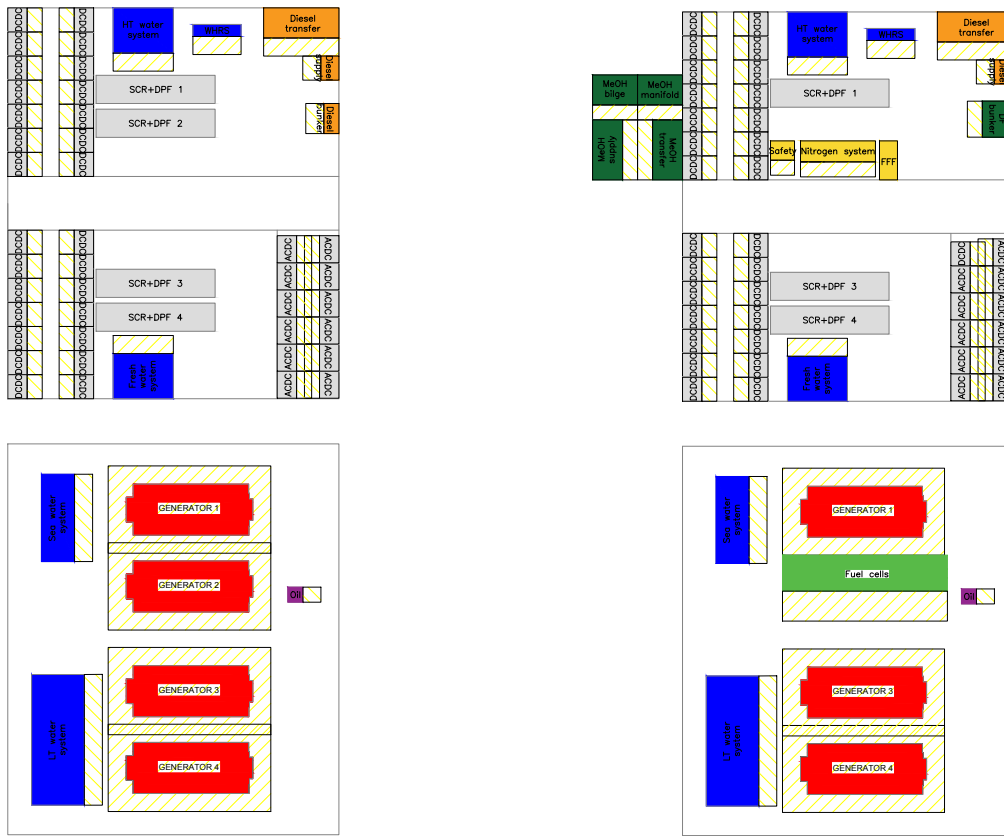


(d) Layout 3.3

Figure C.3: Layout X.3 - No systems on one side of the PR

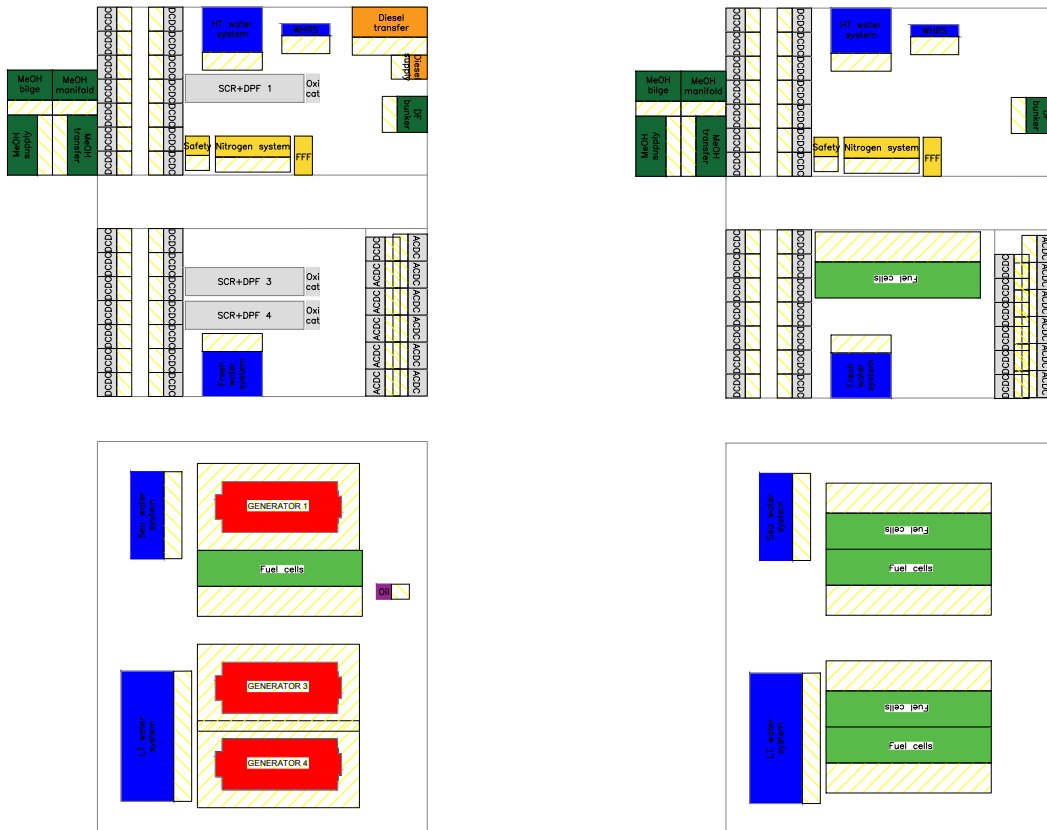


Figure C.4: Layout X.3.B - No systems on one side of the PR - FC on the upper deck



