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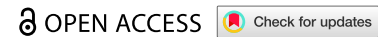


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RESEARCH ARTICLE



Evaluating the functional requirements of novel insulation systems for liquid hydrogen storage tanks using quality function deployment

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ABSTRACT

Beyond thermal performance, the long-term viability of novel cryogenic insulation technologies is contingent upon several factors, such as low cost, durability, minimal or no maintenance, among others. Therefore, finding the optimal insulation concept involves trade-offs among these attributes, especially during early development stages. To assess the functional requirements of novel insulation materials and concepts, this paper presents a systematic approach based on the Quality Function Deployment (QFD) method. A simplified House of Quality (HoQ) model, representing the first phase of QFD, was used to propose and link technical features that meet the identified needs of customers. A survey-based approach was employed to populate the HoQ, leading to the identification of eighteen functional requirements and twenty-two technical features, which were subsequently ranked by the respondents' perceived level of their importance. The results from this study provide a structured decision-support framework and an integrative list of requirements to support improvements in insulation system design. Furthermore, the study proposes strategies for optimizing the development of next-generation hydrogen storage technologies.

ARTICLE HISTORY

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Insulation requirements;
novel insulation concepts;
quality function deployment;
sustainable product design

1. Introduction

Continuous requirements for zero emissions from exhaust gases have intensified the exploration of fossil-fuel alternatives, such as hydrogen. Hydrogen is a non-toxic gas that does not directly contribute to the greenhouse effect (Sand et al. 2023). In its free form, it can be stored and transported either as a pressurised gas or a cryogenic liquid. The cryogenic form, known as liquefied hydrogen (LH₂), is often the focus of discussion due to its higher volumetric energy density. However, the inherent requirement to maintain it at a low temperature of −253 °C presents a major challenge. Because of the substantial temperature difference between liquid hydrogen and the surrounding environment, it must be stored and transported in thermally insulated tanks to prevent costly boil-off losses (Okpeke et al. 2024; Peschka 1992). Consequently, the development of advanced liquid hydrogen tank technologies is necessary to safely and efficiently minimise evaporation under all operational conditions.

Current high-performance LH₂ storage tanks are based on the Dewar design principle, featuring double-walled structures with the space between the walls filled with insulating material under vacuum. The combination of vacuum and insulating material, known as superinsulation, reduces heat transfer through conduction, convection, and radiation (Fesmire 2015; Lisowski and Lisowski 2018). In addition to minimising heat transfer, insulation also prevents condensation and solidification of atmospheric gases on LH₂ tanks, which can cause corrosion (Mital et al. 2006). Various types of insulation used in cryogenic equipment, such as expanded foams, gas-filled powders, and fibrous materials, as well as vacuum alone, evacuated powders and fibrous materials, opacified powders, and multilayer insulations, are discussed in (Barron 1985). Recent studies have examined various aspects of cryogenic insulation for liquid hydrogen storage tanks. For instance, Yin et al. reviewed key technologies and future development of insulation structures for these tanks, highlighting advancements in insulation materials and designs, and categorising them into passive thermal protection and active thermal transfer technologies (Yin, Yang, and Ju 2024).

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New insulation concepts, such as variable-density multilayer insulation (VD-MLI) combined with spray-on foam insulation (SOFI), aerogels, nanocellular foams, or hybrid solutions, are currently being studied. Additionally, extensive research has compared new insulation systems, including multilayer vacuum insulation (MLVI), variable-density multilayer insulation (VD-MLI), multilayer insulation with vapour-cooled shield (MLI + VCS), VD-MLI with vapour-cooled shield (VD-MLI + VCS), and micro-sphere insulation (Aceves, Berry, and Rambach 1998; Hedayat, Hastings, and Brown 2002; Martin and Hastings 2001; Zheng et al. 2019). Moreover, research and innovation projects are exploring various aspects of cutting-edge insulation concepts, such as gas-filled panels (Griffith, Turler, and Arasteh 1993; Mills and Zeller 2008), vacuum insulation panels (VIPs) for liquid hydrogen tanks (NICOLHy), and potential future nanotechnology-based insulation materials like vacuum insulation materials (VIM), gas insulation materials (GIM), and nano insulation materials (NIM) (Jelle, Gustavsen, and Baetens 2010). Although these superinsulation materials provide superior thermal performance, fire resistance, and space savings, they are challenging to produce and install, require more energy during manufacturing, are costly, and pose environmental concerns (Ali, Issa, and Elshaer 2024). Therefore, selecting a suitable insulation for a specific application involves balancing factors such as cost, ease of application, weight, durability, and thermal performance, among others.

