

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**REQUIREMENTS ENGINEERING FOR THE INTEGRATION OF A MARINE  
HYBRID PROPULSION SYSTEM BASED ON UML/SYSML**



**M.Sc. THESIS**

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**Department of Shipbuilding and Ocean Engineering**

**Shipbuilding and Ocean Engineering Programme**

**OCTOBER 2023**



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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

**UML/SYSML'YE DAYALI BİR DENİZ HİBRİT TAHRİK SİSTEMİNİN  
ENTEGRASYONU İÇİN GEREKSİNİM MÜHENDİSLİĞİ**

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**Date of Defense : 09 October 2023**



## **FOREWORD**

Over the past years, my profound interest in the maritime industry and its ongoing evolution has been a driving force, shaping both my academic pursuits and my career aspirations, ultimately culminating in this thesis. I aspire for this work to serve as a concise compass, offering guidance to ship-owners and marine firms seeking innovative engineering solutions. Looking back on these years, I am extremely grateful to everyone who contributed their thoughts, time, and steadfast commitment.

I first want to express my deepest appreciation to my late father, whose encouragement led me to pursue a master's degree in this field. To my family, friends, and Eng. Oussama Najjar, your continuous support has been my anchor throughout this journey. To my esteemed professors at ITU, I am indebted to you for sharing your knowledge and insights, which have been instrumental in shaping this thesis. Likewise, my colleagues at Armona Shipping have been an invaluable resource, offering guidance and generously sharing their wealth of information without reservation.

From the depths of my heart, I extend my heartfelt thanks to each and every one of you. This endeavor would not have been possible without your collective wisdom and unwavering support.

October 2023

Joud TARABISHI  
(Procurement Coordinator)



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## **ABBREVIATIONS**

**CODLAD** : Combined Diesel Electric and Diesel

**SysML** : System Modelling Language

**UML** : Unified Modelling Language





## **SYMBOLS**

- P** : Power  
**K** : Ship Coefficient / Constant  
**V** : Velocity / Vessel Speed





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# **REQUIREMENTS ENGINEERING FOR THE INTEGRATION OF A MARINE HYBRID PROPULSION SYSTEM BASED ON UML/SYSML**

## **SUMMARY**

Putting together requirements, conditions, processes, solution proposals, and other aspects of a project in the form of charts and explanatory illustrations can form a bridge between engineers and stakeholders or clients with business ideas to execute. The project in consideration revolves around converting a present fuel-dependent standard engine-run vessel to a hybrid version relying on batteries and electric motors for different operation modes in concept.

The advantages of this concept discussed in the thesis are numerous and motivating, thus emphasizing how it has risen in popularity significantly during this century to become one of the trending and much-sought processes in the maritime industry. This thesis is hence a simple demonstration of the application of modelling languages to the engineering process. It aims to determine the methods and necessary requisitions for implementing hybrid retrofits into the propulsion systems of present vessels through renovations and upgrades. Modern modelling languages, namely SysML and UML, are used to present the specifications for this project based on predefined factors represented in diagrams and graphics, facilitating the creation of a user-friendly process.

After thoroughly studying the requirements, the various parameters and conditions involved in such a project are determined. This data is then applied to develop flowcharts and models, thus assisting in representing several engineering design concepts involved in integrating the hybrid propulsion system configuration selected after examining the risks, benefits, and constituents of performing this renovation.

Firstly, concepts and terms in the study are introduced and defined. The thesis later dives into the design and configuration steps that facilitate the representation of the researched requirements by the best-fit diagrams. Based on a selected example vessel, these diagrams are constructed and displayed to form developed models representing the initial state and the altered parameters from which the project can be understood and translated. Finally, the simplicity and pros of this representation, in addition to their notability in the management engineering field, are looked into and reviewed.



## UML/SYSML'YE DAYALI BIR DENIZ HIBRIT TAHRIK SISTEMININ ENTEGRASYONU IÇIN GEREKSINIM MÜHENDISLIĐI

### ÖZET

Gereksinimleri, koşulları, süreçleri, çözüm önerilerini ve bir projenin diğer yönlerini grafikler ve açıklayıcı çizimler şeklinde bir araya getirmek, mühendisler ve paydaşlar veya yürütülecek iş fikirleri olan müşteriler arasında bir köprü oluşturabilir. Bu çalışma son zamanlarda mühendislik yönetimi ve proje karar verme süreçlerine yeni bir yaklaşım olarak önem kazanmıştır. Bu nedenle her iki taraf da hem yatırımcıları hem de böyle bir dönüşüm planının uygulayıcılarını etkileyen faktörleri göz önünde bulundurarak ne ve nasıl yapılması gerektiği konusunda hemfikir olabilir.

Söz konusu proje, mevcut yakıtı bağımlı standart motorla çalışan bir gemiyi, farklı çalışma modları için pillere ve elektrik motorlarına dayanan hibrit bir versiyona dönüştürmenin etrafında dönüyor. Tezde tartışılan bu kavramın avantajları sayısız ve motive edicidir, bu nedenle denizcilik endüstrisinde trend olan ve çok aranan süreçlerden biri haline gelmek için bu yüzyılda popülaritesinin nasıl önemli ölçüde arttığını vurgulamaktadır. Bu nedenle bu makale, modelleme dillerinin mühendislik sürecine uygulanmasının basit bir gösterimidir.

Tez yeni inşa yerine mevcut gemilerin tahrik sistemlerine hibrit güçlendirmelerin tadilat ve yükseltmeler yoluyla uygulanması için yöntemleri ve gerekli talepleri belirlemeyi amaçlamaktadır. Modern modelleme dilleri, yani SysML ve UML, bu projenin spesifikasyonlarını, diyagramlarda ve grafiklerde temsil edilen önceden tanımlanmış faktörlere dayanarak sunmak için kullanılır ve kullanıcı dostu bir sürecin oluşturulmasını kolaylaştırır. Sistem mühendislerinin bir modelle etkileşime girdikleri diğer tüm disiplinlerle iletişim kurmaları gerektiğini bilmek, bu tezin modern hibridizasyon örneğini kullanarak sunduğu fikir olan ayrı gereksinimleri okumaktan daha iyi bir hikaye anlatır.

Bununla birlikte, ayrıntıların mevcut gemilerde benzer sistem uygulamalarıyla ilgili bilgilerin mevcudiyeti ile sınırlı olduğu belirtilmelidir. Şu anda uyumlu özelliklerle üretilmekte olan gemilere kıyasla, hibrit tahrik sistemleri için başlangıçta kesilmemiş gemilerde yükseltmeler yapmadan önce çok sayıda faktörün iyi düşünülmesi gerekir.

Gereksinimleri iyice inceledikten sonra, böyle bir projede yer alan çeşitli parametreler ve koşullar belirlenir. Bu veriler daha sonra akış şemaları ve modeller geliştirmek için uygulanır, böylece bu yenilemeyi gerçekleştirmenin risklerini, faydalarını ve bileşenlerini inceledikten sonra seçilen hibrit tahrik sistemi konfigürasyonunun entegrasyonunda yer alan çeşitli mühendislik tasarım konseptlerini temsil etmeye yardımcı olur.

Deniz hibrid tahrik güçlendirme süreci, geminin motorlarının bir kısmının veya tamamının hibrit sistemlerle değiştirilmesini, yeni pillerin ve elektrik motorlarının takılmasını ve geminin kontrol ve izleme sistemlerinin yükseltilmesini içerir. Güçlendirme, yolcu gemileri, feribotlar, kargo gemileri ve açık deniz tedarik gemileri de dahil olmak üzere çeşitli gemilerde yapılabilir ama bu çalışmada en çok standart ticari gemiler dikkate alınmaktadır.

İlk olarak, çalışmadaki kavram ve terimler tanımlanmış ve tanımlanmıştır. Daha sonar tez, araştırılan gereksinimlerin en uygun diyagramlarla temsil edilmesini kolaylaştıran tasarım ve yapılandırma adımlarına dalmaktadır. Seçilen bir örnek gemiyi dayanarak, bu diyagramlar başlangıç durumunu ve projenin anlaşılabilirliği ve çevrilebileceği değiştirilmiş parametreleri temsil eden gelişmiş modeller oluşturulur ve görüntülenir. Son olarak, bu temsilin basitliği ve artıları, yönetim mühendisliği alanındaki kayda değerliklerine ek olarak, incelenir ve gözden geçirilir.

Her diyagramın yardımıyla, projeye farklı bir bakış açısı veya tartışma noktası kazandırılabilir. Bunlar, gantt çizelgeleri, MS proje zaman çizelgeleri, dematel karar verme ve değerlendirme planları, risk değerlendirmeleri vb. gibi ancak bunlarla sınırlı olmamak üzere diğer proje yönetimi araçlarına ek olarak üst seviye sonuçları oluşturabilir. Fikirden başarı aşamasına kadar başarılı bir mühendislik projesinin kurulmasında hayati parçaları oluşturur. Bu, değişimin ilerlemesi konusunda organize bir ortak potansiyel oluşturmaya yardımcı olur.

## **1. INTRODUCTION**

### **1.1. Research Aim**

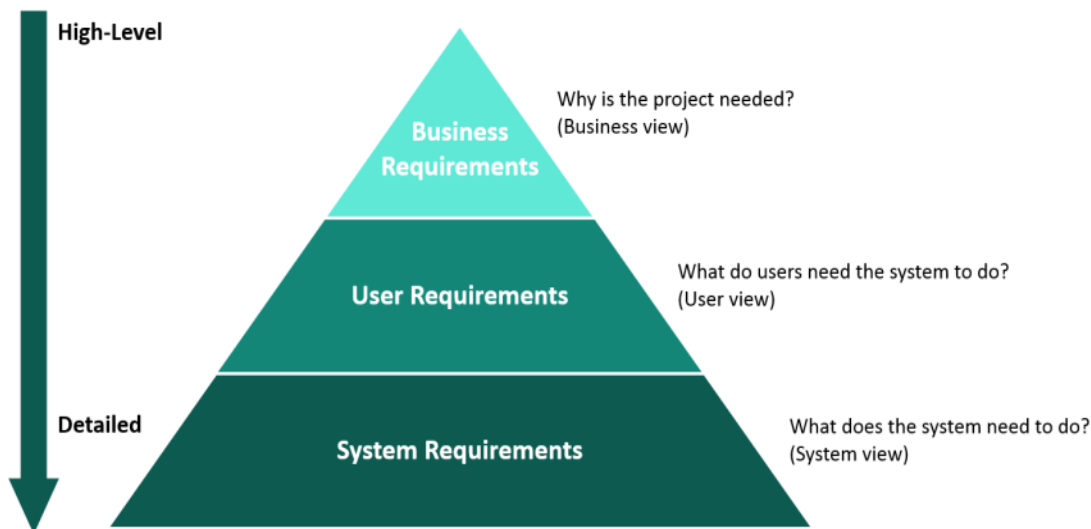
This thesis endeavors to establish methodologies and requisite considerations for the successful integration of hybrid retrofits into existing vessel propulsion systems through renovation and upgrades. The project specifications will be formulated using contemporary modeling languages like SysML and UML, leveraging charts and graphics to facilitate an intuitive approach.

### **1.2. Thesis Objectives**

To achieve the overarching research aim, this study will conduct a comprehensive analysis of the prerequisites, encompassing various parameters and conditions. The pyramid depicted in Figure 1.1 visualizes the hierarchy of factors involved in this endeavor. The insights gleaned will serve as the basis for constructing flowcharts and diagrams that elucidate the engineering designs underpinning the configuration integration of the selected hybrid propulsion system. This selection will be informed by a thorough evaluation of the associated risks, benefits, and constituent elements.

#### **1.2.1. Stakeholder requirements**

Modern ship-owners are driven by a multitude of motives when considering hybridization. The outcomes they anticipate from such an endeavor articulate their distinct requirements. Primarily, hybrid systems offer enhanced operational flexibility, a pivotal factor driving the adoption of electric and cleaner fuel sources to curtail emissions and fuel consumption. This strategic shift augments the vessel's environmental profile and elevates its market demand and reputation. The hybrid design prioritizes reduced weight, space utilization, and minimized noise and vibration compared to conventional motorized systems. It is also expected to yield long-term financial gains through lower maintenance expenses and an extended operational lifespan. [1]



**Figure 1.1:** Requirement Determination Pyramid. [2]

### 1.2.2. System requirements

The application of battery propulsion in extensive commercial shipping necessitates a meticulous evaluation due to the inherent technical constraints of batteries, such as energy density, power density, and lifespan limitations. Additionally, the adoption of hybrid systems impacts operational dynamics, including vessel speed, range, and port infrastructure for recharging.

Current electrical configurations cannot fully compensate for the energy provided by dense fuels. However, hybrid retrofitting can alleviate the load on generators while ensuring comparable energy output. This is particularly pertinent for short to moderately paced routes or scenarios requiring sudden power boosts. Implementing hybrid propulsion necessitates a structurally sound hull and engine room, capable of accommodating additional components. In cases of limited capacity, measures such as reinforcing the vessel's structure or extending the hull may be necessary. Crucial to the system are onboard power storage units and supply systems. This entails suitable battery packs, capacitors, connectors, and pitch control units. Furthermore, integrating renewable energy sources like solar panels, wind turbines, and wave turbines adds an additional layer of complexity.

### 1.3. Literature Review and Concurrent Solutions

The maritime industry's increasing focus on reducing emissions and improving fuel efficiency has spurred the exploration of innovative solutions such as hybrid propulsion systems. Integrating traditional internal combustion engines with electric propulsion components in the form of retrofits holds promise for achieving these sustainability goals while maintaining operational efficacy. To deepen the comprehension of practical implications and challenges associated with implementing hybridization through retrofits in marine propulsion systems, this literature review delves into specific case studies and research studies. Additionally, it examines these endeavors through the lens of Systems Modeling Language (SysML) to enhance the holistic understanding of system interactions and complexities.

Internal combustion engines currently dominate commercial vessel propulsion. While prevalent, these systems are not the sole solution for every scenario. The integration of hybrid alternatives has displayed significant potential, particularly for smaller fleets operating on short routes. Historical precedents illustrate successful hybrid implementations in tugboats and ferries. Notably, diesel-electric and integrated electrical configurations leverage battery packages and appropriately sized generators to power electric motors. Electricity becomes the primary energy source for propulsion and onboard utilities. This approach optimizes efficiency to achieve equivalent performance while minimizing energy consumption and pollution. [3]

Prominent case studies shed light on successful applications of hybrid propulsion retrofits within the maritime context. The "Viking Lady" project, a collaborative effort involving Eidesvik Offshore, Wärtsilä, and DNV GL, stands as a notable example. This endeavor entailed retrofitting a platform supply vessel with a hybrid power system that incorporated batteries, an electric motor, and a dynamic control system. By seamlessly switching between diesel-electric and fully electric propulsion modes, the project achieved substantial reductions in fuel consumption and emissions during different operational phases, underscoring the adaptability and efficiency gains brought about by hybrid retrofits. [4]

In parallel, the "Maersk Pelican" initiative by Maersk Tankers showcased the feasibility of retrofitting existing vessels with hybrid systems. The integration of batteries and an advanced energy management system optimized vessel operations for fuel efficiency. Impressively, the project demonstrated reduced fuel consumption and

emissions, along with the capacity for peak shaving during periods of heightened power demands. [5] These case studies spotlight the positive effects of hybrid retrofits on emissions reduction and operational cost savings, motivating further exploration of such interventions.

Complementing the case studies, research studies provide in-depth insights into technical, economic, and environmental facets of hybrid propulsion retrofitting. An illuminating study by Li et al. [6] delved into the optimal sizing of hybrid systems in retrofit applications. Their methodology, encompassing vessel-specific operational profiles and power requisites, outlined a systematic approach for selecting appropriate battery capacities and engine sizes. This approach aimed to maximize efficiency while minimizing lifecycle costs, reinforcing the significance of tailor-made solutions for optimal hybridization outcomes.

Furthermore, the research conducted by Park et al. [7] delved into control strategies for hybrid marine propulsion systems. By assessing a range of control algorithms, the researchers gauged their efficacy in managing power allocation between conventional and electric propulsion components. Their findings illuminated the superior performance of model predictive control algorithms, emphasizing the role of sophisticated control strategies in fully realizing the potential of hybrid propulsion systems.