(a) Layout 0.4

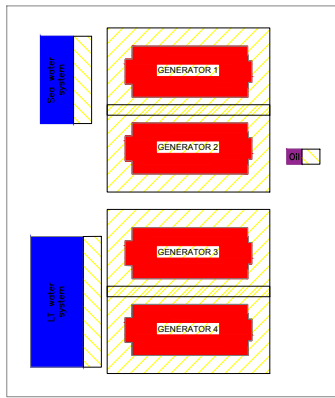
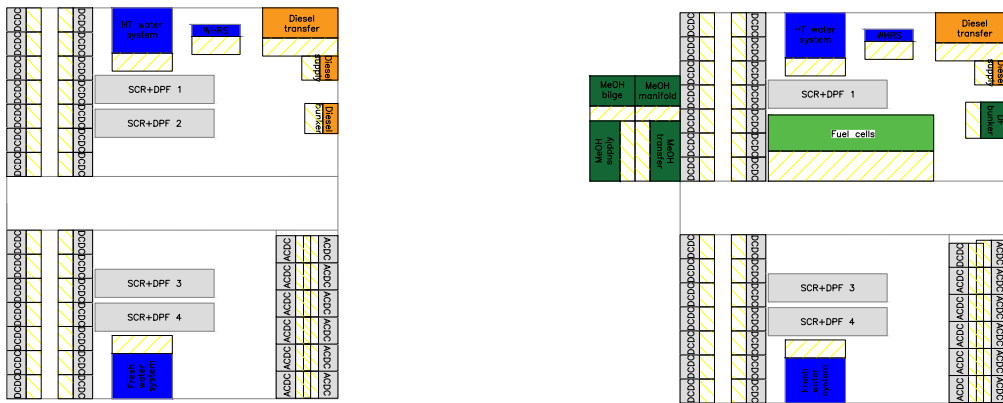
(b) Layout 1.4



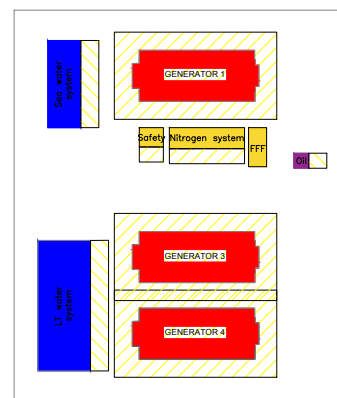
(c) Layout 2.4

(d) Layout 3.4

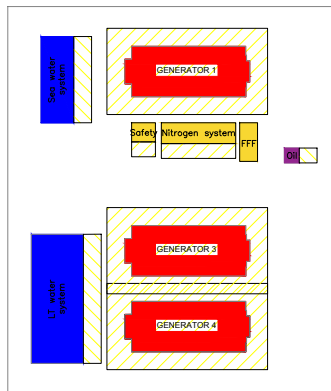
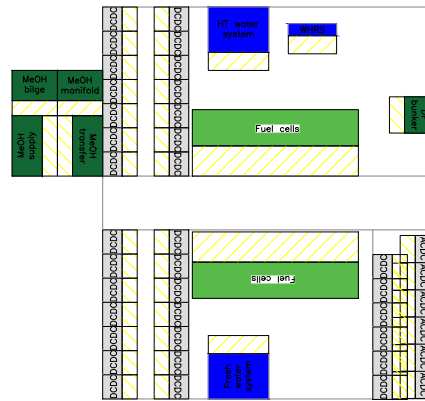
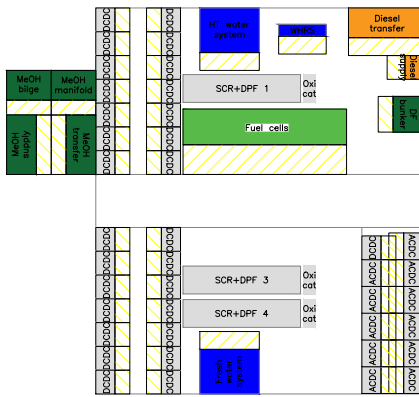
Figure C.5: Layout X.4 - Central wider corridor