Insulation failure can have several adverse effects. It can increase heat transfer into cryogenic vessels by about a factor of 100, potentially causing rapid pressurisation and venting of the cryogen to prevent exceeding the maximum allowable working pressure (MAWP) (Moreno-Blanco et al. 2018). Cases of perlite pulverisation and MLI's sensitivity to thermal shock and vibration, which can cause insulation degradation and potentially create cold spots, have been reported by NASA (Fesmire 2017) and (3M). Vacuum degradation, which compromises the superinsulation of liquid hydrogen tanks, can increase heat transfer, leading to pressure buildup and rupture of the burst disc (Zalosh et al. 1978). Therefore, thermal insulation systems must possess specific properties and meet certain requirements. Jelle (2011) have examined and compared various properties of insulation materials and solutions, primarily in the building sector. A review of thermal insulation materials for energy conservation in buildings was conducted by Ali, Issa, and Elshaer (2024), who highlighted factors affecting thermal performance and key considerations for selecting insulation systems. Le Duong et al also provided an overview of factors influencing the thermal conductivity of building insulation materials, noting that moisture content, temperature difference, and bulk density are the most common determinants (Hung Anh and Pásztor 2021). Kumar et al. conducted a study comparing the properties and performance of building insulation materials across different climate zones. They proposed an optimisation framework based on energy, environmental, economic, and comfort criteria (Kumar et al. 2020).

For liquid hydrogen, insulation system requirements are more stringent than in the building sector due to its cryogenic nature. Liquid hydrogen storage insulation operates under extremely low temperatures, necessitating materials with very low thermal conductivity that remain mechanically and chemically stable. In contrast to building insulation, performance is directly linked to boil-off losses, making thermal efficiency crucial for both process safety and economic viability. Existing literature offers limited insights into the specific requirements for insulation materials and concepts used in liquid hydrogen storage vessels. Therefore, this study aims to contribute to the development of an integrative set of requirements for insulation materials used in liquid hydrogen storage. It provides an extensive overview of key considerations in selecting and designing insulation materials and concepts for liquid hydrogen tanks from technical, economic, and environmental perspectives.

To achieve this, the first phase of the Quality Function Deployment (QFD) method, known as the House of Quality (HoQ), is employed. The QFD approach is a customer-driven quality management system used in product development. A detailed review of the QFD approach is documented in (Chan and Wu 2002; Griffin and Hauser 1993). QFD has been applied across various industries, with essentially no specific prerequisites regarding the types of products/services or the organisations that use it (Chan and Wu 2002). In effect, its application is not bound to any particular industry. Consequently, this study contributes to the extension of the Quality Function Deployment (QFD) method to liquid hydrogen technologies, incorporating sustainability-related considerations. The study provides an early-stage decision-support tool that can guide material/concept selection or design before further data-intensive analyses can be performed. In addition, sensitivity analysis is incorporated to assess the robustness of the findings. To inform the QFD framework, an exploratory sample

was carried out using purposive sampling and a structured survey instrument. The study sample consisted predominantly of researchers specialising in the design and analysis of insulation systems and LH₂ storage tanks. Accordingly, the findings and interpretations presented in this work are grounded in the perspectives and expertise of these professionals.

2. Method description and study design

This study employs the first phase of the Quality Function Deployment (QFD) method, known as the House of Quality. Data for the HoQ analysis are collected through a structured questionnaire designed to gather input on relevant functional requirements. The responses are systematically analysed to support informed decision-making when prioritising functional specifications for new insulation solutions in liquid hydrogen storage tank applications. The following subsections detail the QFD framework, the construction of the HoQ, and the design and implementation of the survey instrument.