#### **1.4. Significance and Constraints**

This study holds significance as an innovative framework for engineering management and decision-making. Utilizing charts and explanatory illustrations as a communication medium fosters alignment between engineers and stakeholders, bridging the gap between conception and execution. Furthermore, vessel retrofits align with the global shift toward green energy and environmental sustainability, making this research pertinent to both industry trends and regulatory imperatives. [8]

All vessels demand power for propulsion and auxiliary functions. Propulsion power is often governed by the power-speed relationship ( $P = kV^n$ ), where  $P$  is effective power,  $V$  is vessel speed, and  $n$  depends on hull characteristics. Additionally, such projects have practical implications and challenges related with service power supports accommodation, cargo, and equipment.

Given these dynamics, the viability of battery reliance remains a pertinent question. [9] The integration of novel components and the adaptation of control systems in retrofit operations pose intricate engineering challenges. Ensuring seamless integration and minimizing operational disruptions are pivotal in actualizing the anticipated benefits of hybrid retrofits.

In addition, economic feasibility hinges on factors such as fuel costs, incentives, and payback periods. The upfront investment required for hybrid systems may be substantial, warranting meticulous cost-benefit analyses to ascertain long-term economic viability. Moreover, effective management and maintenance of hybrid propulsion systems demand specialized training for ship crews. The intricate interplay between diesel engines, electric motors, and batteries necessitates comprehensive understanding and training to address system complexities and potential issues.

It is imperative to acknowledge that this study's scope is limited by available information on similar retrofit implementations. Comprehensive deliberation is crucial when retrofitting vessels originally designed for conventional propulsion systems, as opposed to vessels designed from inception with hybrid compatibility.



## 2. CONCEPTS AND DEFINITIONS

### 2.1. Requirements Engineering

Requirements engineering, often regarded as the initial phase of development within the engineering design process, encompasses the establishment, documentation, maintenance, and management of requirements. [10] This pivotal process involves mechanisms for understanding customers' needs, analyzing their requirements, evaluating the feasibility of proposed ideas, negotiating optimal solutions, validating specifications, and comprehensively documenting the entire procedure. Essentially, requirements engineering bridges the gap between needs and a functional system through disciplined application.

The phases of requirements engineering encompass [11]:

- **Inception/ Elicitation** – that is; deciding on the wants and needs of stakeholders.

This involves identifying the needs and wants of stakeholders to understand what the system is intended to achieve. Techniques such as interviews, surveys, and workshops are used to identify and document user requirements.

- **Analysis** – identifying possibilities and conflicts with the help of cases or stories.

Once the requirements are identified, they are analyzed to determine their scope, feasibility, and priority. The requirements are categorized as functional (features the system must have) or non-functional (system qualities that must be met, such as performance or security).

- **Modelling** – product design and representation with graphics or blue prints.
- **Specification and Documentation** – written and visual.

This phase involves documenting the requirements in a clear and concise manner so that all stakeholders can understand them. This may include use cases, activity diagrams, or textual descriptions of the requirements.

- **Validation** – assessing the consistency and/or checking for errors.

This phase involves reviewing the requirements to ensure that they are accurate, complete, and consistent. This could entail testing the requirements by conducting reviews with stakeholders or against a prototype.

- **Management** – supervising the procedure and execution.

Once the requirements are validated, they must be managed to ensure that they remain relevant and up-to-date throughout the development process. Any changes or updates to the requirements must be tracked and managed through a requirements management system.

### **Requirement Specification Document (RSD)**

Requirement specification, also referred to as documentation, is the process of compiling system and user requirements into a document that outlines project specifications. The clarity, thoroughness, comprehensiveness, and consistency of these requirements are crucial to ensure shared understanding among stakeholders and to prevent misunderstandings during subsequent development stages. The Requirement Specification Document (RSD) serves as a blueprint for system functionality and behavior, acting as a reference point for all parties involved. By identifying needs gaps early, the RSD reduces overall development costs and duration.

The requirements specification step is pivotal in the requirements engineering process, compiling a detailed document that encompasses the requirements imposed on the product's design, verification, and maintenance. [12]

Here are some of the key components that an RSD typically includes:

- **Introduction:** This section provides an overview of the project, including its goals and objectives, scope, and intended audience.
- **Requirements overview:** This section provides a high-level summary of the system's functional and non-functional requirements, as well as any constraints or assumptions that the development team must consider.
- **Functional requirements:** This section describes the system's intended behavior, including its input and output requirements, its interfaces with other systems or hardware, and any performance requirements that it must meet.
- **Non-functional requirements:** This section describes the system's non-behavioral requirements, including its reliability, availability, maintainability, and usability.

- **Acceptance criteria:** This section outlines the criteria that must be met in order for the system to be considered complete and acceptable by the stakeholders.
- **Traceability matrix:** This section provides a mapping of the requirements to the test cases that will be used to verify them, as well as to other related documents or artifacts.
- **Glossary:** This section provides a list of technical terms and acronyms used throughout the RSD, along with their definitions.

Overall, the RSD serves as a detailed description of the system's requirements, providing the development team with a clear understanding of what they need to build and how it shall behave. It is a key document that helps ensure that the final product meets the stakeholders' needs and expectations.

## **2.2. SYSML / UML**

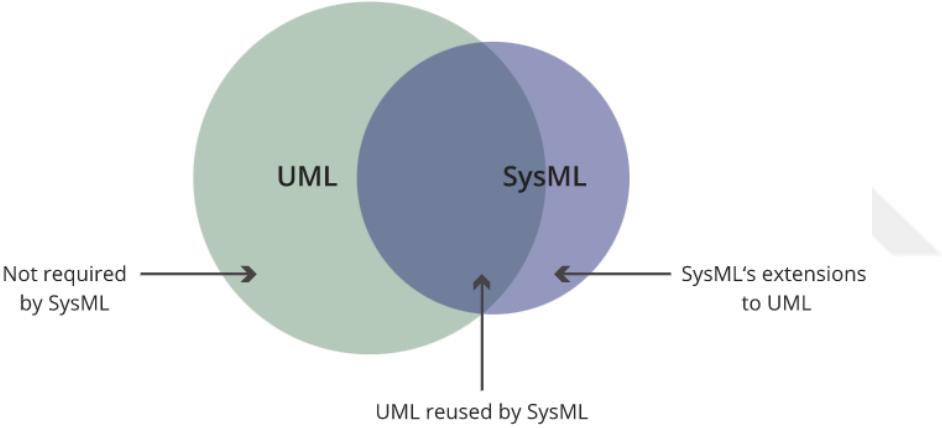
### **2.2.1. History and background information**

Modeling languages are described as artificial languages that are used to express data, knowledge, or systems in an approach that follows a set of standardized norms. These guidelines are designed to aid in interpreting the significance of structural elements. [9] The design and implementation of computer objects, systems, and architectures can be facilitated by a variety of graphical and textual modeling languages.

Two of these graphical modeling languages are known as Unified Modelling Language (UML) and System Modelling Language (SysML). While both modelling languages serve to document software, information, and processes, SysML, being an extension of UML with some customizations, also documents hardware and physical components, facilities, as well as people in the system thereby offering more flexibility and expressiveness for engineers. [13]

The Systems Modeling Language (SysML) was created by the SysML Partners, an informal association of Systems Engineering and software modeling tool experts that was organized by Cris Kobryn in 2003 to create a profile (dialect) of the Unified Modeling Language v. 2 (UML 2) that could be used for Systems Engineering applications.

SysML, which was evolved from the UML as shown in the ven diagram of figure 2.1, and is specifically meant for the model-based development of software intensive systems, makes it possible to apply and document design logic in a methodical way. The SysML is primarily driven by four factors. [14] First, it attempts to provide an integral approach for all engineering disciplines by offering a modeling language that can visualize different engineering aspects in a coherent and consistent manner. Second, it offers modeling of requirements and it helps to systematically trace these requirements to the various system design choices. Third, it offers model based rather than document based development (MBSE: model based system engineering). Last, but not least, it supports the co-design of software versus mechanical and electrical engineering aspects of a system. SysML currently draws much attention in domains like automotive, infrastructure development and command and control systems [15].



**Figure 2.1:** SysML / UML Relation. [16]

**2.2.2. Types of diagrams and their functions**

SysML diagrams merely utilize seven modified UML diagrams, making them relatively simpler to understand and use [17]. These can be divided into structural diagrams and behavioral diagrams.

In this section, the example of a Hybrid SUV is used to show each diagram. The following graphic in figure 2.2 depicts the nine diagrams that make up SysML:

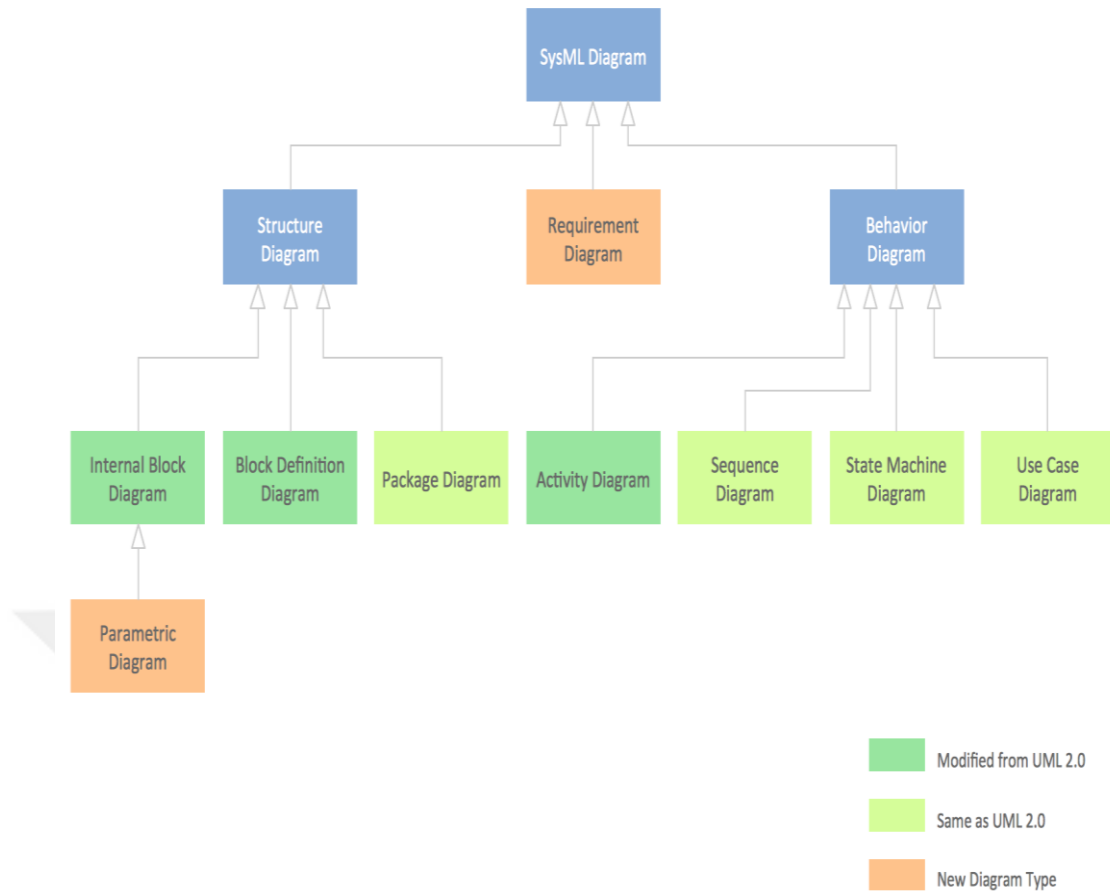


Figure 2.2: SysML Diagram Chart. [18]

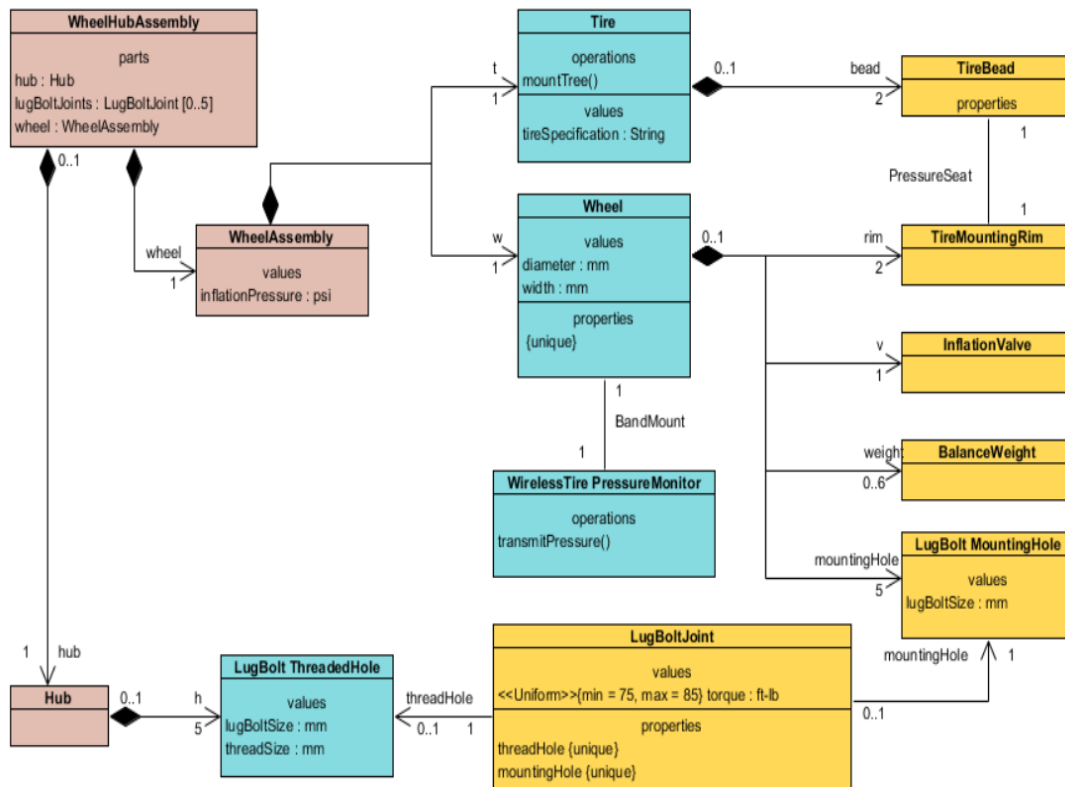
### - Requirement diagram (REQ)

A Requirement diagram shows system requirements and their relationships with other elements. Useful for requirements engineering, including requirements verification and validation (V&V) as can be seen constructed in chapter 4.

The Requirement Diagram for a marine hybrid propulsion system presents a structured representation of the high-level requirements governing the Marine Hybrid Propulsion System. These requirements encompass critical aspects such as power output, efficiency, operational modes, safety standards, and more. The diagram showcases the hierarchical organization of requirements and defines relationships between them, elucidating their dependencies. This diagram serves as a pivotal tool for understanding the specified objectives and criteria that guide system development and performance. *Structural diagrams* are the ones depicting the static aspects or the relations of elements in the system (which show the static components of a software system). These are;

- **Block Definition diagram (BDD)**

[Structural diagram] A Block Definition diagram as in figure 2.4, shows system structure as components along with their Properties, Operations and Relationships. Useful for system analysis and design. Blocks are the basic building blocks of a system. They represent physical or abstract elements of the system, such as components, parts, systems, subsystems, etc.