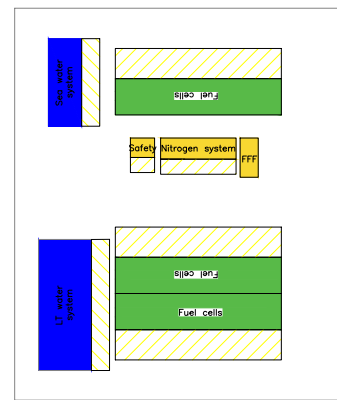
(a) Layout 0.4



(b) Layout 1.4.B



(c) Layout 2.4.B



(d) Layout 3.4.B

Figure C.6: Layout X.4.B - Central wider corridor - FC on the upper deck

Appendix C. Power Room layouts in all scenarios

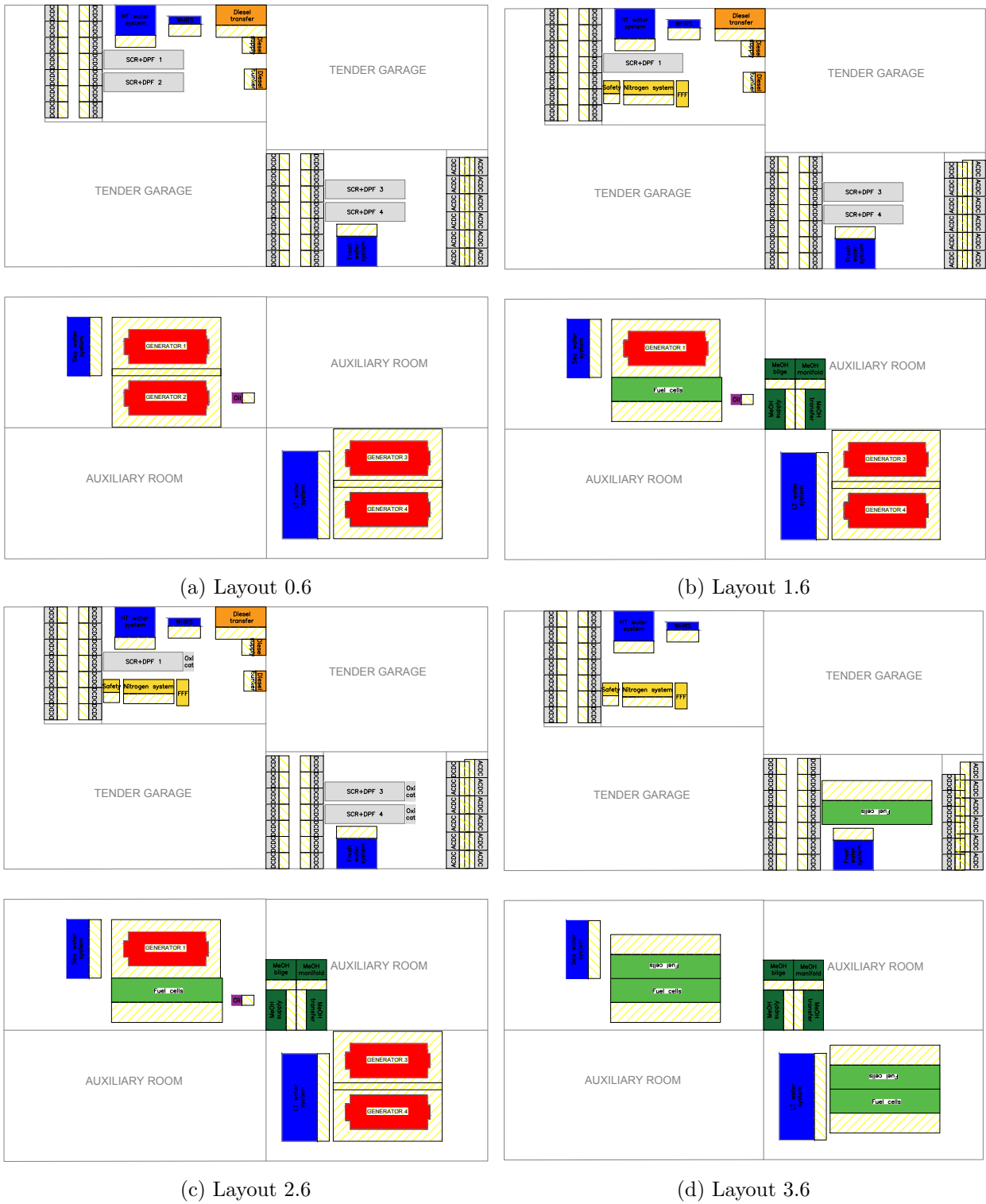
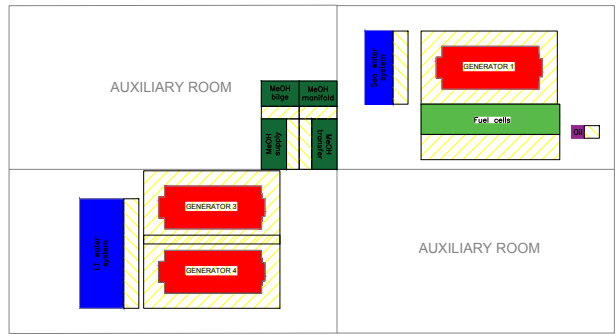
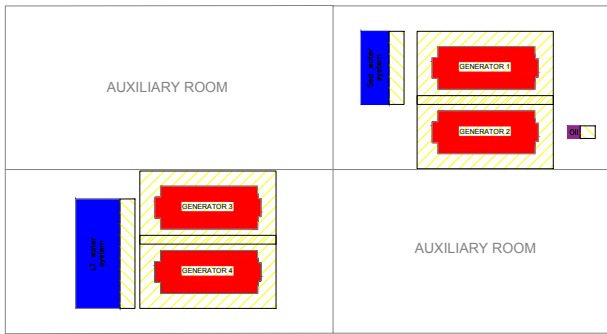
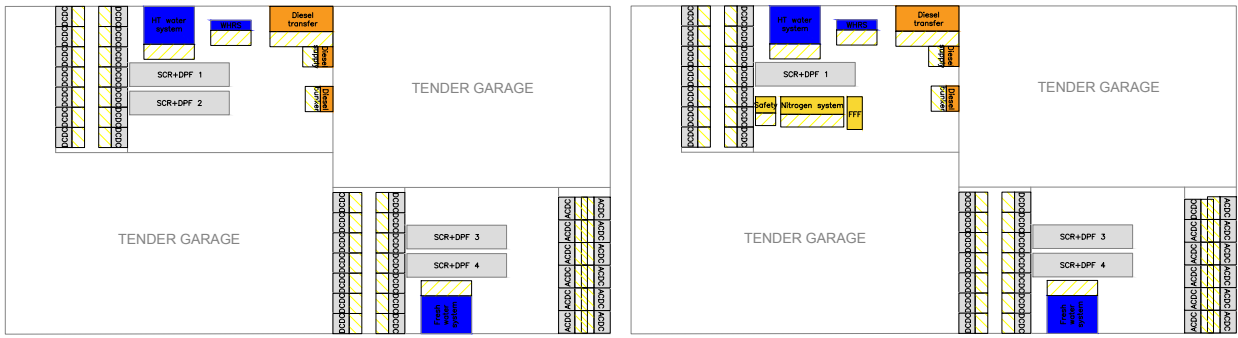
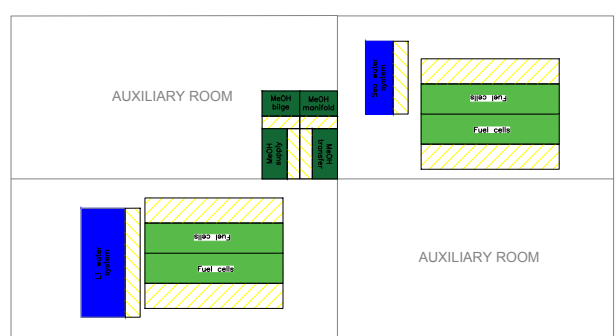
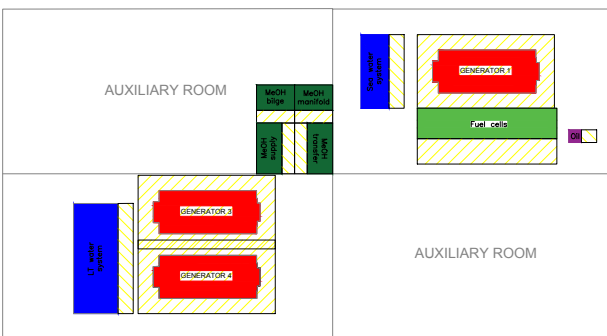
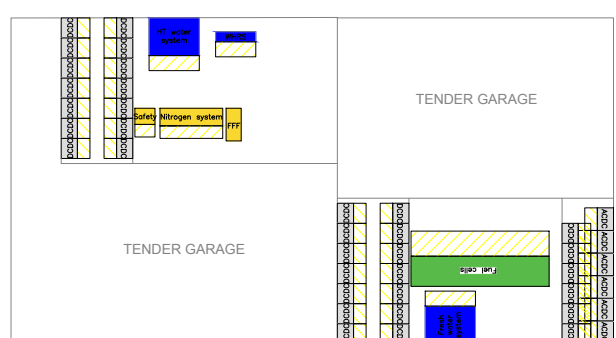
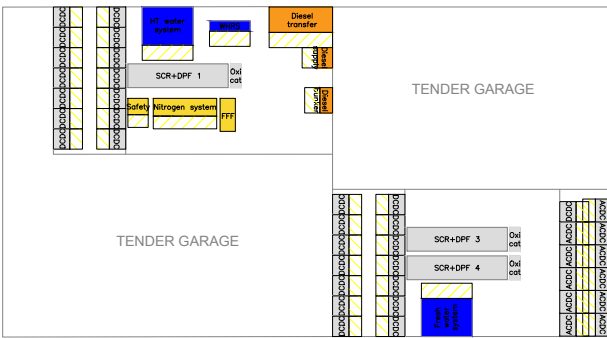