2.1. Quality function deployment (QFD)

QFD is a systematic method for identifying customer needs or requirements and turning them into specific plans to develop products that meet those needs. It is a customer-focused process that transforms customers' demands into product features, ultimately resulting in technical specifications and actions. It significantly reduces the time required for new product development by addressing customer concerns early. QFD is also valuable for identifying and prioritising key areas where quality technology, and engineering effort should be focused. It helps recognise conflicting design requirements and tradeoffs, making it a useful planning tool. Usually, it is divided into four phases: product planning, part deployment, process planning, and production planning. These phases follow a sequential, waterfall-like order (Bahill and Chapman 2015; King 1989). However, not all four phases are necessarily used in every QFD model, and the starting or ending point can vary depending on the project. This study focuses on the product planning phase, commonly known as the "House of Quality".

2.2. The "house of quality" (HoQ) model

The HoQ model proposed by G. Delano (1997) is modified and used in this study, as it contains the commonly used HoQ elements. The simplified model (Figure 1) is used as the basis for assessing the functional requirements of novel insulation materials or concepts, and can be further expanded to serve as a benchmarking approach. Aspects relating to competitive assessment, correlation matrix, and performance targets are

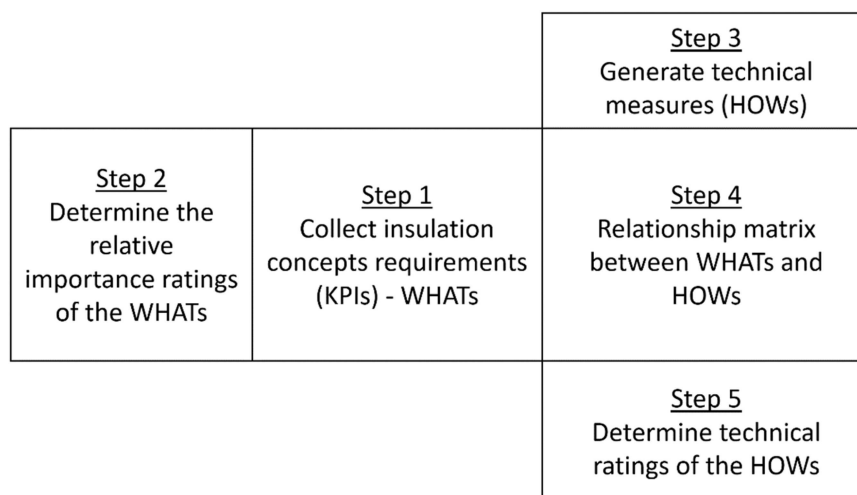


Figure 1. Modified house of quality model.

exempted, as it is both challenging and unnecessary to include all the HoQ elements (Chan and Wu 2005). However, this does not mean they are unimportant in the HoQ process; rather, it helps to prevent inconsistencies.

As shown in Figure 1, the modified HoQ entails the provision of the following elements:

- Customer needs (WHATs): These entail a description, in the customer's own words, of the benefits to be provided by a product or service (Griffin and Hauser 1993). They include customer desires, expectations, and product or service specifications or requirements. In this study, they represent the functional requirements of novel insulation systems that could serve as key performance indicators (KPIs). It is important to note that customers are not only the purchasers/end users but also shareholders, managers, wholesalers, among others. In this study, customer needs, which represent their specifications and requirements for an insulation material or concept, were gathered through a survey.
- Importance ratings of customer needs: Certain customer needs are of higher priority than others. Prioritising customer needs involves assessing their relative importance as perceived by customers. These priorities help in making trade-offs between the cost of meeting a need and the desirability of fulfilling it. Considering the varying degrees of importance, the average relative importance ratings (W_n) of customers' needs can be calculated using Equation (1).

$$W_n = \sum_{k=1}^K W_{nk}/K, \quad n = 1, 2, \dots, N \quad (1)$$

where N and K denote customer needs and the number of customers, respectively.