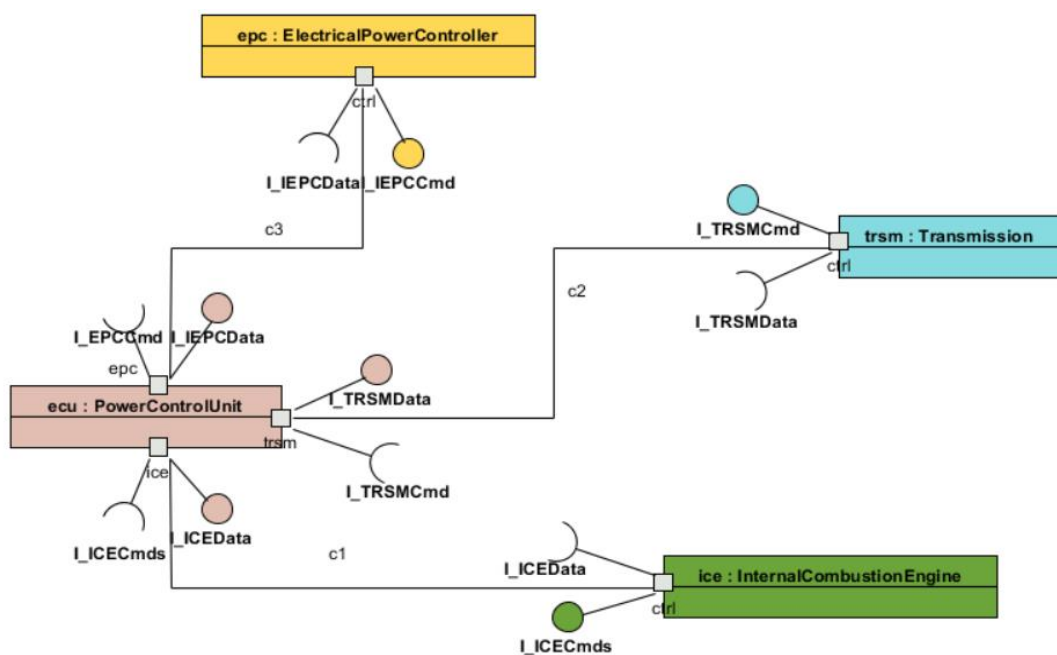
**Figure 2.3:** Block Definition Diagram. [19]

The Block Definition Diagram (BDD) serves as a top-level overview of the Marine Hybrid Propulsion System. Within this diagram, essential blocks are introduced, such as the Diesel Engine, Electric Motor, Batteries, Power Control Unit, Propulsion System, Fuel System, Exhaust System, and Control System. It outlines their relationships, signifying that the Power Control Unit manages interactions between the Diesel Engine, Electric Motor, and Batteries, all of which collectively contribute to the Propulsion System's power generation. Additionally, connections are established between the Diesel Engine and the Fuel and Exhaust Systems, and the Control System communicates with various system components.

It's important to note that while the BDD provides a foundational understanding of the system's structure, detailed connections, interfaces, and behaviors are further elaborated in subsequent diagrams, ensuring a comprehensive system representation.

- **Internal Block diagram (IBD)**

[Structural diagram] An Internal Block diagram similar to that in figure 2.5 shows the internal structures of system components, including their Parts and Connectors. Useful for system analysis and design.



**Figure 2.4:** Internal Block Diagram. [20]

The Internal Block Diagram (IBD) offers a closer examination of the internal components of the Marine Hybrid Propulsion System. It provides insights into how the Diesel Engine, Electric Motor, and Batteries connect internally to both the Power Control Unit and the Propulsion System. Furthermore, it depicts the Control System's communication with these internal components. The IBD visualizes power distribution within the system, offering a more detailed perspective of component interactions, interfaces, and functional relationships, which are pivotal for a comprehensive understanding of system behavior.

### - Package diagram (PKG)

[Structural diagram] A Package diagram shows how a model is organized into Packages. It shows the dependencies between the models, views, and perspectives' component packages as represented in figure 2.6. Useful for model management. Packages are used to organize and group elements of the system into logical units. They enable the management and navigation of large and complex models.

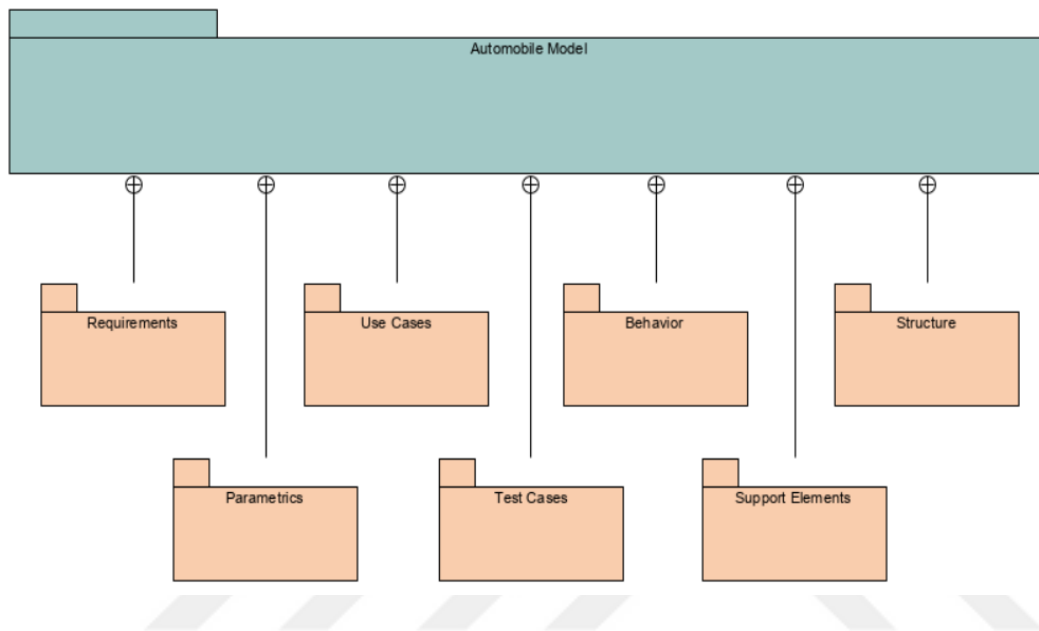
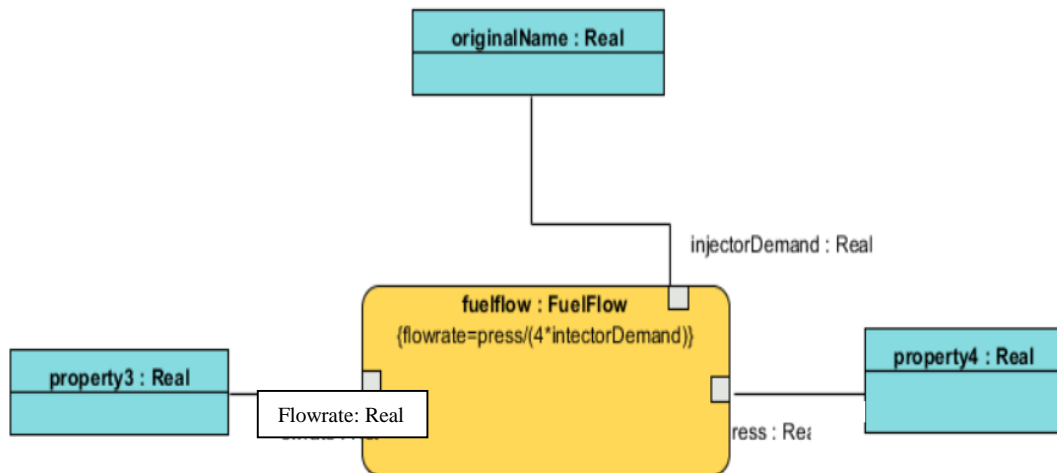


Figure 2.5: Package Diagram. [21]

The Package Diagram serves as an organizational structure for different types of diagrams and models employed in the Marine Hybrid Propulsion System documentation. It delineates relationships between packages, illustrating how they interrelate and depend on one another. Stereotypes can be applied for categorization, facilitating efficient documentation navigation. This diagram offers a structured approach to organizing and accessing the diverse components and aspects of the system documentation.

### - Parametric diagram (PAR)

[Structural diagram] A parametric diagram shows parametric constraints between structural elements. Useful for quantitative analysis. Parametric diagrams like the example in figure 2.7 represent the relationships between system parameters and their values. They are used to model the quantitative aspects of the system, such as performance, cost, and reliability.



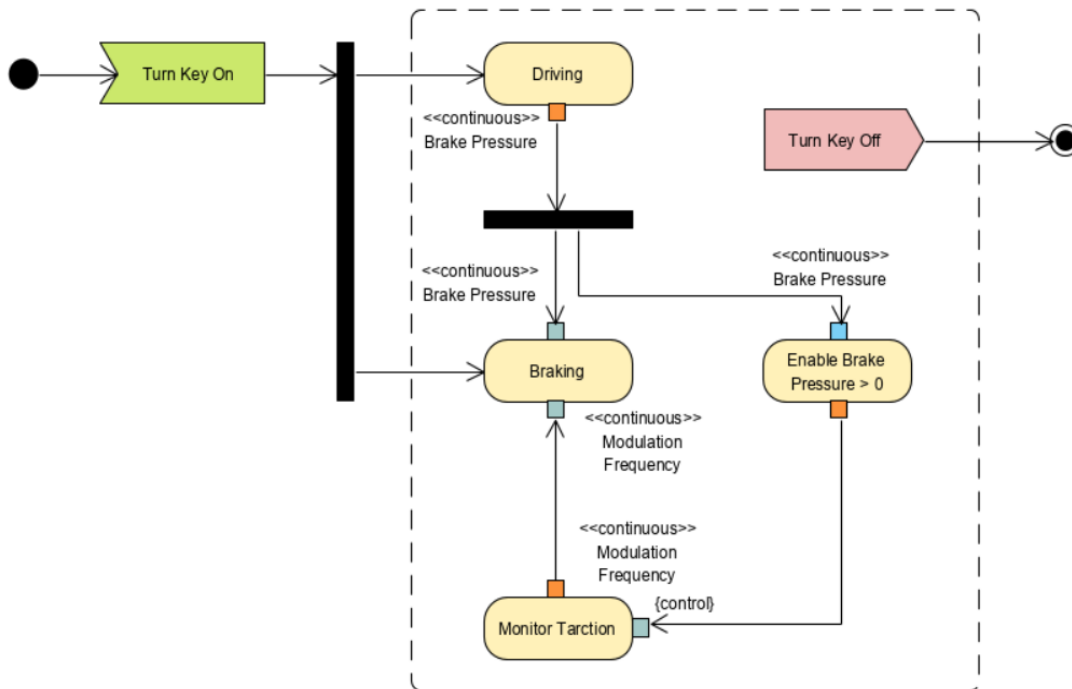
**Figure 2.6:** Parametric Diagram. [22]

The Parametric Diagram delves into the interplay between system parameters (e.g., fuel consumption, speed) and the influencing variables that impact them. It may include quantitative data or formulas to quantify these relationships. This diagram provides valuable insights into how alterations in variables affect system parameters, offering a deeper understanding of the system's performance dynamics.

*Behavioral diagrams* are ones presenting the dynamic aspects and how the system interacts with entities (which show what happens inside the software). These are;

- **Activity diagram (ACT)**

[Behavioral diagram] An Activity diagram, figure 2.3, shows system behavior as control and data flows and intends to model both computational and organizational processes. Useful for functional analysis.

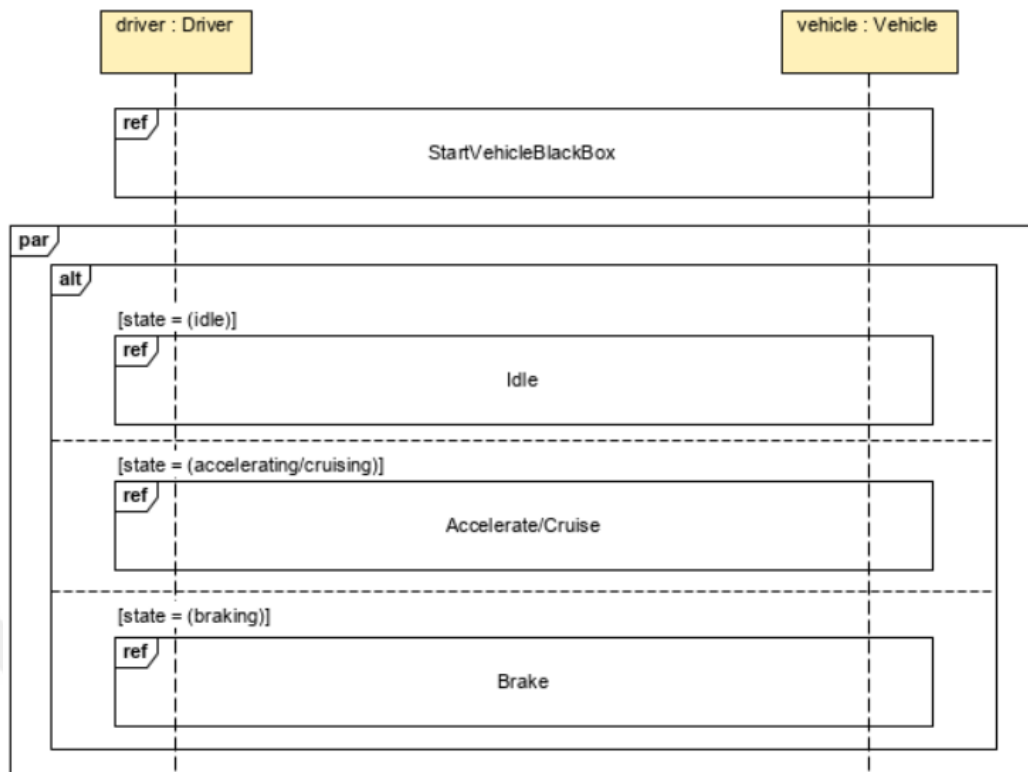


**Figure 2.7:** Activity Flow Chart. [18]

The Activity Diagram for transitioning from diesel to electric mode offers a sequential representation of the steps involved in transitioning from diesel to electric mode within the Marine Hybrid Propulsion System. Activities such as checking battery charge, shutting down the diesel engine, starting the electric motor, and monitoring the electric mode are presented in a clear flow. Decision points and parallel actions are indicated, providing insights into the dynamic process of mode transition. This diagram serves as a valuable tool for visualizing the sequence of actions required during this critical system operation.

- **Sequence diagram (SD)**

[Behavioral diagram] Sequence diagrams show system behavior as interactions between system components. They are sometimes referred to as event diagrams or event scenarios such as in figure 2.8. Useful for system analysis and design.

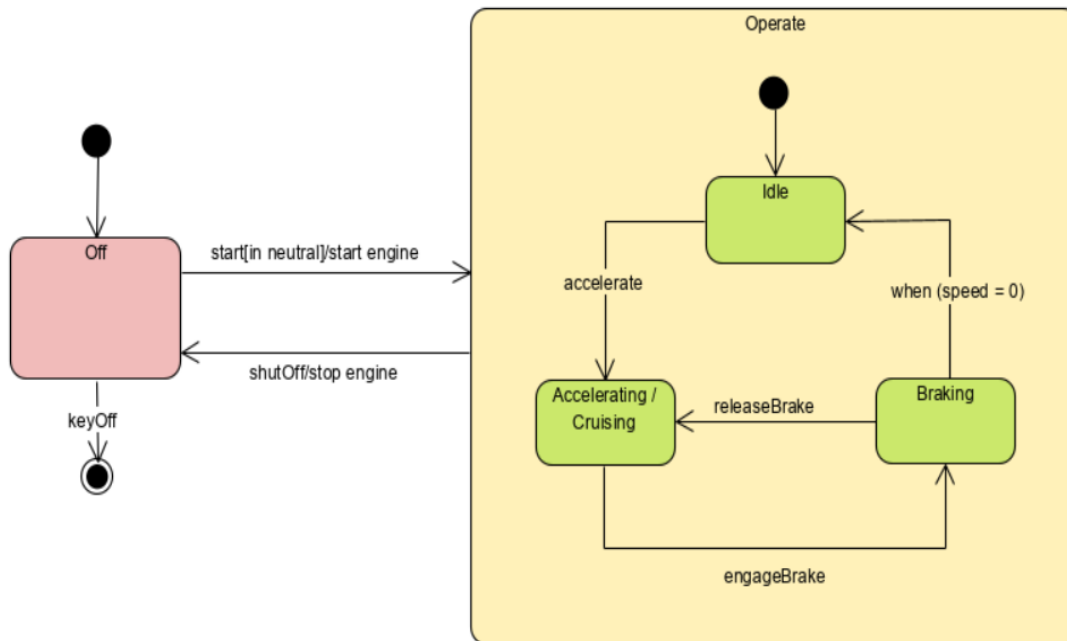


**Figure 2.8:** Sequence Diagram. [18]

The Sequence Diagram for the power distribution management of the marine hybrid propulsion system provides a dynamic depiction of the interactions and communication among key system participants, including the Control System, Power Control Unit, Diesel Engine, Electric Motor, and Batteries, during power distribution management. Lifelines representing these participants are activated to indicate their involvement in specific actions. Messages and return messages detail the flow of communication, while decision points and parallel actions showcase the complexity of coordination. This diagram offers a clear, time-sequenced visualization of how these components interact to manage power distribution effectively.