Figure C.7: Layout X.6 - TG close to the PR



(a) Layout 0.7

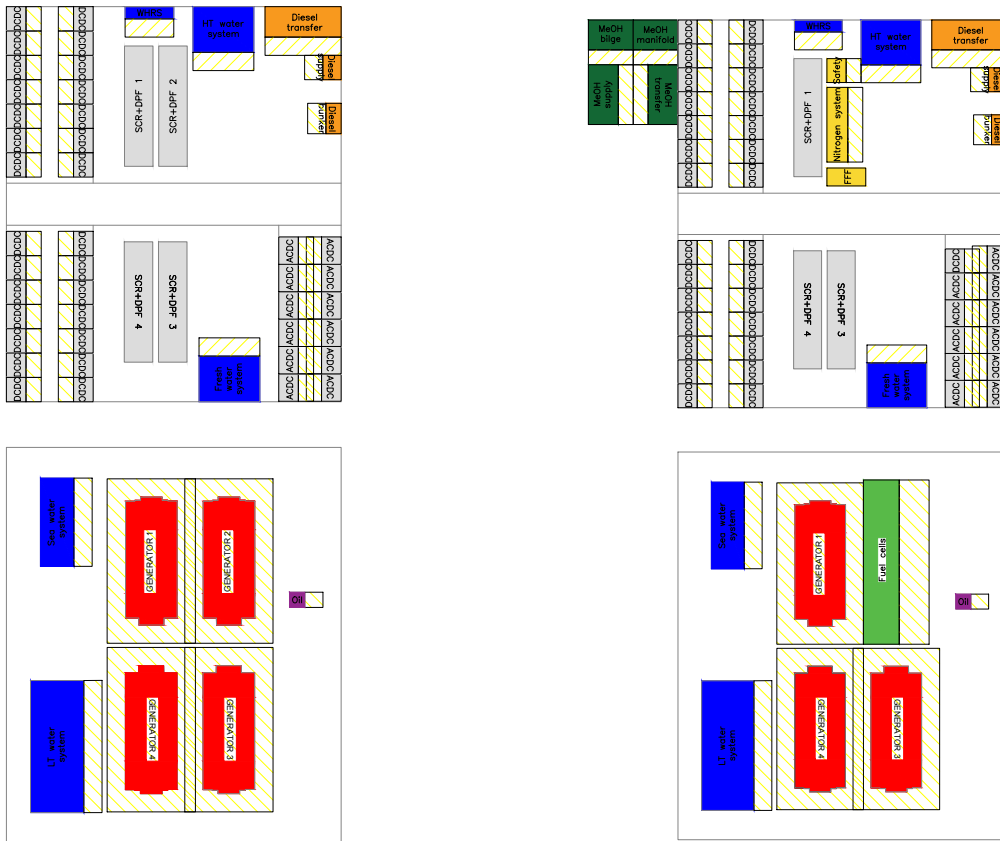
(b) Layout 1.7



(c) Layout 2.7

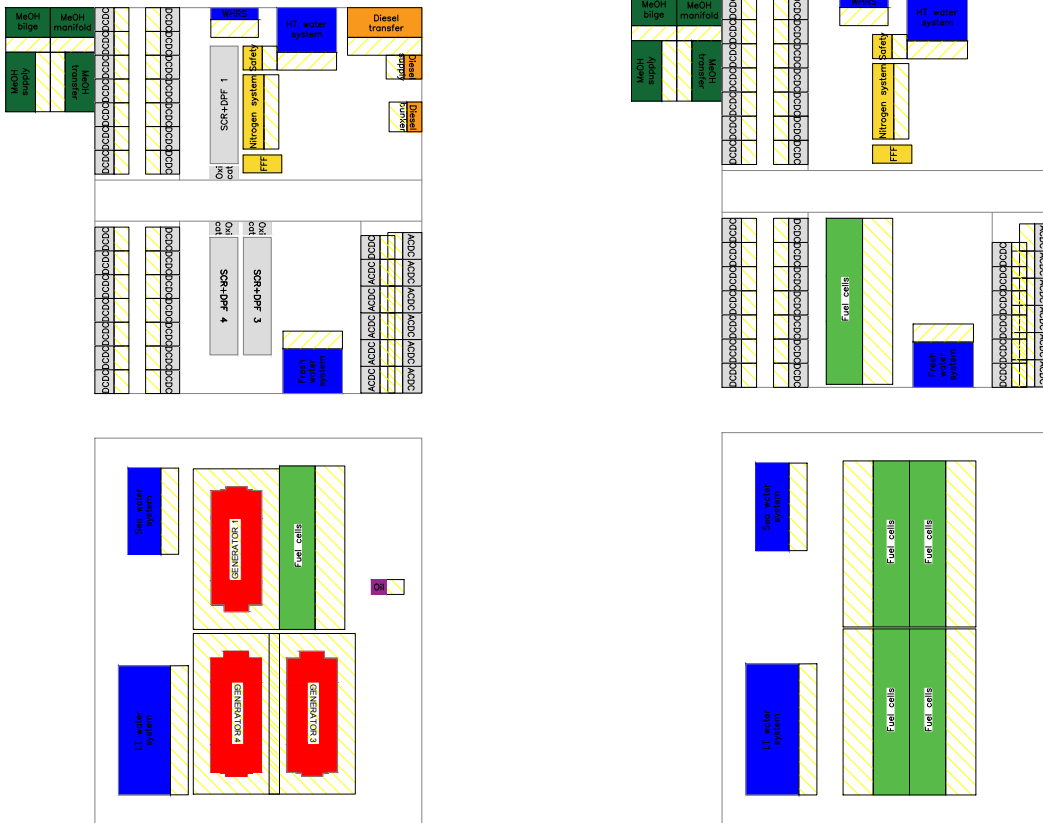
(d) Layout 3.7

Figure C.8: Layout X.7 - TG above the PR



(a) Layout 0.8

(b) Layout 1.8



(c) Layout 2.8

(d) Layout 3.8

Figure C.9: Layout X.8 - PGs rotated in transversal direction

The layouts for a single layer power room are shown below both the overall layout of the tank deck, in Figure C.10, and a layout of the power room arrangement in Figure C.11.

