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Assessing the On-Board Storage and Use of Ammonia as a Fuel Applying the House of Quality

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Abstract: Ammonia as a fuel has been known for several years, but only relatively recently has it attracted interest for study and use as a marine fuel. A forthcoming generation of sustainable, economically viable, and safe technologies for the large-scale onboard storage of ammonia as a marine fuel is being developed. This article presents a structured approach to carrying out Quality Function Deployment (QFD) for evaluating a project solution at the strategic level. The "House of Quality" (HoQ) method is utilised since it provides the means for inter-functional planning and communications among people with different problems and responsibilities. The project requirements are defined and lead to functional technical characteristics to satisfy these needs. The approach allows for the application of a weighting scheme to rank the perceived relative importance of the requirements, the difficulty involved in implementing the technologies, and the relationship between requirements and functional technical characteristics. QFD analysis prioritises safety compliance, technical specifications, emission control, and operational efficiency. The added value of this work is beyond the life of a project since it may provide assistance to the stakeholders in assessing the applicability of ammonia fuel solutions given the resources available to them. This feature will enable the justification of further investment into specific technologies based on their potential impact.

Keywords: ammonia; marine fuels; House of Quality; quality function deployment; alternative fuels

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1. Introduction

The International Maritime Organization (IMO) committed to contributing to the United Nations Framework Convention on Climate Change (UNFCCC)´s adopted strategy for the reduction in greenhouse gas (GHG) from ships. The restrictions on the emission of pollutants [1] set by the regulation authorities (classifiers, international, European regulations) force the ship owners, operators, and all those related to the shipping industry to look for solutions to comply with the regulations with the most suitable solution. The decision to invest in a new fuel compliant with environmental factors is a complex process related to multiple criteria [2–5]. The analysis in [6] revealed the current degree of agreement amongst maritime stakeholders in the debate about the importance of multiple, and often conflicting, criteria for evaluating marine fuels; the top five most important criteria are regulatory compliance, life cycle GHG, fuel cost, air pollution, and occupational health and safety.

Sustainable alternative fuels under consideration are biodiesel, methanol, hydrogen, and ammonia. While the direction of the EU after LNG was to study hydrogen, mainly due to disadvantages such as highly cryogenic storage and low energy density, ammonia has also been recently studied as a shipping fuel. Ammonia was used commercially as early as 1921 [7], and the utilisation of ammonia as a fuel for Belgian motor-buses took place as early as 1943 [8]. As for any alternative fuel, there is a need for an entire supply chain to bolster confidence in its application and foster its adoption. Substantial investment will be required as zero-carbon fuels require the development of new solutions involving adopting new technologies, logistics, and operations. Although ammonia is a good option as a carbon-free fuel, it presents specific challenges in its use in practice. For instance, as fuel oil has a higher heating value (HHV) in the range of 42–47 MJ/kg [9] and liquid ammonia has a lower heating value (LHV) of approximately 18.8 MJ/kg [10], more storage space will be needed.

Motivated by the advantages of ammonia applications and the associated challenges, the NH3CRAFT project has been sponsored by European Commissions to develop a next-generation sustainable, commercially attractive, and safe technology for on-board long-term storage and transportation of NH3 fuel, as well as the use of ammonia as fuel for ships. It is expected that the project will develop new design solutions that will offer the feasibility of 1000 m^3 storage of liquid NH3 at a pressure of 10 bar and demonstrate it on a 31,000 Deadweight Tonnage (DWT) multi-purpose vessel.

In project management, particularly for complex initiatives such as the on-board long-term storage and transportation of ammonia as fuel for ships, a structured approach to Quality Function Deployment (QFD) is paramount for ensuring customer-driven product development and maximising customer satisfaction [11–14]. As an important part of NH3CRAFT, the work presented in this article aims at applying the Quality Function Deployment (QFD) method to evaluate the performance of the developed innovative on-board transportation and storage solutions of ammonia as a marine fuel. It forms the performance management framework for such an innovative solution in terms of sustainability and commercialisation [15–17]. Through this task, the project goal is interpreted in detail, and the development direction and priority are determined alone with the success criteria.

QFD is a structured approach to defining customer needs or requirements and translating them into specific plans to produce products to meet those needs. According to [18], the first phase of QFD, usually called House of Quality (HoQ), is of fundamental and strategic importance in the QFD system since it is in this phase that the customer's needs for the product are identified and then, incorporating the producing company's competitive priorities, converted into appropriate technical measures to fulfil the needs. This work presents the utilisation of the HoQ method as a means for inter-functional planning and communications among people with different problems and responsibilities, guiding them at the early stages of the project. The added value of this work is beyond the life of a project since it may provide assistance to the stakeholders in assessing the applicability of ammonia fuel solutions given the resources available to them. This feature will enable the justification of further investment into specific technologies based on their potential impact.

The first section describes the methodology used to carry out the evaluation of the project demonstrator and desktop studies, followed by the development of Key Performance Indicators (KPIs). The above analysis leads to the definition of requirements or technical functional characteristics to satisfy the customer needs. Lastly, the results of the QFD survey carried out for NH3CRAFT are presented and analysed.

2. Methodology

The HoQ [19], with the necessary modifications, is utilised in this project since it provides the means for inter-functional planning and communications among people with different problems and responsibilities (as is the case in this project). The simplest but most widely used HoQ model [18] contains the customer needs, "whats", and their relative importance. The product requirements "whats" (step 1) or needs, prioritised (step 2), lead to "hows"—technical characteristics to satisfy these needs (step 3). The "hows" and "whats" form a matrix which is a systematic means for identifying the level of relationship between each "what" and each "how" (step 5). Their relationships are measured by following a scale that assigns weights on the relationship. Weighting on the characteristics ("hows") (step 4) shows the difficulty involved in implementing the technologies. The numbers in the boxes of Figure 1, the House of Quality, refer to the model steps.