- **State Machine diagram (STM)**

[Behavioral diagram] A State Machine diagram shows system behavior as sequences of states that a component or interaction experience in response to events. A series of events that may occur in one or more potential states is used to assess and illustrate this behavior as depicted in figure 2.9. Useful for system design and simulation/code generation.

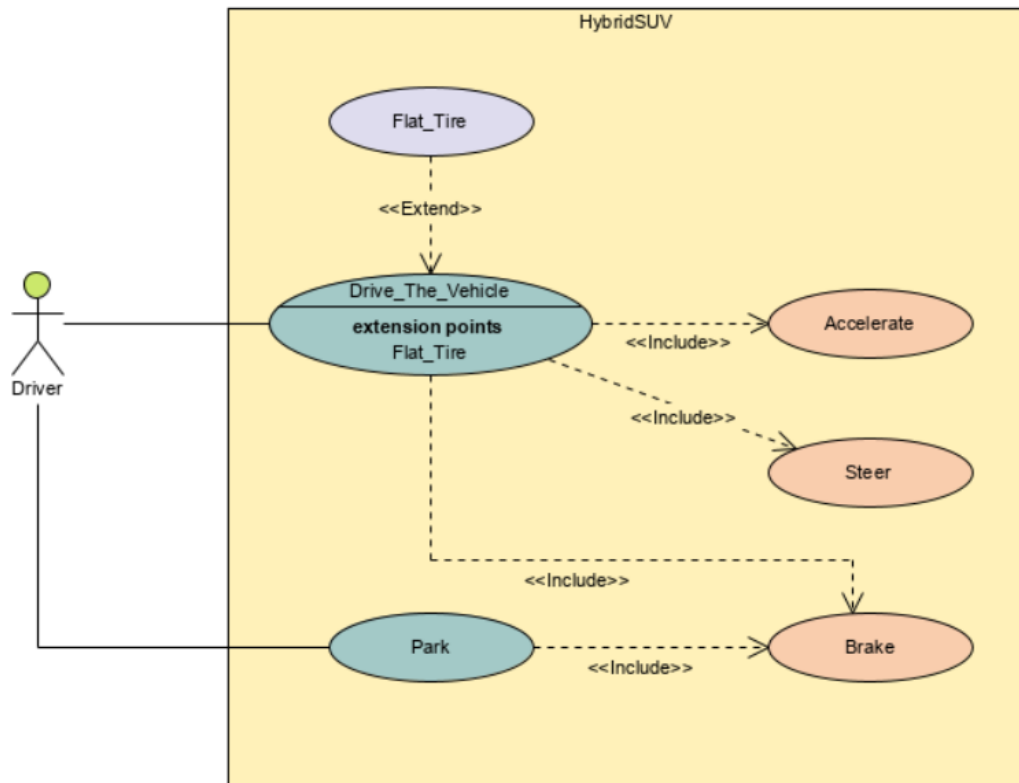


**Figure 2.9:** State Machine Diagram. [23]

The State Machine Diagram for the battery states of the marine hybrid propulsion system focuses on the battery's operational states within the Marine Hybrid Propulsion System, namely Charging and Discharging. Transitions between these states are defined by triggers or conditions, offering a comprehensive view of how the battery responds to varying conditions. If necessary, self-transitions and hierarchical states can be incorporated to capture additional complexity. This diagram provides an invaluable representation of the battery's behavior and state transitions, shedding light on critical aspects of its functionality.

- **Use Case diagram (UC)**

[Behavioral diagram] A Use Case diagram shows system functional requirements as transactions that are meaningful to system users. With reference to figure 2.10, the actors here are often shown as stick figures while use cases are represented by either circles or ellipses. Useful for specifying functional requirements. (Note potential semantic overlap with functional Requirements specified in Requirement diagrams.)



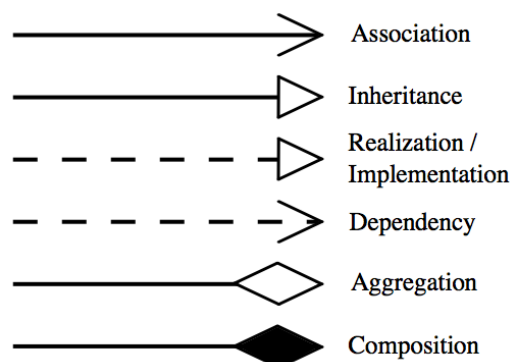
**Figure 2.10:** Use Case Diagram. [24]

The Use Case Diagram provides a high-level view of how external actors interact with the Marine Hybrid Propulsion System. It introduces actors such as the Ship Operator, Control System, and Battery Charging Station, each of which performs specific actions or "use cases." These actions include starting the hybrid system, switching to electric mode, recharging batteries, and monitoring the system's performance. Relationships between actors and use cases, as well as potential use case relationships, are depicted. The Use Case Diagram effectively communicates the system's functionality, highlighting the roles and interactions of external entities.

### 2.2.3. Diagram components and features

Although the many diagram forms often tend to encompass various features, they all adhere and conform to a standardized representation constituted of: A Frame that contains, a Header and a Contents Area. The following are the some of the main symbols used in SysML diagrams [25]:

- **Ports:** Ports are the entry and exit points of a block. They represent the interfaces of the block and enable communication between blocks as in example figure 2.5.
- **Connectors:** Connectors are the lines or arrows that connect ports of different blocks. They represent the flow of information, material, or energy between blocks.
- **Parts:** represent internal structure of blocks as shown in figure 2.4.
- **Actions:** represent system behaviors or actions similar to the flow steps in figure 2.3.
- **Control nodes:** represent decision points and control flow. They can be found in the sequence diagram 2.8 where different flow modes are depicted.
- **Swim lanes:** represent different actors or agents in the system.
- **States:** represent the different states that a system or component can be in like for instance the idle/cruising states in figure 2.9.
- **Transitions:** represent the events or conditions that cause a system to transition between states.
- **Actors:** represent the different actors or users of the system. They can be represented by stick figures in different diagrams.
- **Lifelines:** represent the different actors or objects involved in the system.
- **Messages:** represent the communication between different actors or objects.
- **Relationships:** represent the relationships between different requirements.
- **Stereotypes:** Stereotypes are used to extend or modify the meaning of SysML elements. They enable the customization of the modeling language to fit specific modeling needs.



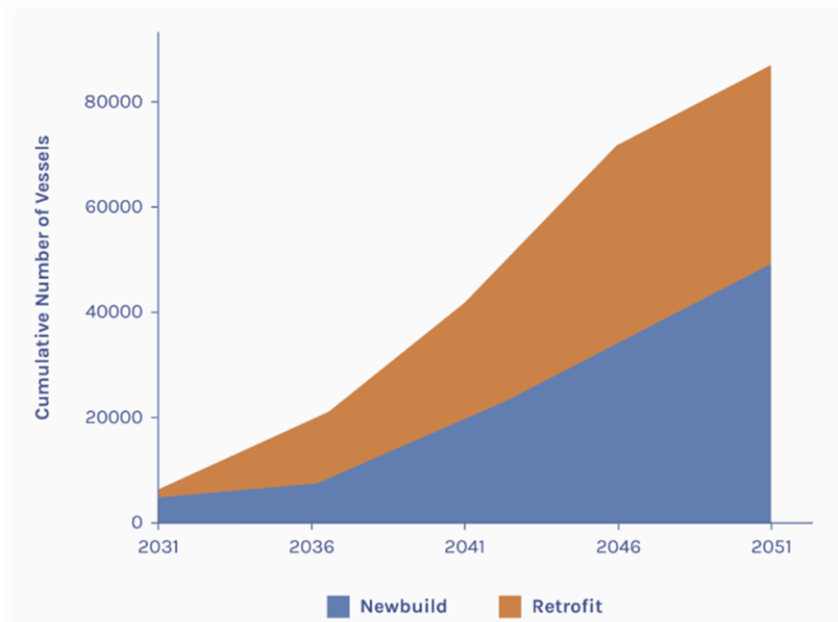
**Figure 2.11:** Types of connectors.

### 3. HYBRIDIZATION BY RETROFITS

#### 3.1. Marine Retrofits

Retrofitting offers a versatile approach to enhancing vessel capabilities, accommodating evolving regulations, and reducing environmental impact. It presents an alternative to building entirely new ships and entails making modifications or improvements to the design, structure, or equipment of existing vessels. This process can lead to improved efficiency, reduced emissions, and enhanced overall performance, contributing to a more sustainable and environmentally friendly shipping industry.

A notable projection from a Transition Strategy research conducted by the Getting to Zero Coalition and the University of Maritime Advisory Services (UMAS) indicates a substantial shift toward retrofits. By the year 2046, an estimated 35,000 vessels are anticipated to undergo retrofits, as depicted in Figure 3.1.



**Figure 3.12:** Amount of newbuilding and retrofitting to zero-emission fuels. [26]

The process of retrofitting can involve several steps:

- **Assessment:** The ship's current condition is evaluated to determine what changes are necessary and feasible.
- **Design:** Engineers and naval architects develop a plan for the retrofit, including modifications to the hull, propulsion systems, navigation equipment, or other systems.
- **Procurement:** The necessary materials and equipment are obtained and shipped to the shipyard where the retrofit will be performed.
- **Preparation:** The ship is taken out of service and brought to the shipyard for retrofitting. The ship is prepared for the retrofit by cleaning, removing old equipment or systems, and making necessary repairs.
- **Implementation:** The retrofit is performed according to the plan developed by the engineers and naval architects. This can involve welding, cutting, and installing new equipment, among other tasks.
- **Testing and sea trials:** Once the retrofit is complete, the ship undergoes testing and sea trials to ensure that it is operating as expected.
- **Certification and approval:** If the retrofit is successful, the ship is certified by regulatory agencies and approved for service.

Examples of some common retrofit options for vessel propulsion systems include:

- **Upgrading to Fuel-Efficient Diesel Engines:** Modern, fuel-efficient diesel engines can significantly reduce fuel consumption and emissions. For instance, the retrofit of the cargo vessel MV Fure West in 2020 involved the replacement of outdated engines with more efficient counterparts.
- **Installing Electric Propulsion Systems:** Electric propulsion systems offer an effective means to curtail fuel consumption and emissions. Finnlines, a Finnish shipping company, retrofitted four RoRo vessels with electric propulsion systems, achieving up to a 50% reduction in carbon dioxide emissions.
- **Switching to Liquefied Natural Gas (LNG) as Fuel:** Retrofitting a vessel's propulsion system to run on cleaner-burning LNG can substantially diminish

emissions. The retrofit of the cruise ship AIDAprima in 2020 resulted in a remarkable 90% decrease in sulfur oxide emissions.

- **Adding Hybrid Propulsion Systems:** Hybrid propulsion systems fuse diverse power sources such as batteries and diesel engines to optimize fuel consumption and emissions. The Norwegian ferry MF Folgefonn, retrofitted with a hybrid propulsion system in 2019, realized a fuel consumption reduction of up to 20%.
- **Implementing Storage Solutions:** Companies like Wärtsilä have retrofitted ships with integrated hybrid power modules that combine engines, battery-based energy storage systems, and power electronics, enhancing energy management and efficiency. [27]

The marine hybrid propulsion retrofit process entails the replacement of ship engines with hybrid systems, the incorporation of new batteries and electric motors, and the enhancement of vessel control and monitoring systems. This retrofitting strategy caters to a range of vessels, from cruise ships to ferries, cargo vessels, and offshore supply vessels. However, it's essential to acknowledge that marine hybrid propulsion system retrofits are accompanied by challenges, including high costs, specialized expertise requirements, potential compatibility issues with existing ship systems, and notable downtime during the retrofit process.

### **3.2. Hybridization of Propulsion Systems**

Marine hybridization entails the integration of hybrid technologies into marine vessels' propulsion systems. Hybrid propulsion systems are diverse in their designs and functionalities, offering a spectrum of advantages and trade-offs. These technologies amalgamate two or more power sources, often combining diesel and electric power, to augment vessel efficiency and diminish emissions. The amalgamation typically involves the parallel or alternating use of multiple energy sources to propel the vessel. Various configurations of components, fuel sources, and energy requirements contribute to the versatility of hybrid systems. [12]

Electric propulsion drives the vessel at lower speeds, while diesel propulsion takes over during high-speed operations. Batteries power the electric propulsion units, which can be charged by the diesel propulsion units or shore power when docked. In the realm of mechanical propulsion, a dual set of engines plays distinct roles. One set solely propels the vessel, while the other generates electricity for onboard electrical systems. A mechanical drive system couples a high-rpm propulsion engine to a low-rpm system, effectively transforming energy output. In contrast, electrical propulsion employs a single engine set connected to alternators to generate three-phase electricity. This electricity powers both the heavy-duty propulsion motors via variable speed drives (VSDs) and onboard electrically-driven systems. [28]

Marine hybridization and vessel hybrid propulsion systems offer several benefits, including:

- **Emission Reduction:** Hybrid technologies help to reduce the emissions of marine vessels, which is important for protecting our environment and reducing our carbon footprint.
- **Enhanced Efficiency:** Hybrid technologies improve the efficiency of marine vessels, which can help to reduce fuel consumption and save costs.
- **Performance Improvement:** Hybrid technologies can improve the performance of marine vessels, allowing them to operate more smoothly and quietly.
- **Operational Flexibility:** Hybrid technologies offer more flexibility in terms of operating modes, allowing marine vessels to switch between diesel and electric power depending on the operating conditions.

Marine hybridization presents a pivotal step towards reducing the ecological impact of maritime transportation while concurrently elevating efficiency and performance. Regulatory requirements are further incentivizing the adoption of hybrid systems, as exemplified by the International Maritime Organization's (IMO) Tier III regulations and sulfur content restrictions. [29]

The hybridization of marine propulsion systems offers a spectrum of technological choices, each with its own set of benefits and challenges. The selection of a specific hybrid technology should be guided by the vessel's operational requirements,

performance objectives, and environmental considerations. Series hybrids excel in efficiency and emissions reduction, while parallel hybrids emphasize simplicity and maneuverability. Other hybrid variations cater to specific needs, such as extended electric-only range or versatile power distribution. By comprehending the nuances and trade-offs associated with different hybrid approaches, stakeholders can make well-informed decisions that align with their sustainability goals and drive the maritime industry towards a greener future. For a selected vessel, the chosen hybrid system is expected to satisfy a number of criteria including but not limited to ship speed and service requirements in a fuel efficient manner. Amongst several types such as those using gas, nuclear, or steam propulsion, this research shall focus on those Diesel based propulsion systems.

The two most common and applicable types for commercial vessels are the CODLAD (Combined Diesel-Electrical and Diesel) and the IEP (Integrated Electric Propulsion). [30] Simply put, the CODLAD system uses an electrical motor powered by a diesel generator connected directly to the propeller shaft while the IEP, also referred to sometimes as a modified CODLAD, comprises diesel generators that produce three phase electricity used to power electrical motors turning propellers or waterjet impellers therefore eliminating the need for clutches and gearboxes as it creates an electrical transmission system rather than a mechanical one. [31]

### **3.3. Maritime Class Rules and Regulations**

Maritime class rules and regulations play a pivotal role in ensuring the safe and reliable retrofitting of hybrid propulsion systems. These rules, established by classification societies such as Lloyd's Register, DNV GL, and ABS, govern various aspects of the retrofit process, encompassing design, construction, installation, testing, and operation of hybrid propulsion systems. Some common requirements that may apply to hybrid propulsion system retrofits as dictated by the DNV include but are not limited to [32]:

- System design and construction must comply with applicable international standards and regulations, such as the International Maritime Organization's (IMO) guidelines for hybrid propulsion systems.
- The retrofit installation must be certified by the classification society to ensure that the system meets all applicable safety and environmental standards.

- The hybrid propulsion system must be tested to verify that it meets all performance requirements and that it will be able to adequately power the vessel under normal operating conditions.
- The vessel's crew must be trained in the operation and maintenance of the hybrid propulsion system to ensure safe and efficient operation.
- The retrofit must not compromise the structural integrity of the vessel, and any modifications to the vessel's hull, machinery spaces or electrical systems must be approved by the classification society.

Overall, the goal of maritime class rules and regulations for hybrid propulsion system retrofits is to ensure that the retrofit is carried out safely and that the resulting system is reliable and efficient, while also reducing the environmental impact of the vessel.

## 4. DESIGN AND ANALYSIS

### 4.1. Selected Standard Vessel

This chapter focuses on the design considerations and analysis of the retrofitting process for a fuel-powered commercial vessel, such as a tanker or a bulk carrier, that employs internal combustion engines for propulsion. The primary objective of this system is to generate optimal thrust for propelling the vessel in a desired direction.