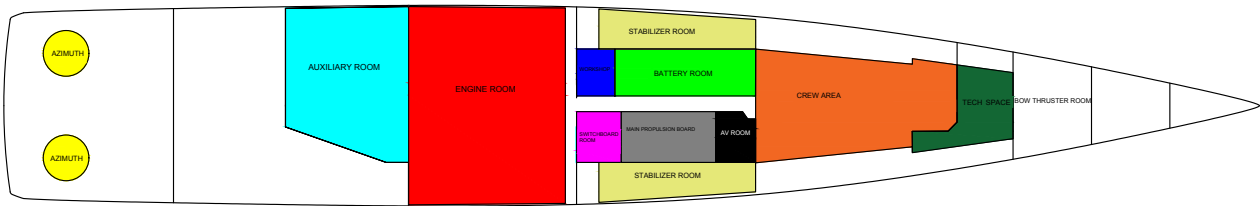


Figure C.10: Single layer tank deck PR layout

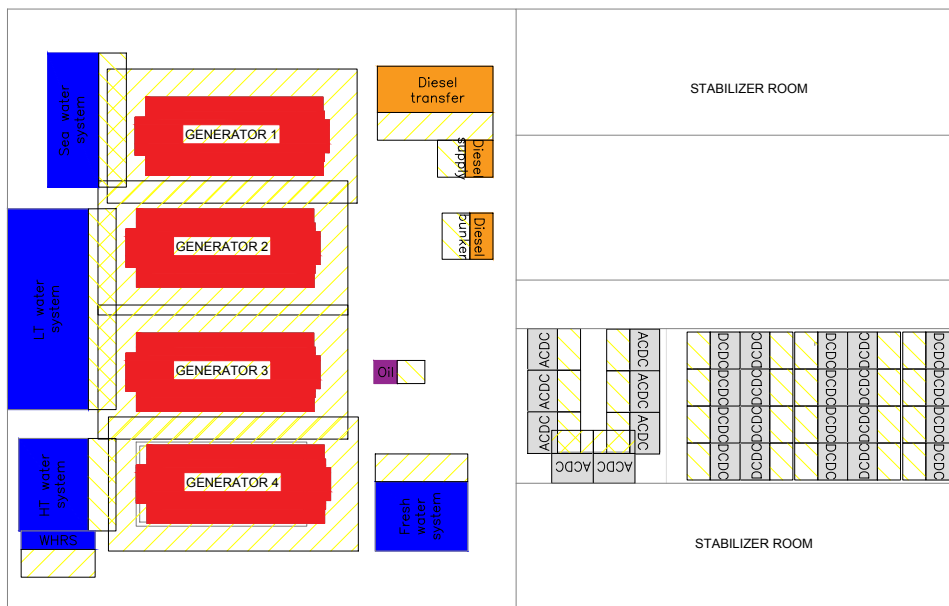


Figure C.11: Current single layer PR layout

D. RESULTS FOR ALL POSSIBLE COMBINATIONS

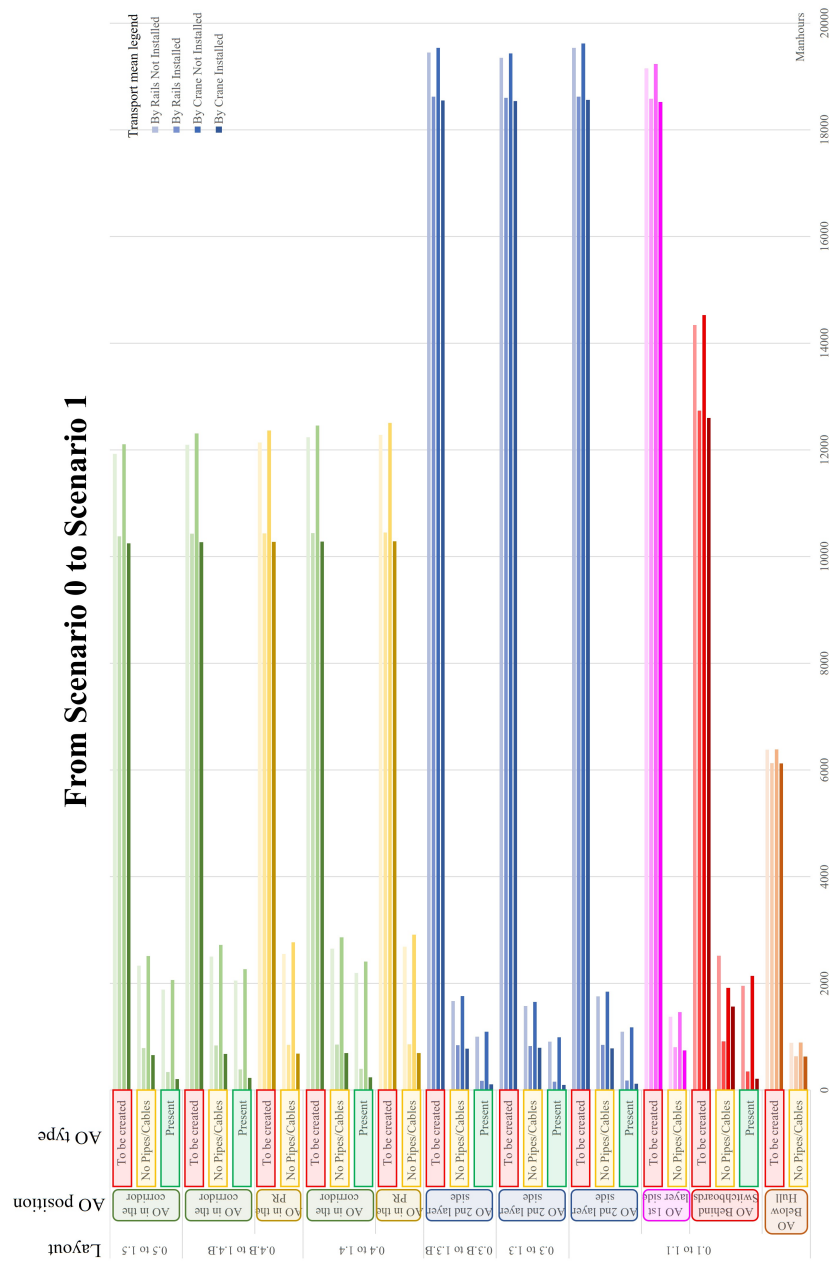