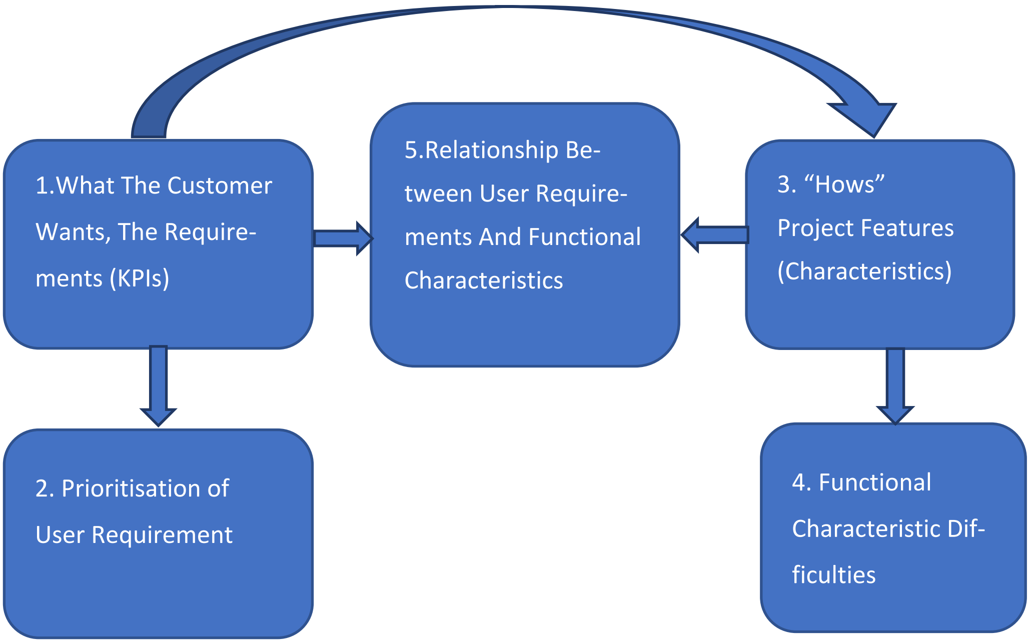

Figure 1. The House of Quality process.

A questionnaire was circulated (among the consortium members) for the purpose of recording the consortium's judgement on the prioritisation of the requirements, the weighting of the functional features' difficulty, and the relationship between user requirements and functional characteristics.

3. User Requirements

The user (project) requirements emerged from the project aim, and some were identified during the project's workshops. The required solution should have a decarbonising impact on shipping; suitability for a very large variety of vessels and operations; potential for the largest commercial uptake and the shortest transition period to a zero-carbon fleet; potential for standardisation; market readiness; and technical–economic justification and social acceptability(Table 1).

3.1. Decarbonising Impact on Shipping

Decarbonisation in shipping refers to strategies aimed at reducing the industry's carbon footprint to mitigate climate change impact. Short-term measures include technical and operational improvements under MARPOL Annex VI to lower carbon intensity. The industry is also exploring alternative fuels and new technologies for long-term solutions to remove greenhouse gas (GHG) emissions from the atmosphere, aligning with the Paris Agreement goals.

The IMO has set targets to reduce carbon emissions per transport work in international shipping. NH3CRAFT contributes to this effort by developing technology for storing and using ammonia onboard, which could eliminate CO_2 and SOx emissions while limiting NOx emissions. NH3CRAFT's goal is to lead a 50% reduction in annual GHG emissions from international shipping by 2050 compared to 2008 levels, ultimately aiming for the complete elimination of GHG emissions and air pollution from shipping.

MARPOL's Annex VI limits the main air pollutants contained in ships' exhaust gas, including sulphur oxides (SOx) and nitrous oxides (NOx), prohibiting deliberate emissions of ozone-depleting substances.

Greenhouse gases (GHGs) are a combination of various gases, with carbon dioxide (CO_2) being the most prevalent, and methane (CH_4) and nitrous oxide (N_2O) present in smaller quantities. Each of these gases contributes to global warming in a unique way. The contribution of each greenhouse gas is assessed by its Global Warming Potential (GWP), which measures the amount of energy that the emission of one tonne of a gas will absorb over a specific period relative to the emission of one tonne of CO^2. By using the IPCC values, which are used by the IMO [20], and the updated CO_2-equivalent factors (CO_2: 1; CH_4: 25; N_2O: 298), the environmental Key Performance Indicator (KPI) within the climate change impact category (*GWP*) is computed using equation [21]:

$$GWP = 1 \times ECO_2 + 25 \times ECH_4 + 298 \times EN_2O,$$

where E stands for the released emissions of a particular gas.

3.2. Suitability for Variety of Vessels and Operations

Ammonia storage should cover the needs of retrofits or new-build vessels, as well as the needs of different ship layouts and operational profiles.

Satisfying the user objectives provides the correct results with the needed degree of precision and facilitates the accomplishment of specified tasks and objectives.

According to ISO 25010, functional suitability represents the degree to which a product or system provides functions that meet stated and implied needs when used under specified conditions. This characteristic is composed of the following sub-characteristics [22]:

- Functional completeness—to the degree that the set of functions covers all the specified tasks and user objectives.
- Functional correctness—to the degree that a product or system provides the correct results with the needed degree of precision.
- Functional appropriateness—to the degree that the functions facilitate the accomplishment of specified tasks and objectives.

Although ISO 25010 itself may not be directly referenced in maritime research regarding ammonia fuel storage systems, the concept of functional suitability is relevant. It ensures that such systems are designed and operated to meet user needs and industry standards for safety and performance.

3.3. Potential for the Largest Commercial Uptake

The application of new technologies in the shipping industry, as well as the efficiency and cost of expanding known technologies for broad adoption by the shipping industry, are areas of uncertainty. The uncertainties linked to performance, cost, and the timely availability of technology often postpone solid strategic investment and decision-making within the industry. The optimal marine fuel is anticipated to be the option that offers the best combined performances in economic, environmental, and social aspects that aid in achieving the maritime decarbonisation objectives while acknowledging the speed of technological advancement and its dissemination [6]. EC legislative proposals and policy initiatives, the emission trading system, FuelEU Maritime for a green European maritime space, and the Energy Taxation Directive have an immediate relation with the maritime sector.

3.4. Potential for Standardisation

The standards ensure that goods or services produced in a specific industry come with consistent quality and are equivalent to other comparable products or services in the same industry.

Standardisation also helps in ensuring the safety, interoperability, and compatibility of goods produced. Some of the parties involved in the standardisation processes include users, interest groups, governments, corporations, and standards organisations [23].