The propulsion process begins with the transfer of fuel from the storage tank to the engine. The fuel is mixed with air within the engine to create a highly combustible fuel-air mixture. Once prepared, the engine's pistons compress this mixture in the cylinder. The ignition of the compressed fuel-air mixture results in an explosion, driving the piston downward. This motion is then transmitted to the crankshaft, subsequently turning the propeller and propelling the ship. This cyclic process continues, with new fuel and air being introduced for continuous power generation.

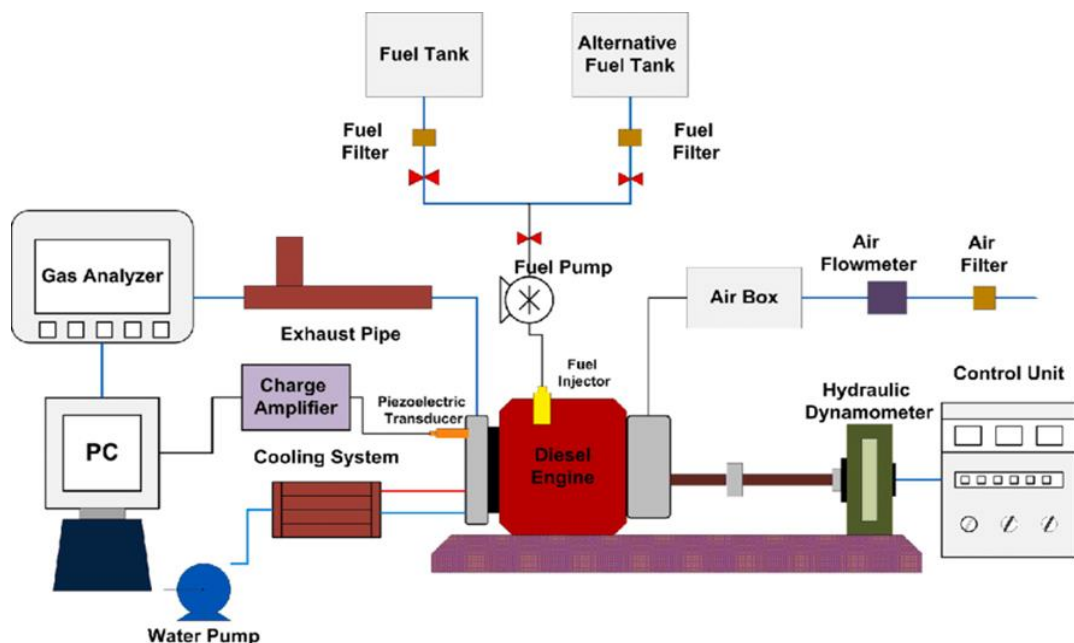


Figure 4.1: Internal Combustion System. [33]

The main components of this system and their functions shown in figure 4.1 are discussed below then transferred into a system configuration in figure 4.2;

- **Engine Room:** The engine room is the heart of the propulsion system, which converts fuel into mechanical energy. The engines in study are assumed to have configurations for a fairly average commercial vessel, thus 8 cylinders, that drive the propellers through a system of gearboxes, shafts, and couplings. They operate by burning fuel in a combustion chamber, producing a high-temperature gas that drives the pistons, which generates the mechanical power to rotate the drive shafts.

Fuel tanks typically located in the lower decks of the vessel store the fuel needed to operate the engine in the right conditions. Fuel pumps deliver the fuel from the tank to the engine through fuel lines that transfer it at the required volume and pressure, and fuel filters that remove impurities like dirt, rust, and water from the fuel to prevent contaminants from damaging the engine and maintain the fuel's quality.

The exhaust system, correctly installed to prevent back pressure, which can affect engine performance, is responsible for removing the spent gases from the engine. It can vary in design from a dry system that expels gas directly from the engine to a wet system that expels gas through a muffler and a water separator.

- **Propellers:** The propellers are attached to the ends of the propeller shafts and are responsible for pushing the vessel through the water. Propellers come in a range of sizes and shapes, depending on the vessel's size and speed requirements. The propellers are typically made of bronze, steel, or aluminum and are fixed or adjustable pitch.
- **Control Systems:** The control systems are used to manage the vessel's speed, direction, and position. The captain can control the vessel's speed using the throttle, and the direction is managed by the helm (rudder), which steers the vessel. Other control systems include the bow thrusters, which provide additional maneuverability, and the anchor system, which allows the vessel to stay stationary.

- **Cooling Systems:** The engine generates high temperatures during operation, and the cooling system helps maintain the engine's optimum temperature. The cooling system can vary in design from a sealed liquid cooling system to an open-air cooling system. The cooling system can be seawater-cooled or freshwater-cooled, depending on the vessel's design and generally consists of seawater pumps, heat exchangers, and radiators.
- **Electrical Systems:** The electrical systems are responsible for providing power to the vessel's equipment and lighting systems. They include generators, batteries, switchboards, and distribution panels.
- **Monitoring Systems:** The monitoring systems are used to keep track of the vessel's performance and condition. They include sensors, gauges, and alarms that provide information on the vessel's speed, engine temperature, fuel levels, and other critical parameters.

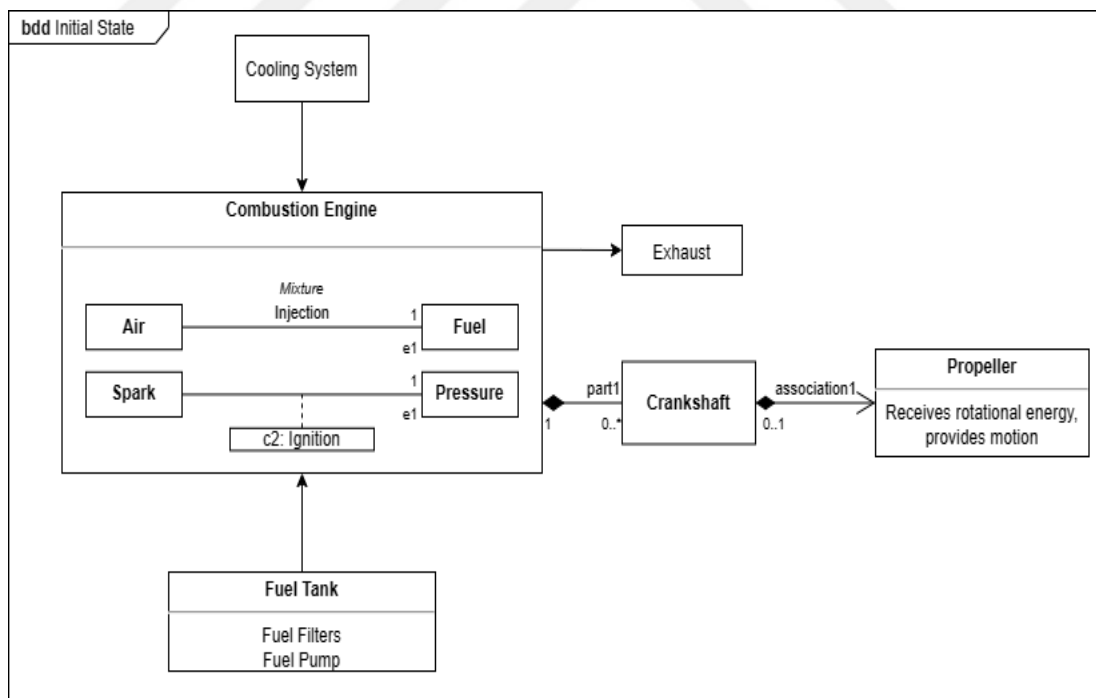


Figure 4.2: Initial State Block Diagram.

## 4.2. Project Requirement Specifications Document

In formulating the project's requirement specifications, a systematic approach was taken to ensure that all aspects of the hybrid propulsion retrofit were thoroughly considered and accurately documented. The following subsection provides insights into the methodology employed to determine the requirements for the hybridization project.

### 4.2.1. Methodology for determining requirements

The process of determining the project's requirement specifications involves collaboration between key stakeholders, thorough analysis of the vessel's operational characteristics, and consideration of industry best practices. The methodology can be outlined as follows:

- **Stakeholder Consultation:** Initial discussions are held with stakeholders, including vessel owners, operators, and technical experts. These consultations aim to identify the primary objectives of the retrofit project and gather inputs on performance, environmental goals, and economic considerations.
- **Functional Decomposition:** The vessel's propulsion system should be decomposed into its primary functional components, such as engines, propellers, control systems, and electrical systems. Each component's role and interaction within the overall system is then thoroughly studied.
- **Literature Review:** In-depth research is conducted to review existing literature, industry standards, and regulations related to hybrid propulsion systems and retrofits. Insights from established practices and case studies are then gathered to inform the project's design and requirements.
- **Performance Analysis:** Extensive analysis is performed on the vessel's historical performance data, fuel consumption rates, emissions profiles, and operating conditions. This analysis provides a basis for setting realistic performance targets for the hybridization project.

- **Environmental Considerations:** Stringent environmental regulations and emission reduction targets, such as those set by the International Maritime Organization (IMO), are taken into account when defining emissions reduction requirements for the project.
- **System Modeling and Simulation:** Computer-based simulations are conducted to model the potential impact of hybridization on the vessel's energy efficiency, fuel consumption, emissions, and operational performance. These simulations allow for the exploration of various scenarios and identification of potential benefits.
- **Stakeholder Prioritization:** The requirements are prioritized based on stakeholder input and the project's overarching goals. Trade-offs are considered between conflicting requirements to ensure a balanced and feasible set of specifications.
- **Iteration and Validation:** The determined requirements are reviewed by technical experts, and feedback is collected to refine and validate the specifications. Iterative discussions and revisions are finally conducted to ensure accuracy and comprehensiveness.

#### **4.2.2. Resultant requirement specifications**

The culmination of this methodology leads to the development of a comprehensive Project Requirement Specifications Document, outlining the functional, performance, technical, integration, and training requirements for the hybrid propulsion retrofit. This document serves as a blueprint for the design, procurement, installation, and commissioning phases of the project. By adopting this systematic methodology, the project ensures that the retrofit solution aligns with stakeholder expectations, industry standards, and the vessel's operational realities, paving the way for a successful and impactful hybridization endeavor.

#### **Functional Requirements:**

- **Power and Propulsion:**
  - Provide propulsion power in both diesel and electric modes.
  - Enable seamless mode switching.
  - Ensure compatibility with the vessel's size and type.

- **Control and Automation:**
  - Implement intelligent control logic for mode switching.
  - Offer user-friendly interfaces for manual control.
  - Monitor and manage power distribution.
- **Safety and Emergency Handling:**
  - Include safety features like emergency shutdown mechanisms.
  - Ensure fire protection and overheat prevention.
- **Efficiency and Emissions:**
  - Optimize fuel consumption and reduce emissions.
  - Comply with environmental regulations.
- **Reliability and Maintenance:**
  - Minimize downtime with reliable system operation.
  - Provide diagnostic tools and predictive maintenance capabilities.
  - Support scalability for future upgrades.
- **Environmental Considerations:**
  - Reduce noise pollution during electric operation.
  - Consider eco-friendly materials and manufacturing processes.
- **User Experience:**
  - Ensure ease of use with user-friendly interfaces.
  - Provide training and documentation for users.
  - Offer customization options to meet specific needs.
- **Support and Service:**
  - Offer technical support and maintenance services.
  - Ensure timely response to support requests.

### **Non-Functional Requirements:**

- **Performance:**
  - Meet power and propulsion performance targets.
  - Achieve a smooth and comfortable transition between modes.
- **Efficiency:**
  - Optimize energy and fuel efficiency.
  - Reduce operating costs.

- **Safety:**
  - Ensure safe operation under all conditions.
  - Comply with safety regulations and standards.
- **Reliability:**
  - Minimize the probability of system failures.
  - Ensure consistent operation over time.
- **Environmental Impact:**
  - Reduce emissions to minimize environmental impact.
  - Comply with environmental regulations.
- **Usability:**
  - Make the system user-friendly and intuitive.
  - Provide clear feedback and warnings.

#### **Performance Requirements:**

- **Power Output:**
  - Define specific power output targets for both modes of operation.
- **Transition Time:**
  - Specify the maximum allowable time for mode transitions.

#### **Technical Requirements:**

- **Power Generation and Distribution:**
  - Specify the capacity and capabilities of power generation components.
  - Detail electrical and mechanical connections for power distribution.
- **Component Specifications:**
  - Provide technical specifications for engines, electric motors, batteries, and other components.
- **Control System Architecture:**
  - Describe the architecture of the control and automation system.
  - Define communication protocols and interfaces.
- **Emission Control Technologies:**
  - Specify technologies used for emission reduction.
  - Detail emission monitoring and control systems.

### **System Integration Requirements:**

- **Compatibility and Interoperability:**
  - Ensure seamless integration with existing vessel systems.
  - Define compatibility standards for components and interfaces.
- **Communication Protocols:**
  - Specify protocols for data exchange between subsystems.

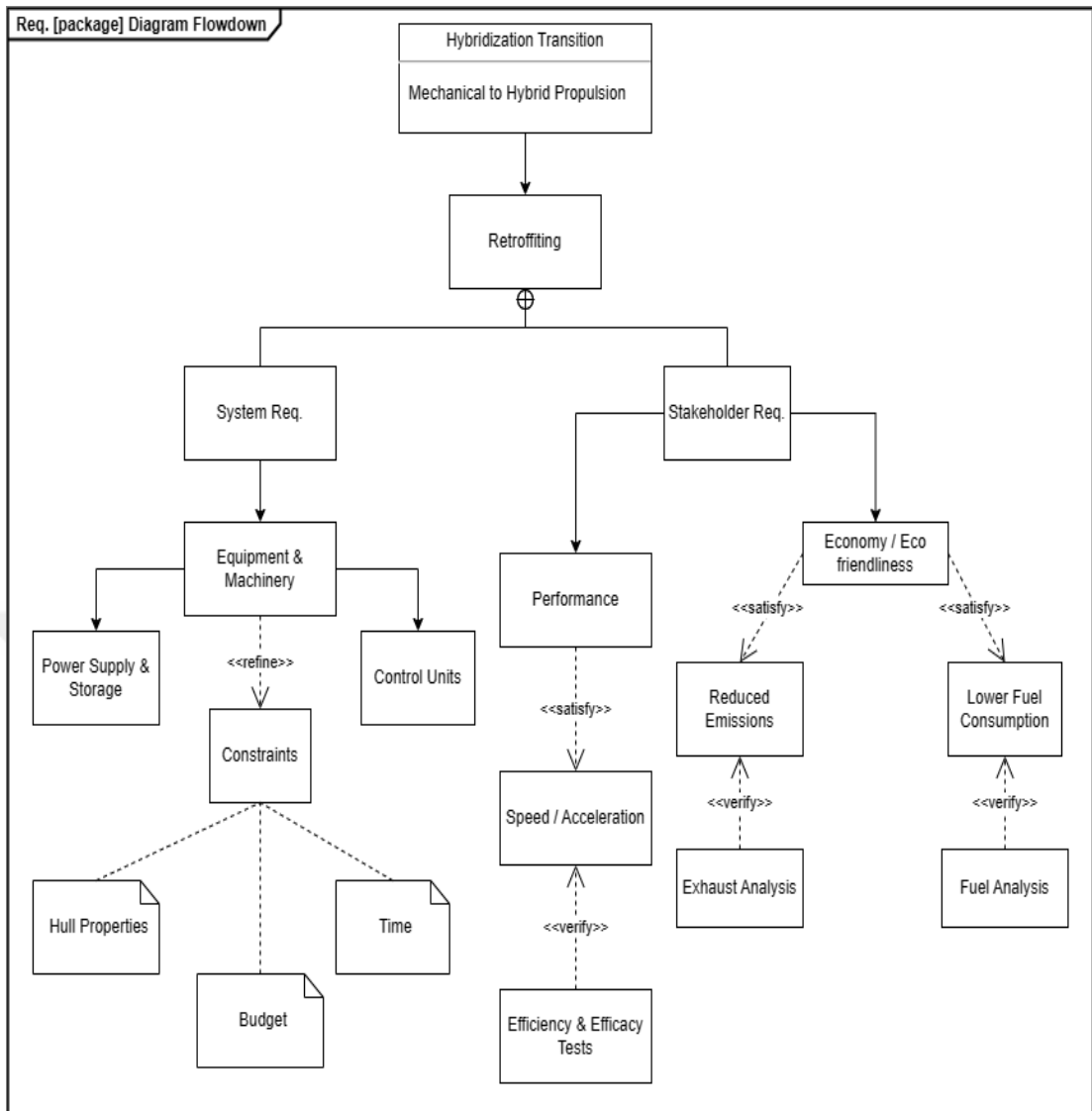
### **Training and Documentation Requirements:**

- **User Training:**
  - Develop training materials and programs for operators and crew.
  - Provide hands-on training sessions.
- **User Documentation:**
  - Create user manuals and documentation for system operation and troubleshooting.
  - Include clear instructions for emergency procedures.