Figure D.1: Total Retrofit Costs from Scenario 0 to Scenario 1

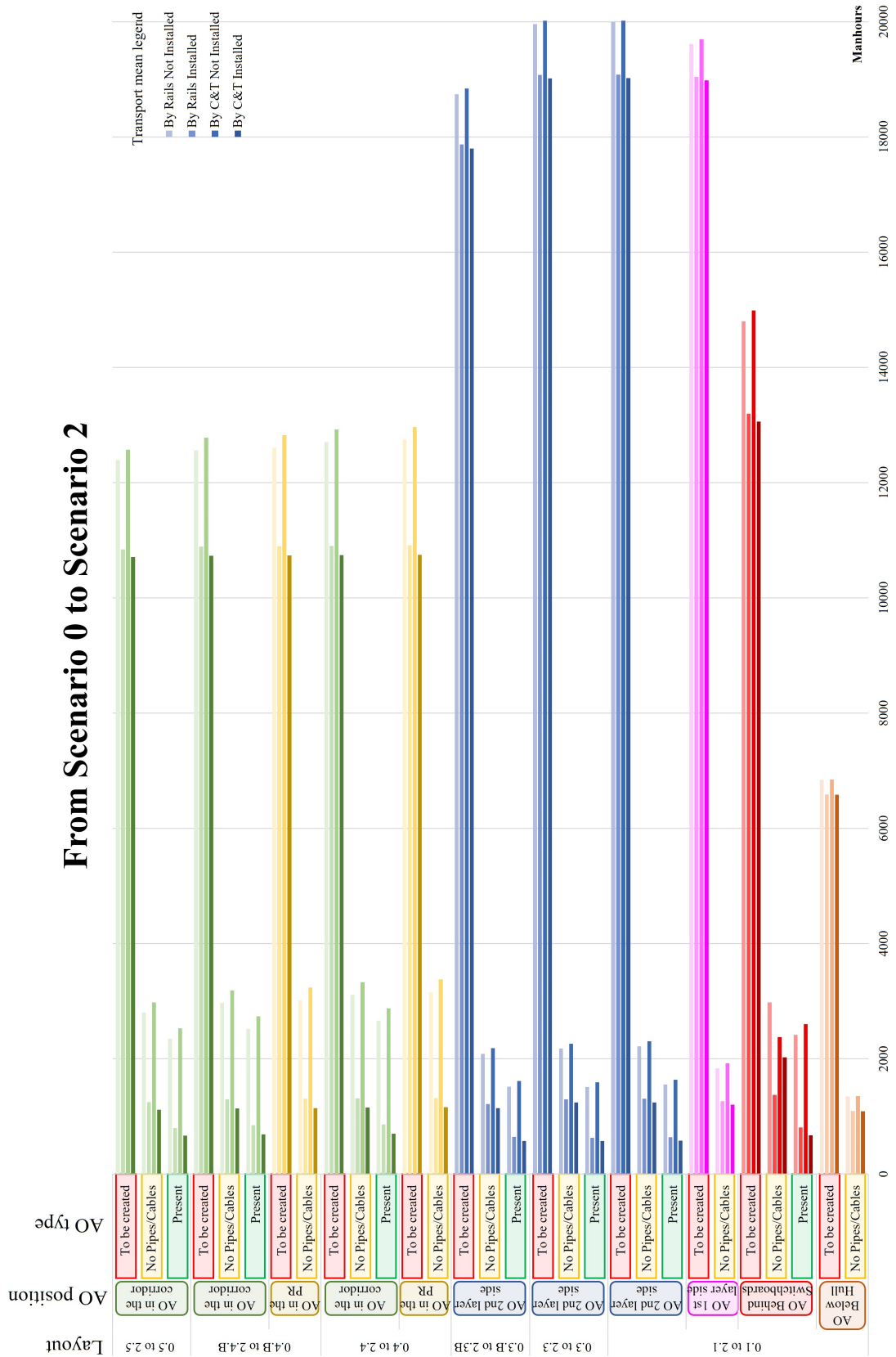


Figure D.2: Total Retrofit Costs from Scenario 0 to Scenario 2

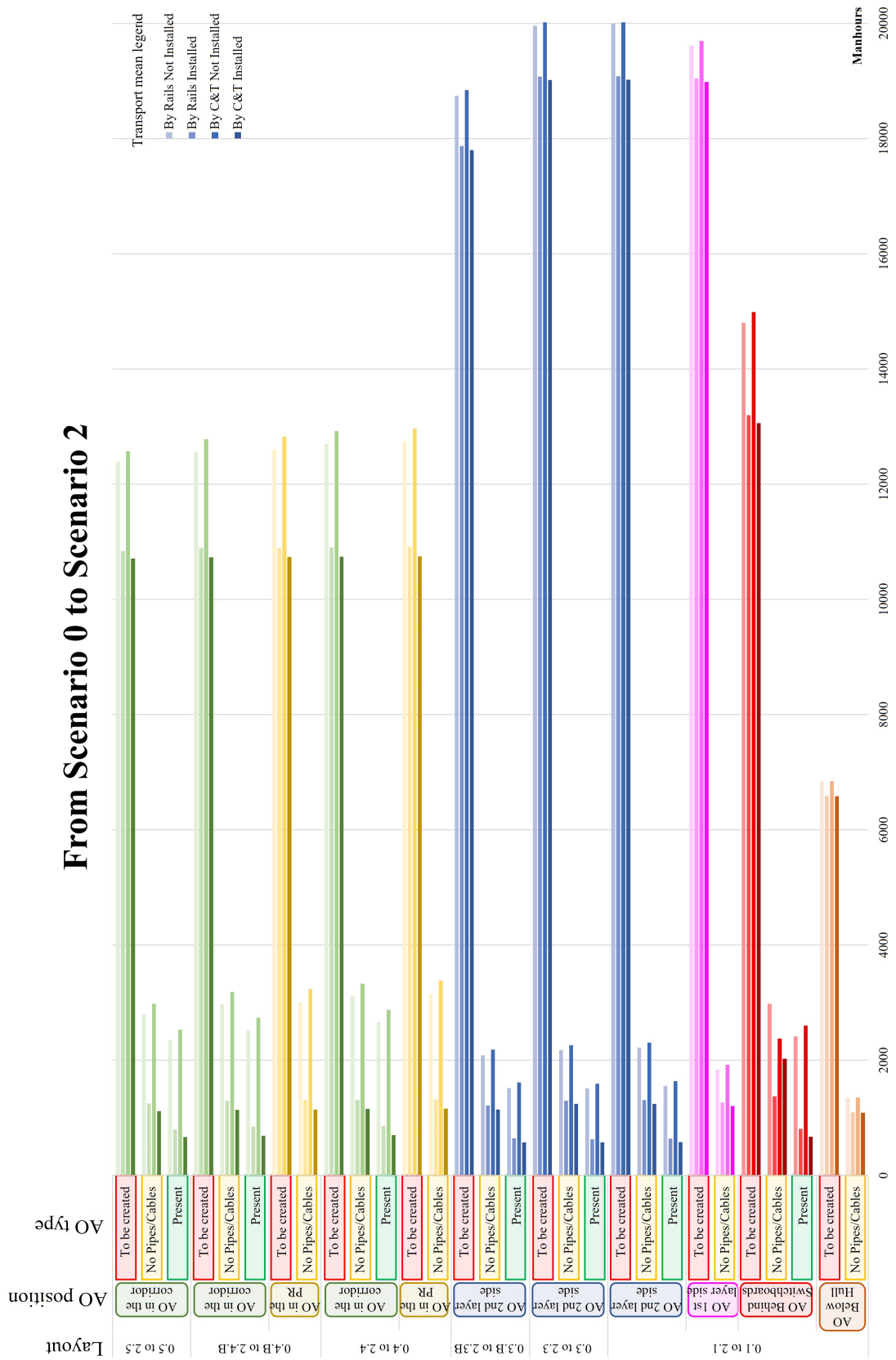


Figure D.3: Total Retrofit Costs from Scenario 0 to Scenario 3