- Engineering characteristics (HOWs): These are the design attributes or specifications of a product or service that, if altered, could influence the customer's perception. They provide guidance on meeting customers' needs and describe the product or service in measurable, quantifiable terms. These characteristics are also known as quality characteristics, technical measures, functional features, or design characteristics. They are derived from current product standards or selected through cause-and-effect analysis to ensure that the HOWs are primary causes of the WHATs (Hauser and Clausing 1988). In addition, the measurement units and directions for improving these engineering characteristics should also be established.
- Relationships between WHATs and HOWs: The relationship matrix is a systematic way of showing which engineering characteristics (HOWs) influence specific customer needs (WHATs) and to what extent. The strength of these relationships is typically assessed by analysing how well the product or service features align with and address customer requirements.
- Technical importance ratings of the engineering characteristics (HOWs): This is the main output of the HoQ process. It represents the significance of each engineering characteristic in enhancing overall customer satisfaction. The importance rating of the engineering characteristics (H_j) is computed using the following simple additive weighting (SAW) formulation in Equation (2).

$$H_j = \sum W_n r_{nj} \quad (2)$$

where W_n represents the score for each customer's needs, and r_{nj} denotes the strength of the relation matrix. The summation is carried out over all customer/user needs (WHATs).

2.3. Scaling

In the HoQ, the relative importance of the customers' requirements (WHATs) and the relationship matrix between the customers' requirements and the engineering characteristics are quantified. Different scoring systems have been reported in various studies (Akao 2004; Cohen 1995; Day 1993; Griffin and Hauser 1993; Guinta and Praizler 1993; Hauser and Clausing 1988). The unification of the multiple scales used in the HoQ is essential to operating the HoQ process and making calculations comparable. The question of

interest here is: what scale applies to the importance scores for customer demands, and the scoring system used in the relationship matrix. In this study, the following scales are adopted:

- **For measuring the relative importance of WHATs:** A 9-point scale with a 5-point Likert subscale, shown in Figure 2, is used to measure the relative importance of customers' requirements.
- **For measuring the relationship between each WHAT and each HOW:** A 9-point scale using a 6-point Likert subscale, as shown in Figure 3, is adopted to measure the relationship matrix between customers' requirements and engineering characteristics.

2.4. Data collection

Purposive sampling technique was applied in this study to generate an exploratory sample. This approach is adopted because it is suitable for suggesting requirements for a new product or gathering information to explore a new area (Johannesson and Perjons, 2014). An exploratory sample does not necessarily have to be statistically representative of an entire population; rather, it may comprise a small number of individuals that can provide valuable information. The objective here was to identify a group of individuals with a special interest in novel insulation systems who could provide substantive insights into insulation requirements. To this end, a Microsoft Forms questionnaire was created to collect the information needed to conduct a QFD analysis of an insulation system using the HoQ framework.

The preliminary lists of functional requirements (customer requirements) and engineering characteristics required for the questionnaire were predefined through a structured process. First, a thorough analysis of the body of research on insulation materials, industry design guidelines, and specifications relevant to liquid hydrogen storage systems was conducted. This ensured the initial inclusion of all essential performance, safety, and sustainability considerations. Second, these preliminary lists were reviewed by subject-matter experts, whose input helped improve them and ensure that all requirements were relevant. Lastly, the lists were compared to practical engineering constraints, including manufacturing and installation feasibility, cost implications, and operating and maintenance requirements. This procedure resulted in a final set of functional requirements and engineering characteristics that are comprehensive and grounded in engineering practice, thus providing a robust basis for the QFD analysis. A pilot test was then carried out with a small group of respondents to assess the questionnaire's clarity and usability. Minor changes were made to the language structure and consistency in response to the feedback received. The final version of the questionnaire was then distributed to participants for data collection.