The end users benefit from using off-the-shelf reliable product and design solutions for adopting ammonia as a marine fuel for both new building constructions and retrofit projects in the maritime industry, meeting different operational needs.

3.5. Market Readiness

Maturity of a new technology is not enough for commercial success without market readiness. Market readiness is about having the right products or services for the target customer. The market readiness level (MRL) measures the maturity of an emergent or real, but unmet need/demand in the envisaged market, considering the potential obstacles, e.g., industrial standards, competition, economic and societal resist [24]. Switching to the usage of low-carbon energy sources using alternative fuels and new technologies for the introduction of the proposed solution into commerce should overcome the obstacles.

The introduction of a developed technology to the market can be divided into nine Technology Readiness Levels (TRL), ranging from TRL 1—basic principles observed—to TRL 9—actual system proven in an operational environment [25].

The measurement of the market readiness level is carried out by checking if the criteria used to describe the level are fulfilled [26]. One method to evaluate the present and anticipated readiness level is to compare MRL and TRL by positioning them on a chart with MRL and TRL as the horizontal and vertical axes, respectively [27]. The proximity of their intersection to the chart's upper right corner indicates a greater degree of market or product readiness for commercialisation.

3.6. Technical Aspects

Although ammonia has long been known as a potential fuel, its use for the propulsion of vessels is a relatively new option; so, the technology is under development.

Technical factors that need to be evaluated include the following: 1. the necessity for fuel pre-treatment; 2. the adaptability of the engine to existing ships; 3. the impact on engine performance; 4. the influence on engine emissions; 5. the effect on components of the engine combustion chamber; 6. energy efficiency considerations; 7. the demand for maintenance; 8. durability (considering the long-term usage of alternative fuels); and 9. potential unexpected technical issues [28].

Existing technologies on retrofitting and new designs of ships for alternative fuels, including ammonia, are at a TRL 5 level. Our proposed technology of a "one-stop solution", by achieving TRL 7, incorporates all aspects for safe storage of ammonia in large vessels.

3.7. Economic Aspects

The decision to use ammonia as a fuel, in addition to the technical adjustments mentioned above, has economic consequences as well. The economic evaluation, apart from the fuel cost price (if considered individually, it is clearly more expensive), should include capital expenditure (CAPEX) for the systems needed (fuel preparation, auxiliary systems, after treatment systems); operating expenditure (OPEX), including emissions' treatment; and expenditure related to hazards and accidents (RISKEX).

The net present value (*NPV*) as an economic indicator, should be measured over the entire life cycle of the vessel (vessel's life of 25 years) for a discount rate (r) that corresponds to the current borrowing interest rate prevalent in the shipping industry. Equation (1) shows the Net Present Value (*NPV*).

$$NPV = \sum_{i=1}^{25} \frac{Cash\ Flow_i}{(1+r)^i} - Investment\ cost$$

The investment cost includes fuel preparation and auxiliary systems after treatment systems.

3.8. Socio-Political Aspects

Public acceptance for the use of ammonia as fuel is important as this will influence all stakeholders (producers, users, policy makers). This will be influenced by public perception and the development and observation of safety regulations, as well as the media [15].

Socio-political aspects that shall be taken into consideration are as follows [28]:

- Acceptance by society.
- Public sentiment.
- Support from policies.
- Support from government.
- Security of energy supply.

3.9. Health and Safety

This requirement helps companies measure the monetary costs of health and safety prevention efforts. Ammonia, a common cargo in gas carriers, has a long history in the shipping industry. Its handling procedures and safety measures are well-established due to extensive industry experience. The idea of utilising ammonia as a fuel would necessitate an expansion in operations and human engagement with it. This would call for the careful establishment of comprehensive and standardised training programs [29]. Health and safety issues that must be taken into consideration are the following ones [28]:

- Risk of explosion/fire due to flammability.
- Toxicity risks.
- Requirements for safe handling and storage.
- Safe usage and asset safety.
- Risk of occupational injuries.
- Need for staff training and workforce re-qualification.
- Impacts on public health.

Measures for securing health and safety could be lifesaving appliances, tank safety systems, crew training man hours, a number of leakage detection devices, safeguards in case of leakages, a number of leakage simulations, and a number of safety protocols.

Table 1. Requirements.

Requirement	Measuring	Target
Decarbonising impact of shipping	GHG emissions	At least 50% by 2050 compared to 2008
Suitability for variety of vessels and operations	ISO 25010 Functional Suitability Functional: completeness, correctness, appropriateness	Fit for a demonstrator, and 5 vessel types
Potential for the largest commercial uptake	Time for uptake and transition	Max commercial uptake Min transition period
Potential for standardisation	Number of multi-purpose transferable modular units	Max number of multi-purpose transferable modular units
Market readiness	Checking the criteria	Market testing and validation
Technical aspects	Technology readiness levels	Achieving TRL 7
Economic aspects	NPV could be calculated for a period of 25 years	Estimate economic values for the entire life cycle of a vessel discounted to today's value
Social acceptance	Aspect list	Measures for fulfilment
Health and safety	Aspect list	Measures for fulfilment

4. Technical Functional Characteristics

The project requirements "whats" or needs lead to "hows"—technical functional characteristics to satisfy these needs.(Table 2) In this section, the project solution is described in terms of engineering characteristics that are directly affected by customer perceptions. Ammonia has been transported as cargo in large quantities in gas carriers for some time; so, there is quite a lot of knowledge in dealing with properties like toxicity and corrosiveness, as well as fire and explosion. When using ammonia as a fuel, properties such as slow ignition, NOx and NH_3 slip, and emissions will require attention. Ammonia fuel shall be bunkered on-board, stored in a sufficient for the trip amount, be supplied and prepared through an appropriate system, and transferred into power. All the aforementioned functional features shall be designed considering safety rules, the protection of human lives, and with respect to the environment. The requirements in the IGC Code can therefore provide useful guidance on how to design fuel storage systems for ammonia. The IGC Code contains specific material requirements for ammonia fuel containment under Section 17.12 and these are expected to be applied in marine fuel storage tanks. In addition, the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) aims to minimise the risk to ships, their crews and the environment given the nature of the fuels involved.