### **Other Requirements:**

- **Regulatory Compliance:**
  - Comply with maritime regulations and safety standards.
  - Ensure adherence to environmental laws and regulations.
- **Cost Considerations:**
  - Define budget constraints and cost-effectiveness requirements.
  - Include considerations for system affordability.
- **Lifecycle Management:**
  - Address long-term maintenance, repair, and component replacement.
  - Consider end-of-life disposal and recycling.

The SysML requirement diagram as shown in figure 4.3 is a summary of the system as well as the stakeholder requirements discussed in chapter two with their respective constraints and verification methods.



**Figure 4.3:** Requirements Chart.

Figure 4.4 is a representation of some of the system requirements discussed earlier which include both functional and non-functional requirements. Each requirement must have branching purposes it serves as in the power and propulsion function. Figure 4.5 on the other hand shows the system and user's top-level functional requirements with their defined objectives.

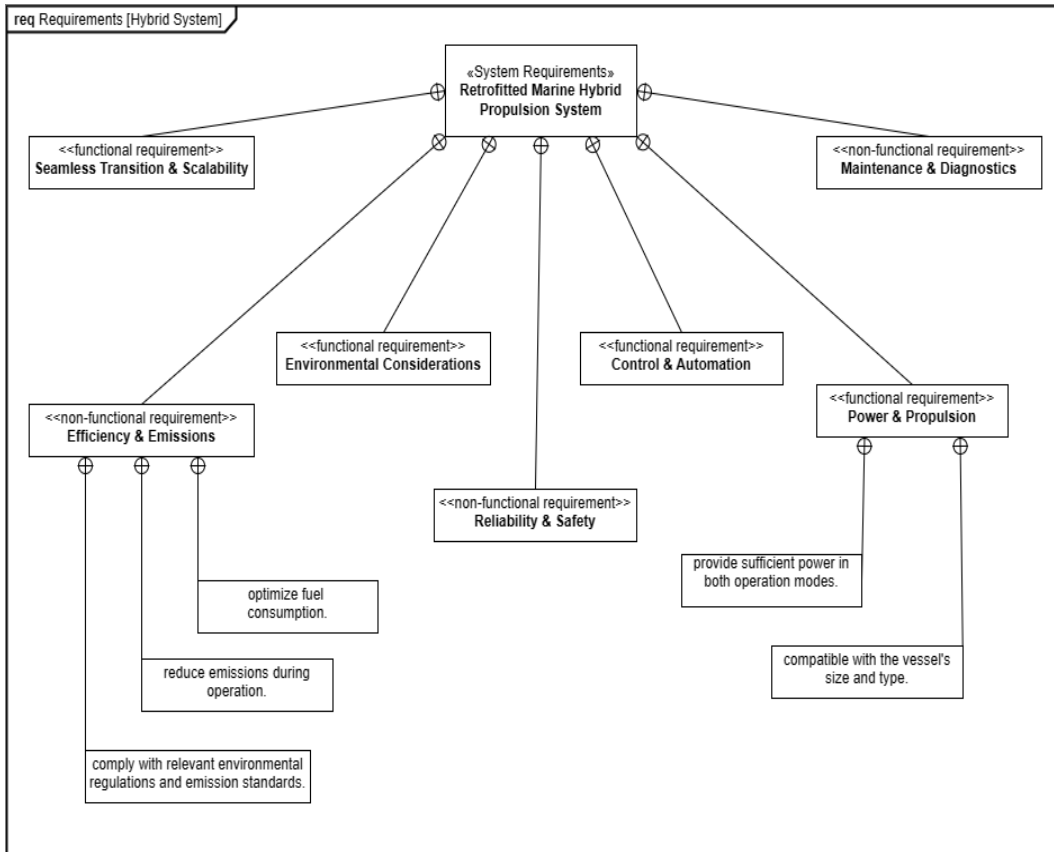


Figure 4.4: System Requirements.

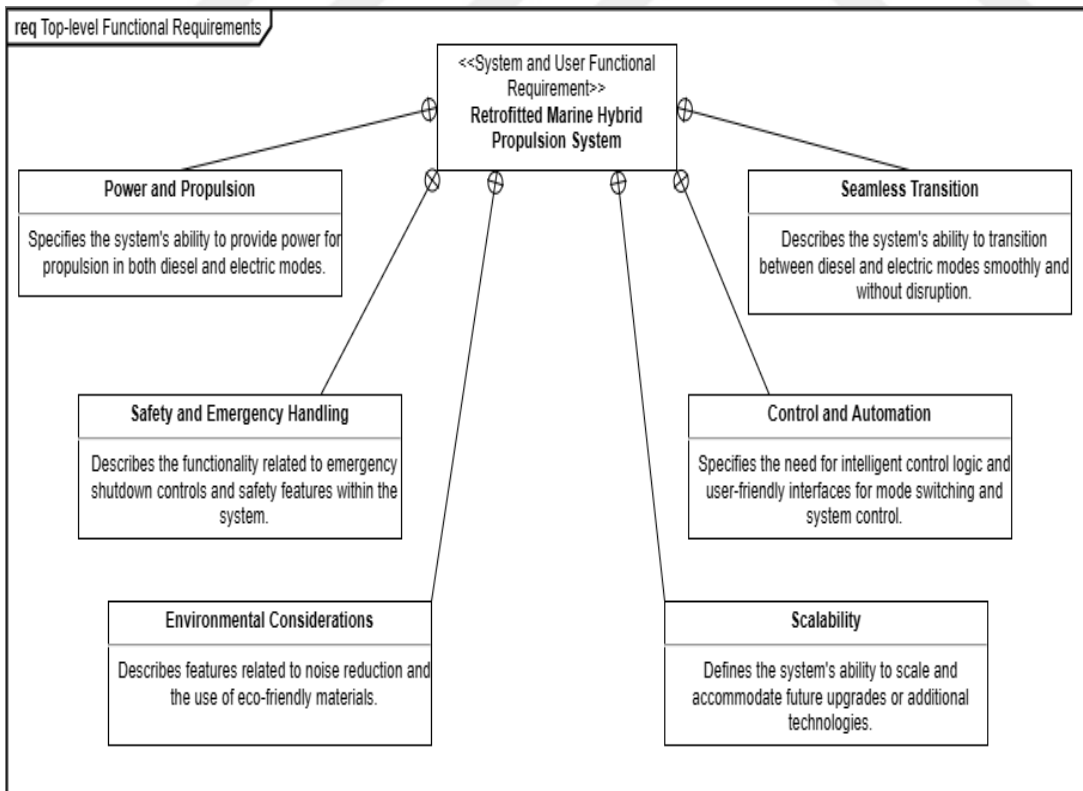
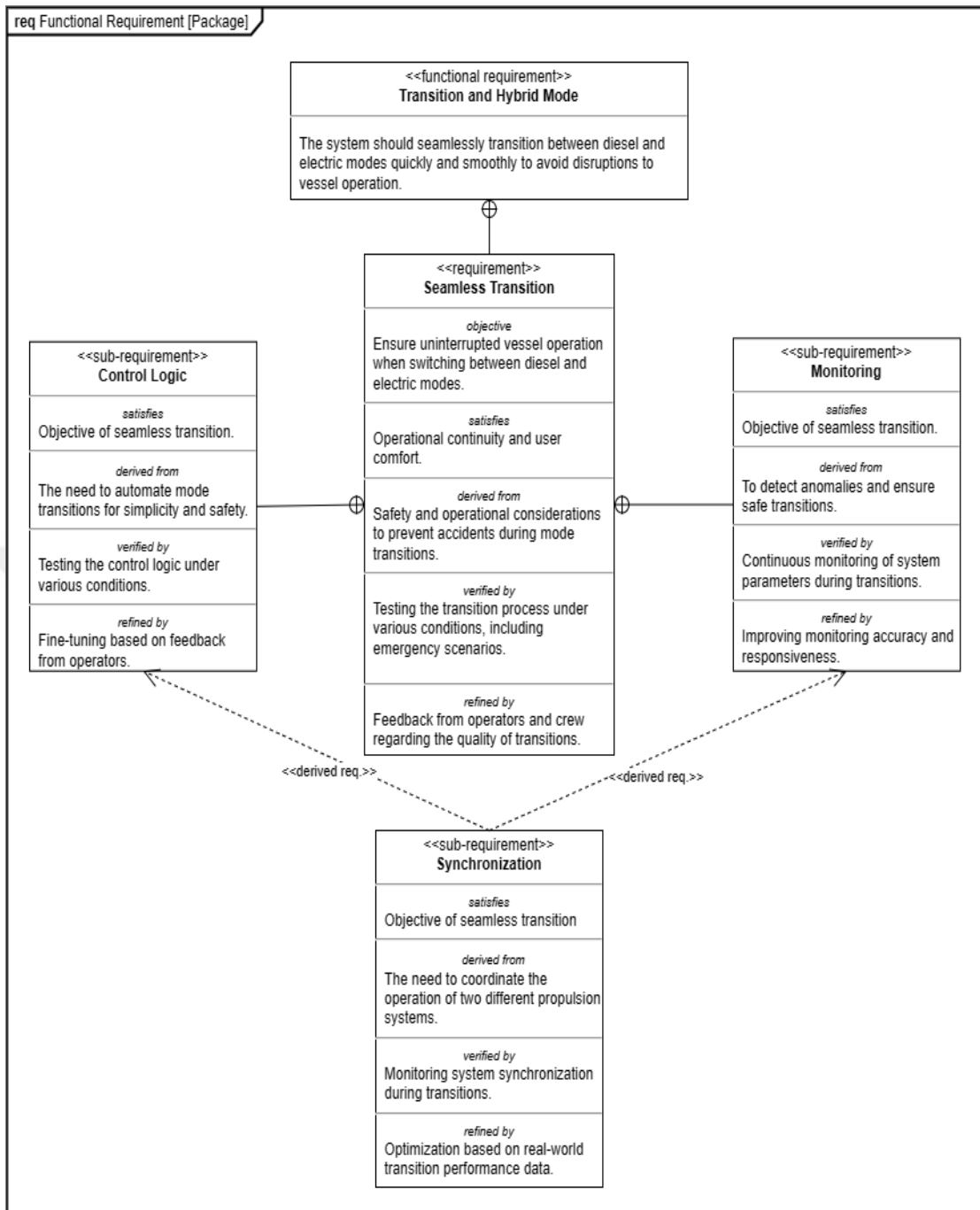


Figure 4.5: Functional Requirements.



**Figure 4.6:** Functional Requirement Package.

Figure 4.6 shows the selected Transition and Hybrid Mode functional requirement's packages. This sub-requirement tree outlines the Seamless Transition functional requirement, its objective, derivation, verification methods, and refinement process. Synchronization here is a derived requirement connecting control logic and monitoring.

### 4.3. Modifications Determined

The hybridization of a vessel's propulsion system through retrofits entails several necessary alterations. These alterations are essential to enable the hybrid system's successful integration with the existing mechanical propulsion and the achievement of the RSD targets. During the vessel's docking, the following modifications will be executed to meet the project requirements specified in Section 4.2:

- **Installation of an Energy Storage System (ESS):** The first essential modification entails the installation of a high-capacity lithium-ion battery bank as the Energy Storage System (ESS). These batteries are strategically chosen for their ability to store surplus energy generated by the propulsion system during low-demand periods, such as regenerative braking and diesel engine operation. Notably, their selection is based on their high energy density and capability to handle continuous charge and discharge cycles.
- **Electric Motor Installation:** Another critical component is the installation of a Permanent Magnet AC (PMAC) electric motor, appropriately sized and positioned in either the vessel's engine room or shaft alley. The motor's sizing meticulously aligns with the vessel's displacement and performance requirements, ensuring efficient electric propulsion.
- **Battery Management System (BMS):** The Battery Management System (BMS) further enhances the technical capabilities of the system. It diligently monitors the state of charge and condition of the battery bank, preventing overcharge or deep discharge to maximize battery life. Additionally, the BMS actively balances the charging of individual battery cells, thereby providing optimal performance and system longevity.
- **Power Electronics:** Integral to the project's success is the integration of new power electronics components, including inverters and rectifiers, into the system. These components facilitate the seamless transformation of DC battery voltage to the required AC voltage for the electric motor and vice versa. Advanced controllers play a pivotal role in managing power flow between the battery bank and the electric motor.

- **Installation of a Power Management System (PMS):** The addition of a Power Management System (PMS) is indispensable for optimizing the vessel's propulsion system. The PMS governs the complex energy flow between the ESS, auxiliary generators, and propulsion systems. Electrical system modifications are imperative to guarantee sufficient power distribution to the electric motor and battery bank. This may necessitate modifications to the electrical panel, wiring, and related safety equipment, all essential to fulfilling seamless power management conditions.
- **Control System:** A meticulously engineered control system plays a pivotal role in managing the intricate interaction between the diesel engine and the electric motor. This system judiciously selects the power source based on demand, battery state of charge, and other pertinent factors, thus optimizing efficiency in line with the project's technical requirements.
- **Shaft Generator or Generator Set:** To meet power generation demands, the project includes the installation of a shaft generator or generator set. This innovative addition allows the vessel's propeller shaft to double as a generator, producing power to charge the battery bank or serve as a range extender.
- **Fuel System Modifications:** Modifications to the fuel system are executed to ensure compatibility with the reduced load when operating in conjunction with the electric motor. These modifications include the installation of a fuel flow control system and emission control technologies, such as the selective catalytic reduction (SCR) system designed to reduce pollutants in exhaust gases. These modifications seamlessly align with the project's technical and environmental objectives.
- **Propeller Modifications:** Propeller design enhancements are meticulously implemented to optimize the hybrid system's efficiency. These alterations guarantee and are essential for improved performance, particularly during low-speed operations where the electric motor provides less torque than a diesel engine.

- **Operational Procedures:** In tandem with the technical modifications, new operational procedures are devised to align with the hybridization. These procedures encompass the management of battery charge and discharge, ensuring seamless integration and efficient operation of the hybrid propulsion system.

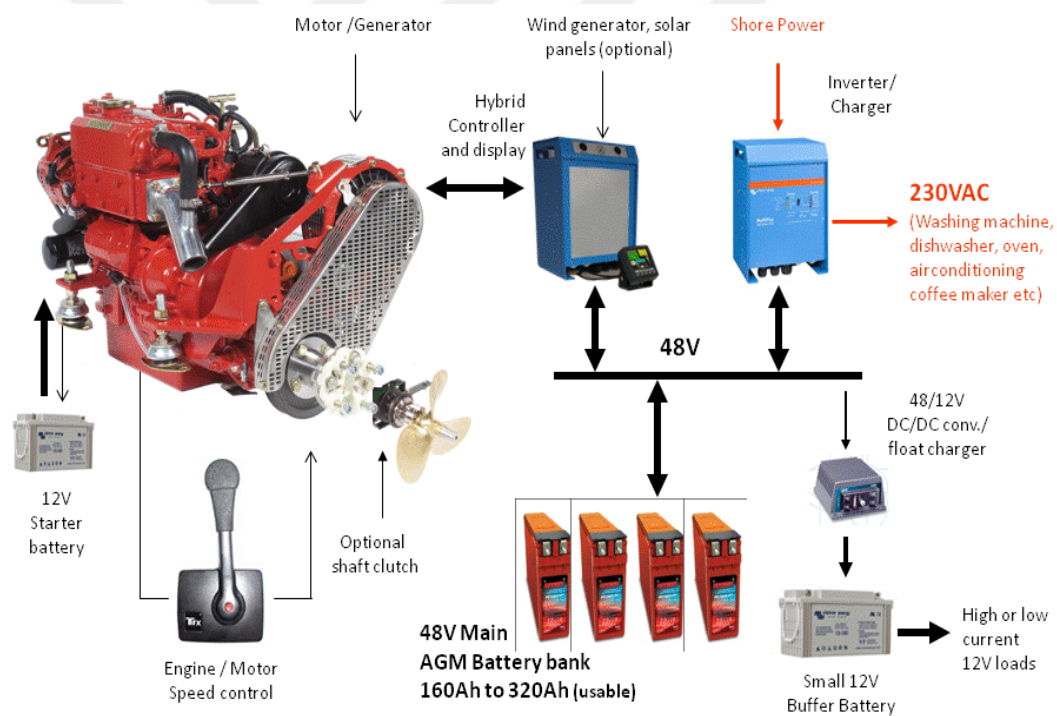
Prioritizing electric propulsion when feasible, utilizing stored energy from batteries or ultra-capacitors during low-load conditions, employing adaptive control strategies to minimize engine load and optimize fuel consumption during various vessel operations, and continuously monitoring and adjusting propulsion modes to minimize fuel consumption while maintaining performance are all essential elements in achieving the project's technical and operational requirements.