The respondents, who have expertise in insulation materials and liquid hydrogen storage, were tasked with evaluating the customer demands based on their perceptions of the relative importance. They were further asked to write and rate any additional customer demands they considered necessary for the insulation material or concept. The respondents were also instructed to rank the relationship between the

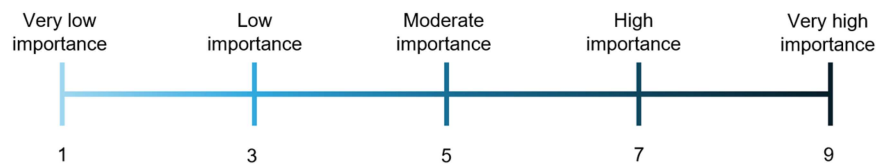


Figure 2. Adapted scoring system for customers' needs.

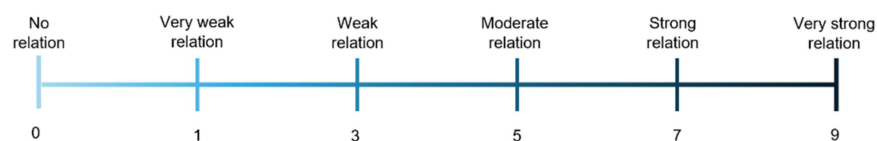


Figure 3. Adapted scaling for the relationship matrix.

predefined engineering characteristics and the insulation concept requirements. Lastly, they were asked to add any other engineering characteristics they believe are necessary and that, if altered, would impact the insulation concept requirements. To ensure the rankings are robust and reliable, a sensitivity analysis was conducted. It is important to note that using predefined customer requirements and engineering characteristics in the survey could introduce selection bias, potentially underrepresenting certain priorities, especially those that are context-specific or emerging. To address this, respondents were encouraged to comment on the lists, facilitating the identification of missing requirements.

To minimise potential bias, responses were collected anonymously. An excerpt of the questionnaire can be found in the Appendix. It is important to note that participation in the survey was voluntary, and respondents were informed of the study's purpose; thus, completion of the questionnaire was taken to imply informed consent. Furthermore, no institutional ethical review was considered for this research, as the QFD survey is considered low risk and non-sensitive, and no vulnerable population was included. That notwithstanding, the principles of voluntary participation, informed consent, privacy, and confidentiality were adhered to.

3. Results and discussion of findings

This section presents the study's findings on the functional requirements of new insulation systems for liquid hydrogen storage tanks. The section begins with an analysis of the survey feedback, followed by a brief description of the identified customer requirements and engineering characteristics. Additionally, the populated HoQ is shown as a heat map, from which the importance ranking of customer requirements and engineering characteristics is presented.

3.1. Survey feedback

The study sample comprised 35 respondents, of whom 24 responded and were analysed. This represents a satisfactory response rate (68.57%), given that approximately 20–30 respondents are sufficient to capture 90–95% of customer requirements (Griffin and Hauser 1993). The respondent pool consisted largely of researchers (91.7%), with a small proportion of shipyard engineers (8.3%). Regarding their research experience in insulation system design, almost half of the respondents are involved in the design and analysis of energy- and cost-efficient tank insulation for large-scale LH₂ tanks (45.8%), while the majority have experience in LH₂ storage tank research (87.5%).

The respondents were selected based on their scholarly contributions through peer-reviewed publications, funded research projects, or at least 2 years of research and/or teaching experience in fields such as insulation technologies, heat transfer, cryogenics, energy systems, and/or materials engineering. This approach ensured that the participants possessed the necessary expertise to provide informed assessments. Using an academic expert panel is consistent with previous QFD-based studies in which domain knowledge and analytical rigour are essential in evaluating design requirements in the absence of standardised quantitative data (Akao 2004).

The data obtained from the respondents were subsequently used to develop the HoQ in the next subsection. It should be noted that the participants' backgrounds could have some bearing on the results obtained in this study. This is because the weightings may be biased more towards theoretical performance parameters, given the academic backgrounds of most participants. To mitigate this effect to some extent, a sensitivity analysis was performed.