4.1. Emission Reduction Compliance

In order to satisfy the user's requirement of decarbonisation of shipping in the long-term or mid-term by reducing GHG emissions to the atmosphere, the solution of emission reduction compliance is needed, as outlined in the International Gas Carrier (IGC) Code [30].

The set target of the project is to pioneer the reduction in GHG emissions by at least 50% by 2050 compared to 2008 and the eventual "elimination of total GHG emissions and air pollution" from shipping (zero-emission waterborne transport before 2050), remaining consistent with the Paris Agreement. IMO adopted a revised strategy to reduce greenhouse gas emissions from international shipping to net-zero by or around 2050. That makes ammonia an alternative fuel since it is carbon-free and sulphur-free. However, in internal combustion (IC) engines that burn ammonia, NH_3 slip occurs leading to concerns related to nitrogen oxide (NOx) and nitrous oxide (N_2O) emissions. The NOx and N_2O emissions are regulated by IMO (Regulation 13 of MARPOL Annex VI).

Therefore, the system designed by NH3CRAFT project should employ an optimum combustion strategy and concept to minimise NOx emissions and comply with the regulation. There are various well-established methods to reduce NOx emissions, which can be broadly categorised as fuel modification (e.g., using additive, etc.), the in-cylinder method (e.g., split injection, modification of nozzle diameter, etc.), after-treatment technologies (e.g., SCR (Selective Catalytic Reduction) to control NH3 slip and possible additional catalysis to control N_2O, etc.), or a hybrid system of the above [23]. All methods have pros and cons, and researchers in NH3CRAFT will need to review them in detail and make the decision by conducting a comprehensive comparison among them in terms of their efficiency, cost, technical maturity or suitability of implementation. This will be rated as 'Functional Characteristic Difficulties' during the HoQ survey.

4.2. Efficiency for the Operation

The quantity of fuel stored on-board shall offer adequate reserves in accordance with the voyage. The available energy stored in the fuel tank is transformed into useful work power measured in g/kWh. The amount depends on the operation at sea before it reaches the next bunkering station. That determines the fuel tank(s) volume.

The target volume set for the fuel tank of the demonstrator in this project is 1000 cubic metres. To achieve this target, the functional features to be considered will include the tank with appropriate capacity and its piping system, and the availability of the cargo space and its general arrangement, as well as the associated process safety management strategy. The difficulties in achieving such functional features will be reviewed during the HoQ survey.

4.3. Tank Integration On-Board

- In maritime vessel design, the strategic placement of fuel tanks is paramount to maintain operational efficiency while adhering to safety regulations. Fuel tanks can be situated on an open deck or within the hull, leveraging void spaces to minimise impact on cargo capacity. Compliance with MARPOL regulations dictates the permissible proximity of fuel tanks to the external hull.

- Efficient design seeks to minimise piping work and facilitate fuel system operations, particularly in dual-fuel scenarios, by positioning fuel storage in close proximity to Main Engine (M/E) consumers. Conversely, for safety and comfort, fuel tanks are placed as far from living quarters as regulations allow.
- Ammonia tanks, due to their hazardous nature, require careful consideration regarding their placement relative to ship and cargo operations. Mechanical protection is considered when ideal distancing is not feasible. The IGF Code provides guidelines for tank location, offering both deterministic (Section 5.3.3) and probabilistic (Section 5.3.4) approaches, with the latter often permitting closer proximity to the side shell—a common practice for LNG fuel tanks.
- The introduction of additional fuel tanks necessitates a thorough assessment of their impact on vessel stability and longitudinal strength. The dimensions and positioning of these tanks are critical factors that influence stability and may impose limitations on loading conditions.
- This comprehensive approach to tank integration ensures that vessel design not only meets regulatory compliance but also optimises operational functionality and safety.

4.4. Compliance with Technical Specifications

Ammonia is corrosive, and because of that, special attention is required for the infrastructure, employing materials to withstand corrosiveness. As regards compliance with technical specifications due to its corrosive nature, ammonia requires special consideration for infrastructure, and using materials that can resist corrosion. These principles are applied to the transport of anhydrous ammonia in carbon manganese steels under the IMO IGC Code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk)—refer to Section 3.2 of this report, issued in 1986.

The requirements applicable to cargo tanks, pressure vessels, and cargo piping systems include these constructional or operational measures to limit stress corrosion in carbon manganese steels: The steel should be fine-grained with a specified minimum yield strength of 355 N/mm^2 and with a maximum yield strength not exceeding 410 N/mm^2.

Moreover, one of the following constructional or operational measures should also be implemented:

- Use lower-strength material with specified minimum tensile strength not exceeding 410 N/mm^2 or post-weld stress relieving.
- Maintain the carriage temperature close to the boiling point of −33 °C, but never above −20 °C.
- Ammonia should contain not less than 0.1% w/w water.
- Furthermore, nickel steels containing more than 5% nickel are not suitable, which implies that the typical nickel steel materials used for storage of LNG containing 9% nickel are not appropriate for storage of anhydrous ammonia [29].
- Material selection is a very important task, as it will directly affect the technical efficiency, cost and safety performance of the developed system. However, it is also a challenging task as the decision has to be made considering a wide range of criteria. The level of difficulties in the selection process and its follow-on implementation will need to be rated during the HoQ survey.

4.5. Safety Regulation Compliance

The utilisation of ammonia as a marine fuel introduces significant safety considerations due to its toxicity and challenges in gas dispersion management. To safeguard the vessel and its crew, comprehensive system design reviews are imperative, utilising methodologies such as Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), or Failure Mode and Effects Analysis (FMEA). These assessments aim to pinpoint potential risks across various aspects of the system's operation.

- In the NH3CRAFT project, such evaluations will be conducted to recommend preventive measures or contingency plans to address identified risks. Recognised operational hazards include fire, explosion, toxicity exposure, hull corrosion, operational delays, equipment malfunctions, and gas leakage—a particularly critical failure mode.
- Components susceptible to gas leakage, such as bunkering manifolds, flange connections, tanks, pipes, valves, and gas engines not designed with a gas safety engine zone necessitate vigilant monitoring. Implementing protective measures like enclosing fuel pipes within ducts when passing through enclosed zones is one strategy to mitigate risks.
- Adherence to the IGF Code and classification society rules mandates the installation of safety systems including gas detection, fire detection and suppression, and emergency shutdown capabilities. Leveraging experience from liquefied gas carrier operations can provide valuable insights into specific storage, distribution, and personal protective equipment (PPE) requirements.
- Moreover, it would be advantageous to have experience with the transport of ammonia in liquefied gas carriers, including specific requirements for storage, distribution, and personal protective equipment (PPE). The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) offers some statutory requirements to guide its application on ships powered by ammonia.