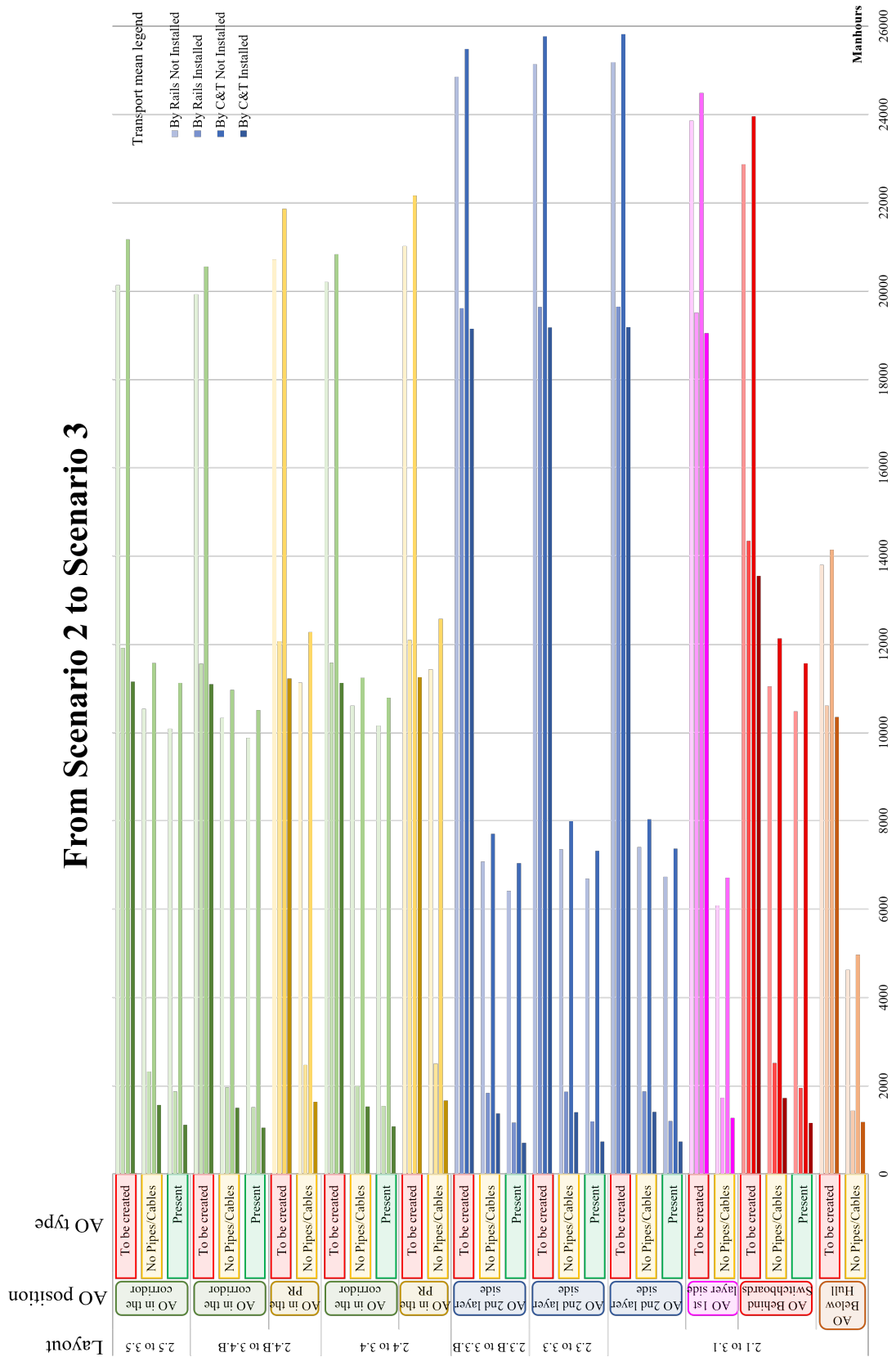


Figure D.5: Total Retrofit Costs from Scenario 2 to Scenario 3

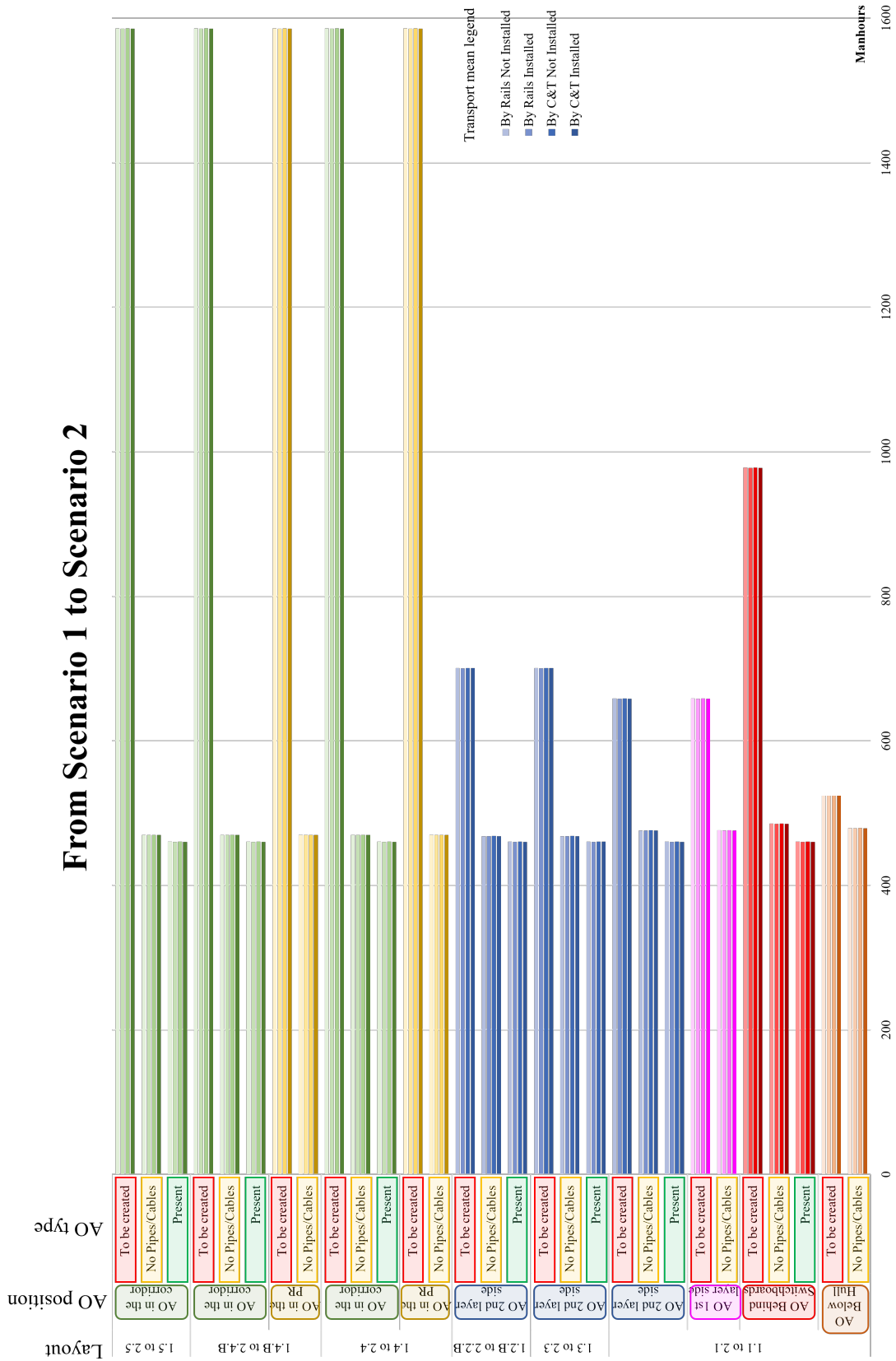


Figure D.6: Total Retrofit Costs from Scenario 1 to Scenario 2

TCC vs TRC – Vessel not in dry dock – AO No Pipes/Cables



Figure D.7: Total Retrofit Costs from Scenario 1 to Scenario 2

TCC vs TRC – Vessel not in dry dock – AO To be created



Figure D.8: Total Retrofit Costs from Scenario 1 to Scenario 2

E. FEADSHIP CONFIDENTIAL