- **Hull Modifications and Structural Reinforcements:** Critical to the success of the project is the consideration of hull modifications and structural reinforcements. Depending on the weight and placement of new components, structural adjustments to the vessel's hull may be imperative to securely accommodate the installation of new components, such as the electric motor and energy storage system. These modifications also play a pivotal role in ensuring the vessel's structural integrity, optimizing hydrodynamic efficiency and resistance, enhancing stability, and improving ride comfort.
- **System Redundancy:** To ensure operational reliability and safety, redundancy in critical systems is paramount. This redundancy, in conjunction with the incorporation of fail-safe mechanisms, safeguards both the vessel and its crew. Continuous monitoring of critical components swiftly detects anomalies and triggers automatic safety protocols, ensuring the highest level of safety for all onboard. These measures strictly adhere to maritime safety regulations and industry best practices. Importantly, redundancy not only enhances safety but also guarantees uninterrupted vessel operations, even in the event of component failures.
- **Data Logging and Remote Monitoring:** The implementation of data logging systems and remote monitoring capabilities is instrumental in the collection of critical performance and health data. Real-time data monitoring enables

informed decision-making and efficient troubleshooting. Simultaneously, data logging and remote monitoring contribute to safety, efficiency, and environmental impact reduction, aligning with the project's technical and non-functional requirements.

- **Environmental Compliance:** Central to the project's mission is strict adherence to environmental regulations and standards. This entails implementing technologies and practices that effectively reduce emissions and minimize the vessel's ecological footprint.

Overall, retrofitting a vessel with a hybrid propulsion system requires careful planning, engineering, and installation to ensure safe and efficient operation. The potential resultant setup can be seen in figure 4.4.



**Figure 4.7:** Hybrid Propulsion Component Diagram. [34]

Retrofitting vessels with hybrid propulsion systems introduces a series of challenges and limitations that must be carefully navigated. Each proposed alteration requires meticulous planning, collaboration with experts, and adaptive strategies to overcome obstacles. While challenges related to space, weight, compatibility, complexity, and financing exist, they are not insurmountable.

By engaging in thorough design, interdisciplinary collaboration, and adherence to safety protocols, retrofitting projects can achieve successful integration and deliver on the promises of improved efficiency, reduced emissions, and a greener maritime future. The ability to address these challenges head-on, combined with an unwavering commitment to innovation and sustainability, will drive the maritime industry towards a more environmentally responsible and efficient path.

#### **4.4. Final State**

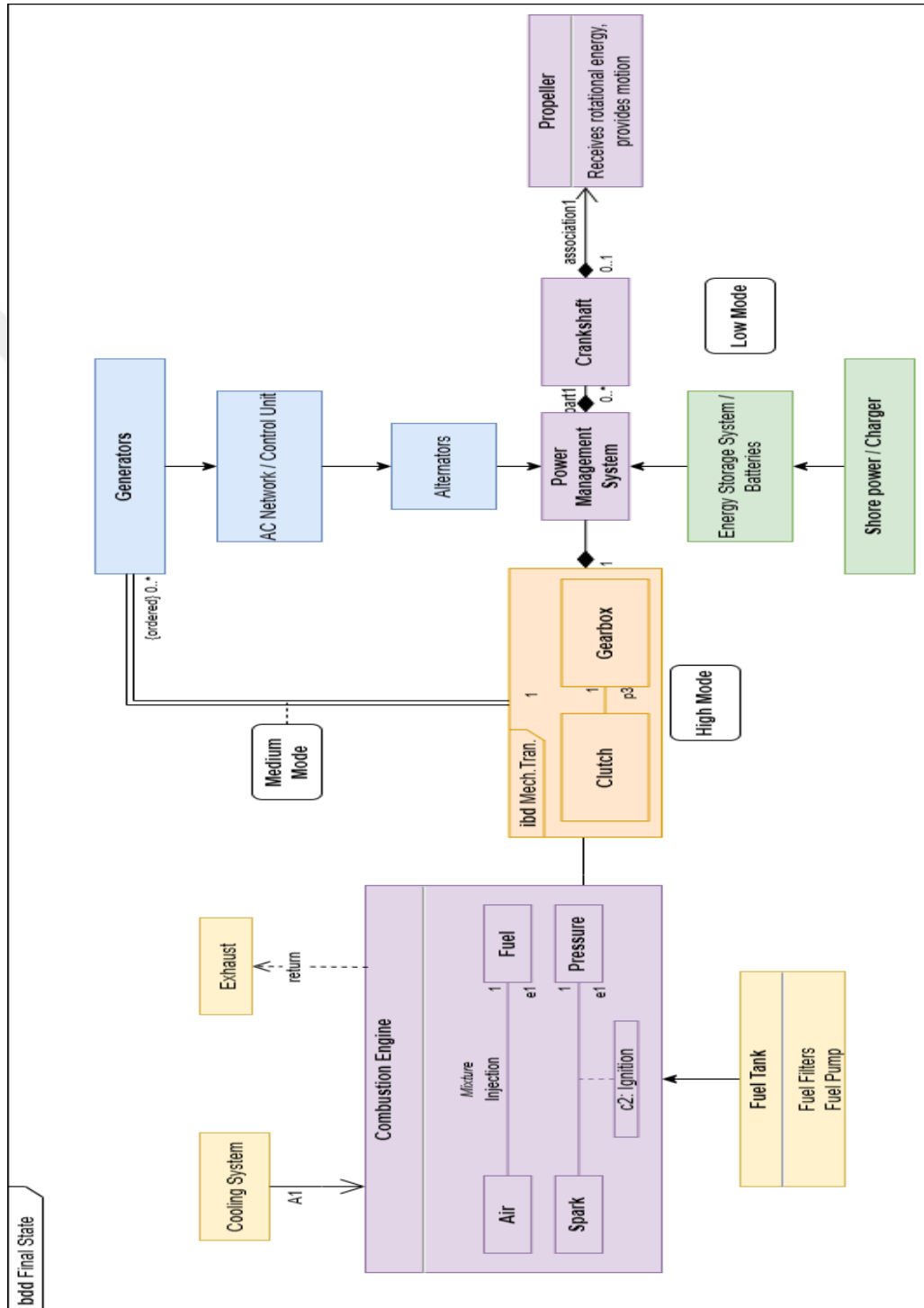
##### **4.4.1. Functional diagrams**

A block definition diagram is a brief representation of the system structure. The main elements being the generator, motor, battery and shaft have been illustrated as parts of a block below with each component being a branch and having its own function in the system.

Figure 4.5 illustrates three operation modes; high, medium and low, are assumed for which different working configurations can be engineered since the power demands vary. [35] High speed, represented in orange, would require greater energy that only the main engine could suffice for, whereas medium speeds (blue route) can be compensated using the electrical units to decrease fuel combustion and mediums are a controlled combination of both for utmost results. Low speeds on the other hand, in this case displayed in green, can be handled using the stored electrical power from the banks. The block diagram depicts the propulsion system as a unit in the vessel, the internal block diagram which entails the components of the block and their connections to each other can be seen in the definition diagram of figure 3.5 as well.

Internal Block Diagrams (IBDs) are used to display the enclosed structural contents of Blocks so that they can be "wired" using approaches from Interface Based Design. Note that double lined arrows here are used to interpret a link between two processes. The simple, mainstream mechanical propulsion form relies on heavy fuel oil. Component arrangement creating a second power source connecting to the propeller's rotation can be adjusted based on vessel type and hull structure, while maintaining a consistent flow order. Hybridized propulsion involves the use of batteries as an extra, independent power source. Battery storage enables optimal engine loading, furnishes electrical spinning reserve, assists propeller shafts, and reduces peak loads. Batteries enhance system response times and overall power train reliability.

The number of motors and generators is dictated by the ship's duties and purpose, with either being switched off to achieve optimal outcomes. [36] Hence one or the other can be switched off to achieve the most suitable outcome and the circuit would continue uninterrupted.



**Figure 4.8:** Final State Process and Component Flow.

#### 4.4.2. Behavioral diagrams

An activity diagram (Figure 4.6) depicts functional behavior flow. It showcases three transition scenarios for a vessel employing a hybrid propulsion system: Case A relies solely on main engines for acceleration, Case B utilizes battery power for short distances at low speeds, and Case C combines both electricity and average fuel consumption for optimal operations.

Case A is to count solely on the main two stroke engines for more acceleration and a power boost from the combustion of heavy fuel oil. Case B uses only the electricity from the storage batteries for short distances at relatively low speed for maximum economy and minimum environmental damage. Case C counts on both options being electricity and an average fuel consumption functioning of the main engine for optimal operation conditions.

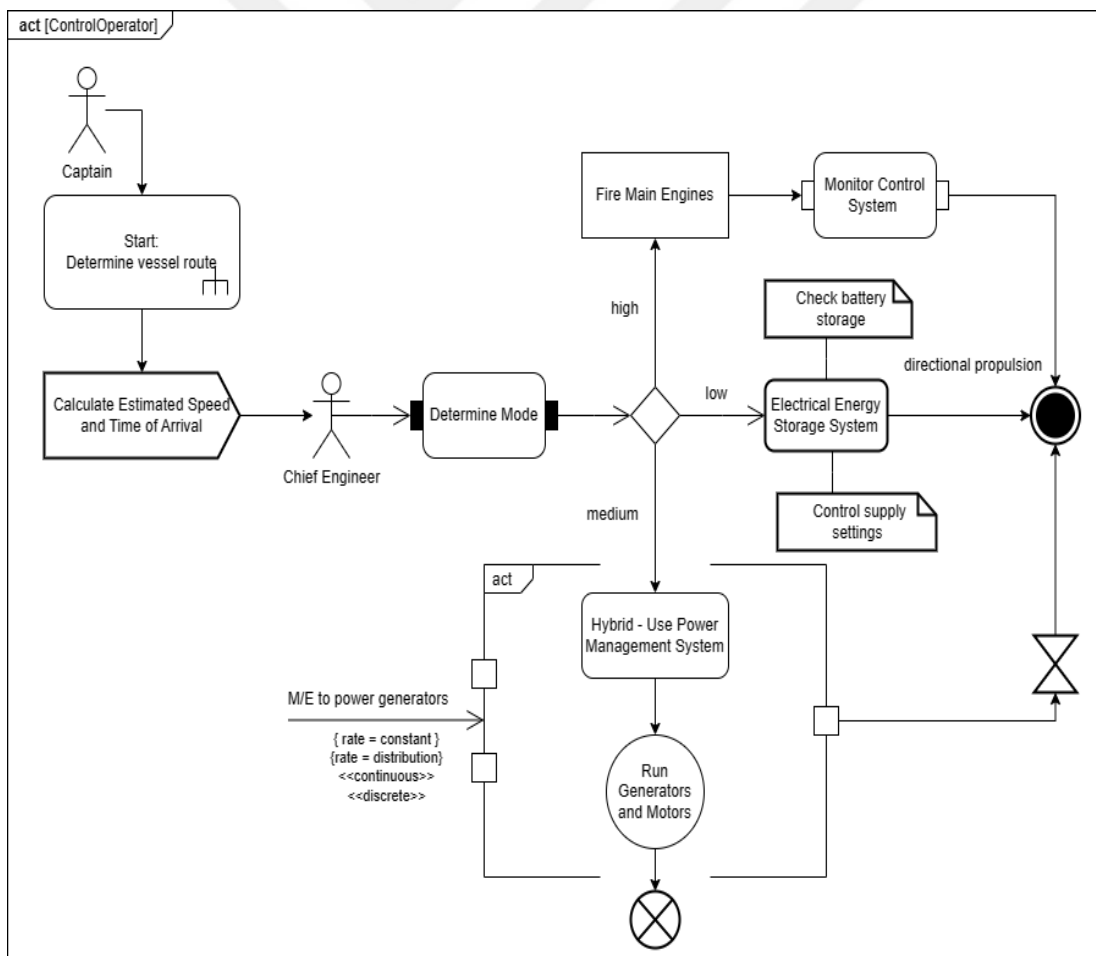
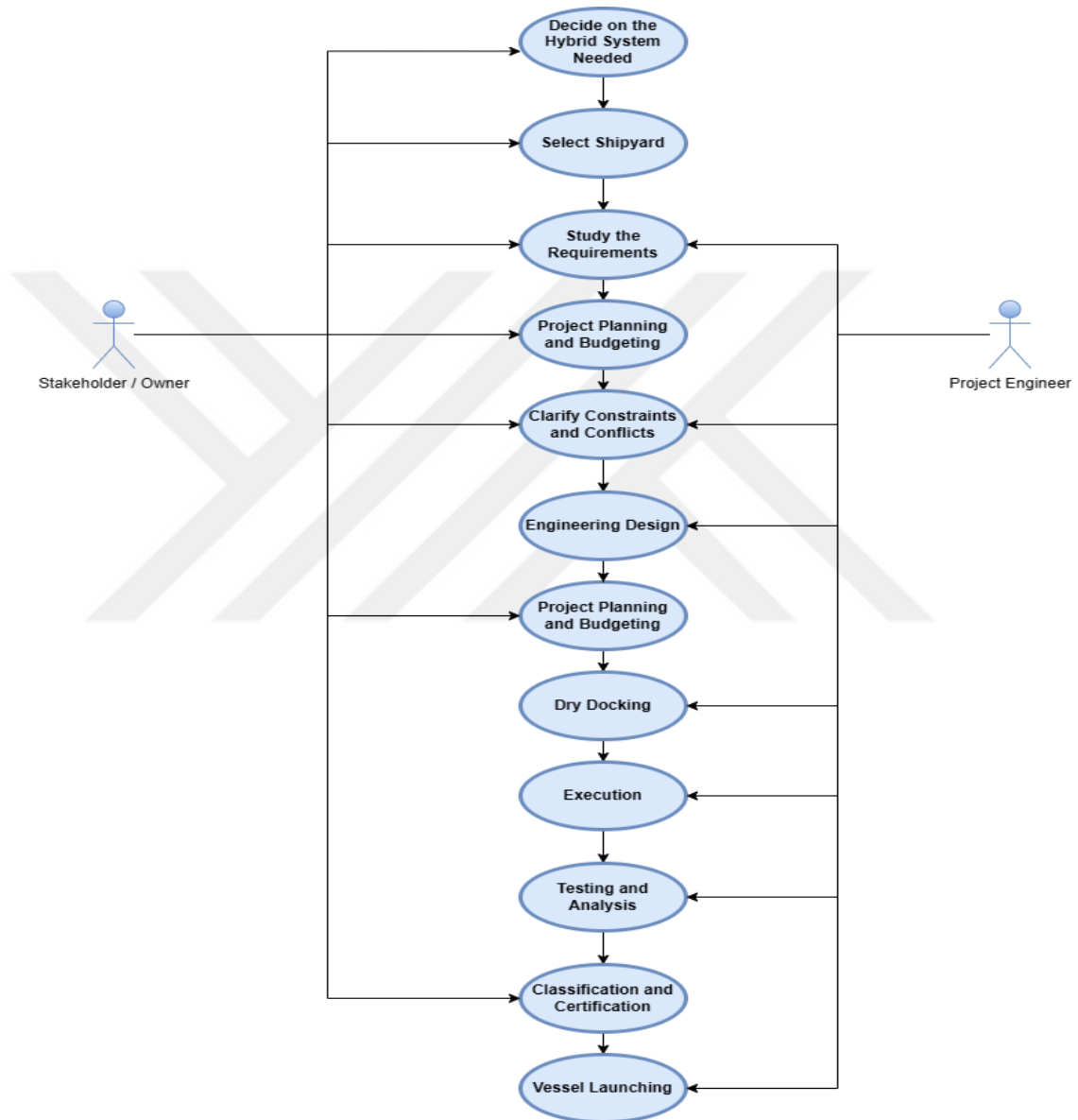


Figure 4.9: Activity and Case Diagram.