An evaluation of cost, efficiency, technical reliability, suitability and feasibility of safety measures to be implemented will be considered as 'Functional Characteristic Difficulties' during the HoQ survey.

Table 2. Technical functional characteristics.

Characteristic	Unit	Target
Emission reduction compliance: GHG emissions, nitrogen oxide (NOx) and nitrous oxide (N_2O), NH3 slip	%	At least 50% by 2050 compared to 2008
Efficient for the operation	m^3	1000 (for the demonstration)
Tank integration on-board	m	As for the reference to Section 5.3.3 of the IGF code, it states that the ship's breadth/5 or 11.5 m from the side shell is the required distance. Section 5.3.4 mentions a distance of 0.8 m
Compliance with technical specifications: construction materials, withstanding corrosiveness	N/mm^2	ref. to IGF 355 < yield strength < 440
Safety regulation compliance		ref. to IGF

5. Implementing the QFD-Based Method for Evaluating a Project Solution

5.1. The HoQ Survey

In order to understand the customers' needs and determine the direction and priority of the project development, a relevant study has been conducted by implementing QFD-based method discussed above. This study was carried out via a wide-ranging survey using a questionnaire adjusted from the HoQ model introduced in the previous section. The respondents of this survey are members of the project consortium and external advisory board with various backgrounds, including engineering designers and consultancies, the IACS classification society, industrial partners and SMEs, ship management companies, and technical universities. In total, 26 questionnaire responses were collected and validated.

To summarise, the HoQ survey was conducted following five steps, as illustrated in Figure 2.

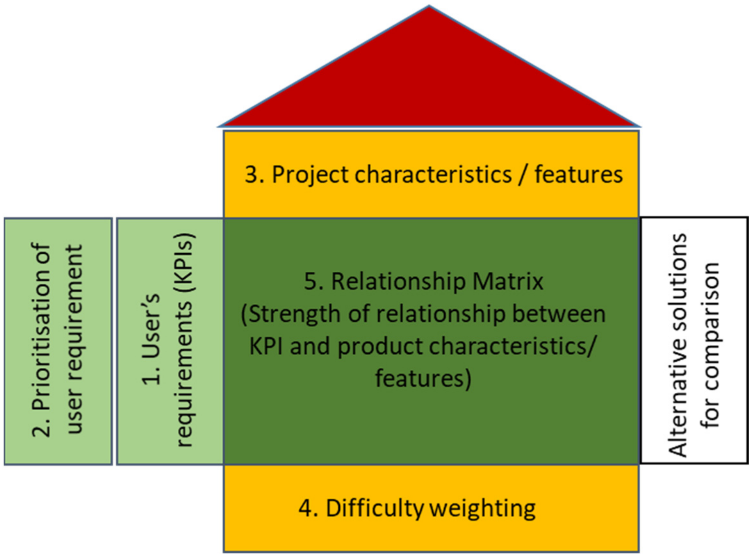

Figure 2. The adapted "House of Quality" [19].

- Step 1: Define user's requirements, i.e., the KPIs.

The success of the project is measured by the level of satisfaction of the user's requirements, i.e., the 'whats', the KPIs. These requirements are determined based on the project aim, the Grand Agreement and through discussions at the project's workshops. As discussed in Section 3, the KPIs from nine aspects were selected for this study, including the following:

- Decarbonising impact of shipping.
- Suitability for a variety of vessels and operations.
- Potential for the largest commercial uptake and the shortest transition period to a zero-carbon fleet.
- Potential for standardisation.
- Market readiness.
- Technical aspects.
- Economic aspects.
- Socio-political aspects.
- Health and safety.

- Step 2: Prioritisation of the user's requirements.

In this step, the weights for each KPI are assigned. Based on the importance level of each KPI, a weighting factor of 1 to 10 is rated by each respondent to prioritise the KPI from low to high.

- Step 3: Define project functional characteristics/features.

The KPIs can be achieved by developing relevant functional features, i.e., the 'hows'. As discussed in Section 4, these features to be considered are as follows:

- Emission reduction compliance.
- Efficient for the operation.
- Tank integration on-board.
- Compliance with technical specifications: construction materials and withstanding corrosiveness.
- Safety regulation compliance.

- Step 4: Determine the difficulties of functional features.

In this step, the difficulty levels of each functional feature defined in Step 3 are measured on a scale of 1 to 10, with 1 being the easiest and 10 being the most difficult. It is indicative of how difficult, costly, and technically feasible it is to deploy such a functional characteristic.

- Step 5: Develop the relationship matrix.

The strength of the relationship between user requirements and functional characteristics is shown in the crossing between the horizontal and vertical columns (Figure 3). A requirement could be related to more than one functional characteristic. The relationship was ranked on a scale of 1 (weakest) to 10 (strongest).

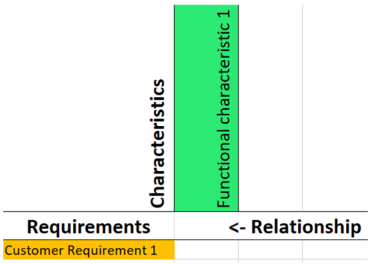

Figure 3. Relationship between user requirements and functional characteristics.

The data gathered from the above process were transferred to an excel worksheet to build an HoQ.

5.2. Result Presentation

The respondents of the survey are from different organisations and it is important to take into account their background when analysing the results. However, since there are a number of responses to the questionnaire from each category of the organisations and each answer is equally important, it was agreed among the consortium to use an average answer within each category of the organisation in terms of KPI-weighting factors and functional feature difficulty levels.

- Prioritisation of the users' requirements

The survey results of KPI prioritisation for different organisations are shown in Figure 4. As can be seen from the figure, decarbonisation is the most important KPI for all organisations except ship management companies, which gave more priority to economic considerations, and health and safety. Regarding the KPIs of health and safety, though their weight is not the heaviest, these are one of the top priorities for all organisations. This is in line with the project's main objective that the solution developed should be sustainable and reliable.

Moreover, ranking seems to vary among the partners. The decarbonising impact of shipping was shown at the first place by the IACS Classification Societies with an average score of 10, followed by suitability for a variety of vessels and operations, which was depicted firstly by the IACS Classification Societies with 9.5. Furthermore, the potential for the largest commercial uptake and the shortest transition period to a zero-carbon fleet was presented firstly by the IACS Classification Society with 8.5. The potential for standardisation was depicted firstly by the IACS Classification Society with 8. Market readiness was shown at the first place by the Engineering Designers and Consultancies with 8. Furthermore, technical aspects came at the first position by the Industrial Partners and SMEs, with 8.75. Moreover, economic aspects were depicted firstly by the Ship Management Companies, with 9. Socio-political aspects were depicted firstly by Technical Universities, with 7.8. Lastly, health and safety was shown by ship management companies in the first place, with 9.5.

In addition, considering all respondents as a whole, an average ranking of each KPI can be seen in Table 3 below.

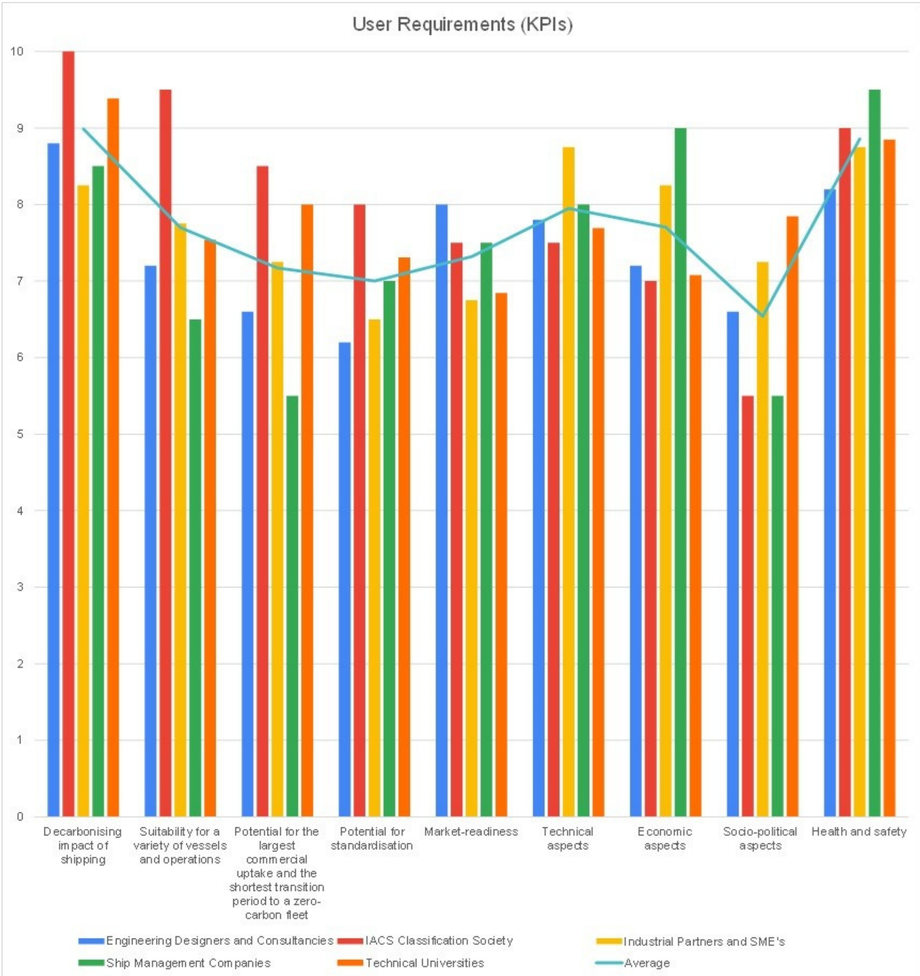

Figure 4. Requirement prioritisation by the NH3CRAFT consortium members.

Table 3. Average rating of the importance level of each KPI.

KPIs	Importance
Decarbonising impact of shipping	9
Suitability for a variety of vessels and operations	8
Potential for the largest commercial uptake and the shortest transition period to a zero-carbon fleet	8
Potential for standardisation	7
Market readiness	7
Technical aspects	8
Economic aspects	7
Socio-political aspects	7
Health and safety	9

- Functional Characteristics' Difficulties

The difficulties involved in implementing the project characteristics were scored from 1 to 10 (1 being less difficult) by the partners in order to indicate how difficult, technically feasible and costly it is to deploy each functional characteristic (Figure 5).

Overall, most organisations viewed safety regulation compliance as the most difficult feature to implement. However, for ship management companies, the hardest task is tank integration on-board.

Similar to KPI prioritisation, difficulty ranking also varies among the partners. The IACS Classification Society rated emission reduction in the first place, with a score of 9.5. Engineering designers and consultancies considered the efficiency of the operation as the hardest task, with a score of 7.8. Tank integration on-board was presented firstly by the ship management companies with 9.5, while compliance with technical specifications was depicted firstly by the IACS Classification Society, with 10.0. Safety regulation compliance was rated by IACS Classification Society in the first place, with 10.0.