A use case diagram relates system transactions to external users. Actors are stakeholders or vessel owners and engineers overseeing the project. Both actors engage in different steps and occasionally make correlated decisions by mutual agreement. Diagram 4.10 illustrates steps from hybridization initiation to document completion and vessel deployment.



**Figure 4.10:** Use Case Diagram.



## **5. DISCUSSION AND CONCLUSION**

The maritime industry is standing at the threshold of a transformative era, one that promises enhanced energy efficiency, reduced emissions, and a more sustainable future. This thesis has delved into the fundamental aspects of hybrid propulsion systems, their benefits, challenges, and the process of retrofitting existing vessels to incorporate these innovative solutions and advancements into existing vessels. By examining case studies, industry trends, and technical considerations, this research aimed to contribute to the understanding of this vital transition in maritime propulsion and this chapter concludes the journey by summarizing key findings, discussing implications, and offering insights into the path forward.

### **5.1. Implications and Future Directions**

The pivotal role of the shipping industry in worldwide trade underscores its significance in the context of climate change. A staggering majority of global merchandise relies on maritime transportation, ranging from everyday consumer goods to critical industrial resources. Yet, this industry's prominence also raises concerns regarding its environmental footprint. Emissions from marine vessels contribute substantially to air and water pollution, as well as the emission of greenhouse gases (GHGs) into the atmosphere. To address these challenges, stringent regulations have been established, such as the International Maritime Organization's (IMO) Tier III, emission control areas (ECAs), and energy efficiency design index (EEDI) standards, which have set benchmarks for emissions reduction and energy efficiency. [37]

Recent international efforts, exemplified by the Paris Climate Conference (COP21) in 2015, have intensified the resolve to combat climate change. The shipping industry is increasingly embracing the need for cleaner operations and stricter emissions standards, leading to a paradigm shift in propulsion systems. While fossil fuels have long been the staple power source for ships, the quest for sustainability is compelling the exploration of alternative solutions.

The integration of hybrid propulsion systems, combining traditional internal combustion engines with electric motors and energy storage, holds promise for both environmental conservation and operational efficiency. This evolving landscape underscores the need for innovative solutions that reconcile commerce and sustainability. [38]

The implications of this research extend beyond technology itself. The maritime sector's journey towards sustainable practices is not only guided by environmental concerns but also shaped by economic imperatives and regulatory pressures. The findings underscore the importance of fostering collaboration among stakeholders – shipowners, regulatory bodies, technology providers, and researchers – to facilitate the seamless integration of hybrid propulsion systems. Governments around the world are recognizing the need for supportive policies and incentives, aligning with industry aspirations for cleaner and greener maritime operations.

While success stories of retrofit projects signal progress, challenges persist. Financial considerations, technical complexity, and effective integration are still areas of concern. As the hybrid propulsion field evolves, future research can contribute by refining system designs, optimizing operational strategies, and developing cost-effective solutions. Exploration into alternative energy sources, such as hydrogen and fuel cells, could broaden the horizons of sustainable marine propulsion. [39]

## **5.2. Summary of Findings**

The exploration of marine hybrid propulsion systems has revealed the potential for revolutionizing maritime transportation. By strategically combining conventional internal combustion engines with electric motors and energy storage systems, vessels can achieve remarkable gains in operational efficiency.

Case studies of retrofit projects showcased the feasibility of integrating electrical components with existing mechanical systems, leading to significant improvements in fuel consumption, emissions reduction, and operational versatility. Amidst an industry landscape evolving to embrace sustainable practices, the adoption of hybrid propulsion systems has emerged as a critical step forward.

In the pursuit of sustainability, the significance of well-defined and effectively communicated requirements cannot be overstated. Requirements serve as the foundation upon which successful engineering endeavors are built. However, the

manner in which requirements are formulated and presented is crucial in conveying the essence of a system. This is where Systems Modeling Language (SysML) emerges as a potent tool for requirements engineering.

SysML transcends the conventional practice of documenting intricate details and delves into the realm of abstract and conceptual modeling. This shift is pivotal as it aligns requirements within a holistic system engineering framework. The power of SysML lies in its ability to present the system's context through interconnected models, thereby enhancing understanding and communication among multidisciplinary teams. By fostering a visual representation of the project's scope, relationships, and dependencies, SysML accelerates the comprehension of complex systems, ultimately contributing to effective decision-making and project management. [40]

### **5.3. Closing Remarks**

The culmination of this study resides in the practical application of modeling techniques for hybridizing vessel propulsion systems. The journey to propel ships towards greater sustainability necessitates a collaborative approach that encompasses stakeholders, engineers, and regulators. This research serves to contribute to this collective effort, inspiring further research, policy evolution, and industry partnerships. The maritime industry's future is one of transformation, resilience, and innovation, with hybrid propulsion systems serving as the propelling force toward a greener horizon. Leveraging tools such as SysML, in conjunction with project management methodologies, amplifies the ability to navigate this transformative journey.

The models created within the framework of SysML and with the help of the program draw.io [41] offer multi-dimensional insights into the intricate facets of retrofitting vessels for enhanced performance and reduced environmental impact. These models, accompanied by complementary project management tools, including Gantt charts, risk assessments, and decision-making evaluations, provide an organized panorama of the project's evolution. Such visual aids foster a shared perspective, promote transparency, and facilitate the achievement of project objectives.

In conclusion, the symbiotic relationship between the shipping industry and climate preservation underscores the urgency for sustainable innovation. The integration of hybrid propulsion systems within maritime vessels represents a tangible stride towards

this imperative. Through collaborative efforts, embracing technological advancements, and utilizing advanced tools like SysML, the shipping industry can navigate the path towards a more environmentally conscious future. This journey epitomizes the capacity of human ingenuity to harmonize commerce with environmental stewardship, thus steering the maritime sector towards uncharted waters of sustainability because the voyage towards sustainable maritime practices is an endeavor of collective responsibility. The hybridization of propulsion systems symbolizes the industry's commitment to safeguarding our oceans and ecosystems while ensuring economic viability. The convergence of traditional mechanical engineering with modern electrical advancements represents the synthesis of human ingenuity and environmental stewardship.

As vessels chart their course towards cleaner horizons, collaboration remains the compass guiding the way and as we navigate these uncharted waters, may our shared determination illuminate the path ahead, steering us towards a future where maritime excellence and environmental preservation sail hand in hand.

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## APPENDICES



## **APPENDIX A – Requirement Specifications Document (RSD)**

[Company Name]

### ***Vessel Propulsion System Hybridization Using Retrofits Requirement Specification Document***

Version: 1.0

Date: [Current Date]

## **1 Introduction**

### **1.1 Purpose**

The purpose of this document is to provide a detailed specification of the requirements for the hybridization of vessel propulsion systems using retrofits. It serves as a reference for the project team, stakeholders, and other interested parties.

### **1.2 Scope**

This document outlines the scope of the vessel propulsion system hybridization project and defines its functional and non-functional requirements. It also describes the project's constraints, dependencies, and assumptions.

### **1.3 Definitions, Acronyms, and Abbreviations**

N/A (Please refer to previous chapters)

### **1.4 References**

N/A

### **1.5 Standards**

Engineering standards such as ASME and IEEE, IMO and DNV Maritime Classification standards, rules and regulations are to be followed.

## **2 Background**

### **2.1 Project Drivers**

#### **2.1.1 Problem Statement**

The maritime industry is facing increasing pressure to reduce emissions and improve fuel efficiency. Retrofitting existing vessel propulsion systems with hybrid technologies can help achieve these goals. The successful implementation of such retrofits would enable reduced fuel consumption, lower emissions, and improved environmental sustainability.

### 2.1.2 Product Position Statement

For ship-owners and operators who seek to enhance fuel efficiency and reduce emissions, the vessel propulsion system hybridization project aims to retrofit existing propulsion systems by integrating hybrid technologies and optimizing energy usage. Unlike traditional propulsion systems our solution offers improved fuel efficiency, reduced emissions, and increased operational flexibility.

### 2.1.3 Stakeholders

Representative | Description | Type | Responsibilities | Success Criteria | Involvement  
| Deliverables | Comments / Issues

--- | --- | --- | --- | --- | --- | --- | ---

[Ship-owner] | Owner of maritime vessels | Business Expert | Manage vessel operations, ensure compliance | Reduced fuel costs, lower emissions, improved operational performance | Requirements reviewer | Feedback on feasibility and impact | -

### 2.1.4 User Profiles

Representative | Description | Type | Responsibilities | Success Criteria | Involvement  
| Deliverables | Comments / Issues

--- | --- | --- | --- | --- | --- | --- | ---

[Vessel Operator] | Operates vessel propulsion system | Technical User | Monitor system performance, manage energy usage | Improved fuel efficiency, optimized power distribution | Requirements reviewer | Reports on system functionality | -

## 2.2 Product Information

### 2.2.1 Product Viewpoints

*User Point of View:* The system should provide a user-friendly interface for vessel operators to monitor and control the hybrid propulsion system.

*Function Point of View:* The system should efficiently manage power distribution between the conventional propulsion system and the hybrid technologies, optimizing fuel efficiency.

*Technical Point of View:* The system should integrate seamlessly with the existing vessel propulsion infrastructure, retrofitting the necessary components while ensuring compatibility and reliability.

*Environmental Point of View:* The system should result in reduced emissions and improved environmental sustainability, aligning with regulatory requirements and industry best practices.

### 2.2.2 Product Modes and States

Low, medium and high operation states shall be setup. In addition, the system must have normal operation mode, maintenance mode, and system diagnostic processes.

### 2.2.3 Major Product Constraints

*Budget Constraint:* The hybridization project budget is limited to \$X.

*Compatibility Constraint:* The retrofits should be compatible with the existing vessel propulsion infrastructure and comply with relevant regulations and standards.

*Performance Constraint:* The hybrid propulsion system should achieve a minimum fuel efficiency improvement of X% compared to the original system.

### 2.2.4 Usage Models

[Description of the typical operational scenarios and usage patterns of the vessel propulsion system hybridization project.] (please refer to previous chapters)

## 3 Functional Requirements

### 3.1 System Architecture

3.1.1 The hybrid propulsion system shall be designed as a retrofit solution that integrates with the existing vessel propulsion infrastructure.

3.1.2 The system shall consist of hybrid technologies, including [specify the hybrid technologies to be incorporated].

3.1.3 The system shall include control and monitoring components to manage the hybrid propulsion system.

### 3.2 Hybrid System Control

3.2.1 The system shall provide a user-friendly interface for vessel operators to monitor and control the hybrid propulsion system.

3.2.2 The interface shall display relevant information, such as power distribution, energy storage levels, and system performance metrics.

3.2.3 Vessel operators shall be able to manually adjust the hybrid system settings based on operational requirements.

### 3.3 Power Management

3.3.1 The system shall optimize power distribution between the conventional propulsion system and the hybrid technologies to maximize fuel efficiency.

3.3.2 The system shall prioritize the use of stored energy from the hybrid technologies before utilizing conventional fuel sources.

3.3.3 Power management algorithms shall be implemented to ensure seamless and efficient transitions between power sources.

### 3.4 Energy Storage

3.4.1 The system shall include energy storage components, such as batteries or ultra-capacitors, to store surplus energy and provide power during peak demand.

3.4.2 The energy storage system shall have sufficient capacity to support the vessel's operational requirements for a specified duration.

3.4.3 The energy storage system shall be rechargeable and capable of withstanding the marine environment's conditions.

### 3.5 Integration and Compatibility

3.5.1 The retrofit components shall be compatible with the existing vessel propulsion infrastructure, including engines, generators, and control systems.

3.5.2 The hybrid system shall be designed to integrate seamlessly with the vessel's power management and monitoring systems.

3.5.3 The retrofit process shall not negatively impact the vessel's structural integrity or compromise its safety.

## 4 Non-Functional Requirements

### 4.1 Performance

4.1.1 The hybrid propulsion system shall achieve a minimum fuel efficiency improvement of X% compared to the original propulsion system.

4.1.2 The system shall be capable of providing the required power for the vessel's normal operational scenarios.

4.1.3 The response time of the hybrid system control interface shall be less than X seconds for user inputs.

### 4.2 Reliability and Safety

4.2.1 The hybrid system shall be designed with redundant components and fail-safe mechanisms to ensure reliable operation.

4.2.2 The system shall comply with relevant safety standards and regulations, minimizing the risk of accidents or hazards.

### 4.3 Environmental Impact

4.3.1 The hybrid system shall result in reduced emissions, including greenhouse gases and air pollutants.

4.3.2 The system shall comply with applicable environmental regulations and industry best practices for marine vessels.

## 5 Constraints and Assumptions

5.1 Budget Constraint: The hybridization project budget is limited to \$X.

5.2 Time Constraint: The project shall be completed within the agreed timeline of [specify the timeline].

5.3 Compatibility Constraint: The retrofits should be compatible with the existing vessel propulsion infrastructure and comply with relevant regulations and standards.

5.4 Assumption: The vessel's structural integrity is suitable for retrofitting the hybrid propulsion system components without compromising safety.

## 6 Documentation and Deliverables

6.1 The project team shall provide comprehensive documentation, including system design specifications, user manuals, and installation guidelines.

6.2 Deliverables shall be provided at each project milestone as defined in the project plan.

## **7 Acceptance Criteria**

7.1 The hybrid propulsion system shall undergo rigorous testing to validate its performance, reliability, and compliance with the specified requirements.

7.2 The system shall meet or exceed the defined performance targets for fuel efficiency, power management, and emissions reduction.

7.3 Acceptance of the system will be based on successful completion of testing, demonstration of functionality, and stakeholder approval.

## **8 Stakeholder Responsibilities**

8.1 The project team shall collaborate with vessel operators and technical staff to gather requirements, provide updates, and facilitate testing and integration activities.

8.2 The vessel owner/operator shall provide necessary support, access to the vessel, and relevant documentation required for the project's successful execution.

## **9 Project Schedule**

9.1 The project shall follow a structured timeline with defined milestones and deliverables.

9.2 The project schedule shall include activities such as system design, component procurement, retrofit installation, testing, and commissioning.

9.3 Regular progress reviews and status updates shall be conducted to ensure adherence to the project schedule.

## **10 Risks and Mitigation Strategies**

10.1 Risk: Unforeseen compatibility issues between the retrofit components and the existing propulsion system.

Mitigation: Conduct thorough compatibility assessments and feasibility studies prior to component procurement and installation.

10.2 Risk: Delays in component procurement or retrofit installation.

Mitigation: Maintain effective communication with suppliers, monitor procurement progress, and allocate sufficient resources to expedite the process.

10.3 Risk: Insufficient power storage capacity to meet the vessel's operational requirements.

Mitigation: Perform accurate power consumption assessments, select energy storage components with adequate capacity, and conduct thorough testing to ensure compliance.

10.4 Risk: Inadequate user training and knowledge transfer.

Mitigation: Develop comprehensive user manuals, conduct training sessions, and provide ongoing support to vessel operators and technical staff.

## **11 Quality Assurance**

11.1 The project team shall implement quality control measures throughout the project lifecycle to ensure the delivery of a reliable and high-quality hybrid propulsion system.

11.2 Compliance with relevant standards, regulations, and industry best practices shall be a priority.

11.3 Thorough testing, inspection, and validation procedures shall be conducted to verify the system's performance, functionality, and safety.

## **12 Change Management**

12.1 Any changes to the project scope, requirements, or timeline shall be managed through a formal change control process.

12.2 Change requests shall be evaluated for feasibility, impact, and alignment with project objectives.

12.3 Approved changes shall be documented, communicated to stakeholders, and incorporated into the project plan.

## **13 Conclusion**

The "Vessel Propulsion System Hybridization Using Retrofits" project aims to enhance the fuel efficiency and environmental performance of the vessel by integrating hybrid technologies into the existing propulsion system. This Requirement Specification Document serves as a foundation for the project, outlining the functional and non-functional requirements, constraints, deliverables, and acceptance criteria. By adhering to this document, the project team can effectively plan, execute, and deliver a successful hybridization project.

[Signatures]



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