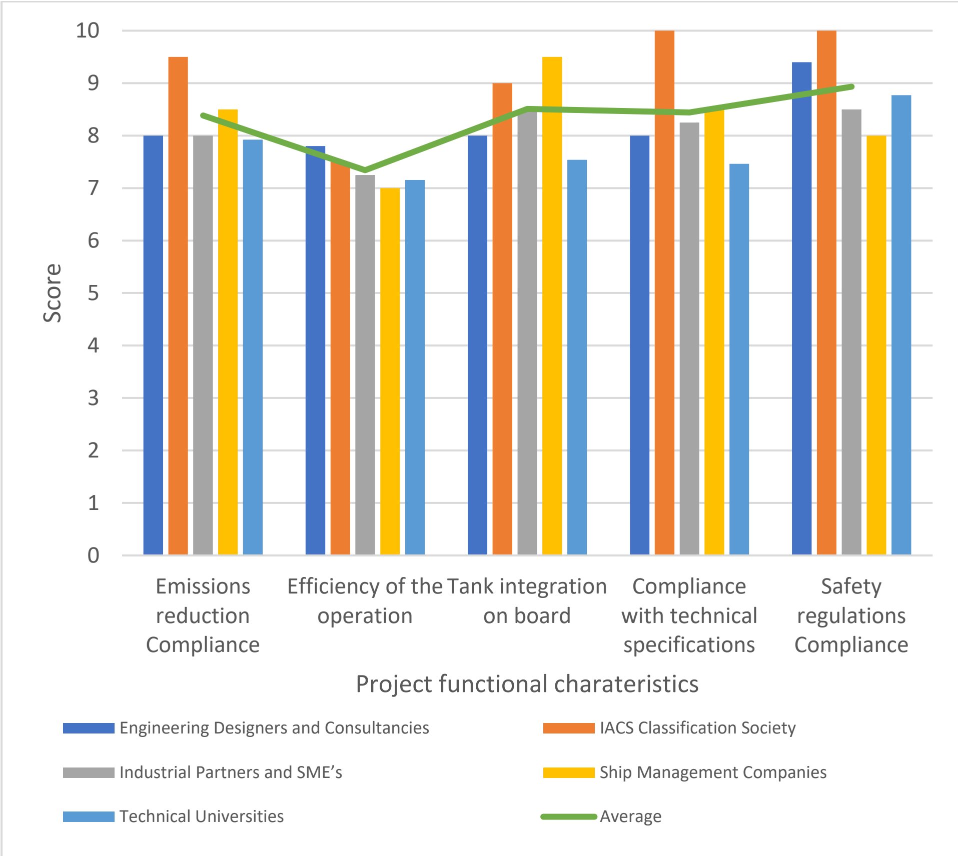

Figure 5. Difficulties involved in implementing the project characteristics.

Considering all respondents as a whole, on average, the hardest functional characteristics to implement was safety regulation compliance, with a score of 8.9. Tank integration on-board came next, rated 8.5. Emission reduction compliance and compliance with technical specifications were shown with 8.4, and, lastly, the efficiency of the operation was depicted with a score of 7.3.

- Relationship between User Requirements and Functional Characteristics

The relationship between user requirements and functional characteristics was marked in the crossing between the horizontal and vertical columns. Some cases appeared with more than one relationship between requirements and characteristics. The relationship was ranked on a scale (1–10).

It was noted that, as shown in Figure 6, the relationship between user requirements and functional characteristics in terms of decarbonising impact of shipping (from highest to lowest) was the following: emission reduction compliance had a score 9, safety regulation compliance had 4, compliance with technical specifications had 3, and the efficiency of the operation had 2.

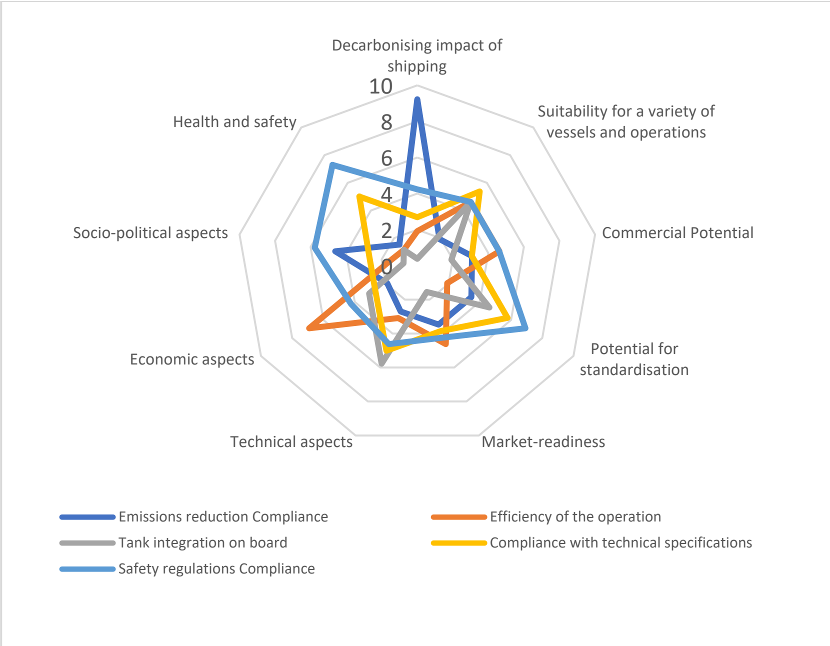

Figure 6. Relationship between user requirements and functional characteristics.

Regarding suitability for a variety of vessels and operations, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: efficiency of the operation, tank integration on-board, and compliance with technical specifications with 5; safety regulation compliance with 5; and emission reduction compliance with 2.

As regards the commercial potential efficiency of the operation, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: safety regulation compliance with 5, emission reduction compliance with 3, compliance with technical specifications with 3, and tank integration on-board with 2.

As far as the potential for standardisation is concerned, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: safety regulation compliance with 7, compliance with technical specifications with 6, tank integration on-board with 5, emission reduction compliance with 3, and efficiency of the operation with 2.

Regarding market readiness, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: efficiency of the operation with 5, compliance with technical specifications with 4, safety regulation compliance with 4, emission reduction compliance with 3, and tank integration on-board with 2.

As for the technical aspects, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: tank integration on-board with 6, compliance with technical specifications with 5, safety regulation compliance with 5, emission reduction compliance with 3, and efficiency of the operation with 3.

As far as economic aspects are concerned, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: efficiency of the operation with 7, safety regulation compliance with 4, tank integration on-board with 3, compliance with technical specifications with 3, and emission reduction compliance with 2.

Regarding socio-political aspects, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: emission reduction compliance with 6, efficiency of the operation with 5, safety regulation compliance with 3, tank integration on-board with 2, and compliance with technical specifications 1.

Finally, regarding health and safety, the relationship between user requirements and functional characteristics (from highest to lowest) was the following: safety regulation compliance with 7, compliance with technical specifications with 5, emission reduction compliance with 2, efficiency of the operation with 1, and tank integration on-board with 1.

5.3. Result Analysis and Recommendations

In light of the results outlined in the preceding section, the technical importance score can be calculated and the priority for improvement can be ranked using the Multi-Attribute Utility Theory (MAUT). This can provide decision-makers with supportive information to direct the project development and prioritise their resource allocations.

The technical importance score of each functional feature is calculated considering its relationship with each KPI and the importance weighting of such KPI, using the equation below:

$$S_i = \sum w_k \times r_i^k \quad (1)$$

where S_i is the technical importance score of the ith technical feature to calculate. w_k is the weights of the kth KPI and r_i^k is the relationship score between ith technical feature and kth KPI. The evaluation results are shown in Table 4. As can be seen, all organisations agreed that the safety regulation compliance is the most important functional feature to implement, while tank integration on-board is the lowest. The score rated for other functional features varies among different respondent categories.

Table 4. The technical importance score for each functional feature.

	Emission Reduction Compliance	**Efficiency of the Operation**	**Tank Integration On-Board**	**Compliance with Technical Specifications**	**Safety Regulation compliance**
Engineering Designers and Consultancies	243	234	179	273	344
IACS classification society	263	255	200	301	378
Industrial partners and SMEs	248	246	193	285	362
Ship management companies	238	236	184	278	349
Technical universities	260	242	188	289	370
Average	**250**	**243**	**189**	**285**	**360**

However, only considering technical importance is not sufficient to make the final decision in terms of project development direction and resource allocation. The difficulty level of implementing each functional feature should also be taken into account. The hardest task may require more resource allocation, such as time, budget, or labour, etc. In other words, this is a multi-criteria decision-making process where the MAUT model can be applied to resolve the disparate units into utility or value, hence becoming comparable [24].

The MAUT comparison results can be seen in Table 5. Accordingly, it can be recommended that development should be prioritised with more resource allocation to implement functional features associated with safety regulation compliance. This is a common view among the respondents from all participating organisations. The lowest in the ranking is tank integration on-board. Although tank integration was considered a difficult task for ship management companies and other industrial partners, it does not have a very strong relationship with the users' requirements; hence, it received a low score in this MAUT assessment. The MAUT score calculated for other functional features varies among different respondent categories.

Table 5. The MAUT score for each functional feature.

	Emission Reduction Compliance	Efficiency of the Operation	Tank Integration On-Board	Compliance with Technical Specifications	Safety Regulation compliance
Engineering Designers and Consultancies	19.3	18.7	16.7	20.4	24.9
IACS classification society	19.7	17.3	16.9	21.6	24.4
Industrial partners and SMEs	19.2	18.2	17.7	20.9	24.1
Ship management companies	19.5	17.6	18.6	21.1	23.2
Technical universities	19.8	18.2	16.7	20.3	25.0
Average	**19.5**	**18.0**	**17.3**	**20.9**	**24.3**

6. Conclusions

The decision to invest in a new maritime fuel due to environmental factors is a process related to multiple criteria. A next-generation sustainable, commercially attractive and safe-for-tank-incorporation technology for high-quantity on-board storage of ammonia as a marine fuel is a complex process involving many factors that need be taken into consideration. The project's respondents comes from different backgrounds; so, a structured approach is needed to achieve common perceptions.

This article presents a structured approach to carry out the Quality Function Deployment method for evaluating the project demonstrator and desktop studies for the best options of ammonia storage on-deck or/and hull-integrated for retrofits or newly built vessels, covering the needs of different ship layouts and operational profiles providing fuel either for on-board production of hydrogen or for direct fuel cell supply or internal combustion engines. The application of the Quality Function Deployment for alternative arrangements will offer a method for comparing different potential solutions.

The applied Quality Function Deployment defined requirements and assisted in transforming them into specific plans to meet those needs. The obvious requirements for meeting environmental regulations are techno-socio-economic. Apart from those, the project's solution, with respect to health and safety issues, shall have the greatest decarbonising impact in shipping; suitability for a very large variety of vessels and operations; potential for the largest commercial uptake and the shortest transition period to a zero-carbon fleet; potential for standardisation; and market readiness. The ranking of perceived difficulty involved in implementing the technologies and the relationship between requirements and functional technical characteristics allows the consortium partners to focus on the most crucial aspects. A feasible solution has to include health and safety aspects as the main requirements, within the regulatory framework or even beyond it, in order to gain social acceptance.

The aforementioned requirements of the intended solution were weighed by the team members in order to highlight the importance assigned to each requirement. All requirements were weighed 7 and above (on a scale of 1–10) in the questionnaire, indicating the high importance attributed to these by the consortium partners. Beyond the impact of decarbonisation, significant weight was attributed to health and safety aspects, showing that attention needs to be paid to these issues. The most important requirements to be considered are technical and financial, and the suitability for a variety of ships and operations.

The main requirements expected to be met, apart from the contribution to GHG reduction (emissions lowered by at least 50% by 2050 compared to 2008 and the eventual "elimination of total GHG emissions and air pollution"), are advancing (by verification and validation of the developed technologies) from TRL 5 to TRL 7.

The project requirements led to technical functional characteristics to satisfy these needs. In order to meet the requirements, the project consortium determined the technical functional characteristics for the project's solution. These were grouped in emission reduction compliance, efficiency for the operation, tank integration on-board, compliance with technical specifications, and safety regulation compliance. Although these are the main groups of functional characteristics, they can be further analysed in relation to specific targeted features. Sources of such data specifically for the case of liquid ammonia as a marine fuel are scarce, but there are data available from other transport sections and storage solutions for other uses. Also, regarding design and safety in the shipping sector, regulations apply in accordance with the IGC/IGF code, and gradual published appendices from the Classification Societies.

Considering all decision-making criteria comprehensively, this QFD recommended that more attention should be paid to improve the functional features associated with safety regulation compliance, followed by activities related to compliance with technical specifications, emission reduction compliance, efficiency of the operation, and, lastly, to tank integration on-board.

The benefits of this work are beyond the life of the project, which will assist the stakeholders to assess the applicability of NH3CRAFT solutions given the resources available to them. This feature will enable the justification of further investment into specific technologies based on their potential impact.

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