3.2. House of quality (HoQ)

The populated HoQ is shown in Figure 4. It includes the customers' requirements, their importance ratings, the engineering characteristics, the relationship matrix between customers' requirements and engineering characteristics, and ultimately the importance ranking of these characteristics. A colour scheme is used for the ratings, and shown as a heat map, with dark green indicating very high values and red very low values. Figure 4 also shows the engineering characteristics that most significantly influence customer requirements. This information is read across the row of the table. For example, the

Customer importance rating	Design/Engineering Characteristics (How's) →	Material (selection) Index	Resource use	Fire resistance rating	Water/gas absorption rate	Thickness	Deformation	Elasticity/bending stiffness	Mean time to repair (MTTR)	Rupture force	Amount of waste	Recycling rate	Environmental impact	Weight/density	Thermal conductivity	Total addressable market (TAM)	Lifespan	Cycle times	Cost of production	Technology readiness level	Market readiness level	Selling price	Regulatory compliance rate
	Customer/User Requirements - (What's) ↓																						
8.3	Effective thermal insulation	8.5	4.2	4.8	6.2	8.5	4.7	3.2	2.5	3.7	3.2	2.6	4.0	5.0	8.9	1.1	5.2	1.1	3.6	4.0	1.3	4.9	4.7
7.2	Fire resistant	8.0	3.2	8.2	4.1	5.5	4.4	3.0	2.1	4.0	3.2	2.5	5.0	4.7	5.0	2.4	4.8	2.2	3.8	3.3	3.4	4.2	6.7
7.3	Durability & long service life	8.0	5.0	4.6	5.2	5.0	6.5	5.6	5.3	6.1	5.0	5.1	5.9	3.1	4.0	3.6	8.8	3.4	5.5	4.2	4.7	5.4	5.2
6.8	Cost-effective	7.8	5.9	3.7	2.7	6.6	2.8	3.2	5.4	4.1	4.8	6.3	4.4	4.8	5.2	7.5	5.1	4.5	8.8	4.6	6.2	8.1	2.4
4.9	Ease of manufacturing & installation	6.1	4.0	1.9	2.0	5.4	3.3	3.8	5.2	2.9	4.2	3.3	3.5	5.0	2.1	3.4	3.7	6.7	5.2	5.5	5.2	5.6	3.3
5.3	Circular/sustainable material and operation	7.6	7.3	3.1	2.5	3.6	2.2	2.0	3.2	2.5	8.4	8.4	8.0	3.1	2.7	4.3	4.4	3.3	4.6	4.0	4.4	4.8	4.9
5.8	Potential for standardization	4.3	3.4	3.1	1.8	2.5	2.0	2.9	4.2	2.9	3.8	4.0	3.5	2.1	1.9	5.7	2.7	3.4	5.2	6.1	6.1	5.0	6.3
5.5	Adaptable to various tank shapes	5.4	2.4	1.9	1.2	5.9	4.2	5.6	3.0	2.9	2.6	1.6	2.3	3.6	2.1	5.3	2.2	2.1	3.8	2.7	2.2	4.0	2.8
5.7	Ease of maintenance	5.5	3.4	2.2	3.0	3.6	3.0	4.0	8.3	2.8	3.5	3.1	3.7	4.2	2.1	3.2	5.9	3.3	3.6	4.2	4.8	4.8	3.9
6.0	Space/volume efficient	5.8	3.4	1.8	2.0	7.2	2.9	2.9	1.8	2.0	3.1	1.5	2.5	6.8	5.6	1.8	1.9	1.5	3.7	2.5	1.1	4.6	2.5
6.1	Scalability	5.0	4.4	2.0	1.8	4.1	2.7	2.8	3.2	2.6	3.0	2.9	3.1	4.9	3.4	6.2	2.8	4.3	6.2	5.4	5.7	5.5	3.7
5.7	Potential for the largest commercial uptake	5.6	3.6	3.3	3.0	3.9	2.0	2.8	4.0	2.8	3.1	3.6	3.1	4.1	4.0	7.4	4.4	5.2	6.8	6.5	7.7	7.6	6.1
6.7	Moisture/gas impermeability	6.9	2.6	3.3	7.5	3.9	2.9	1.9	2.0	4.6	1.6	1.4	2.4	2.3	3.4	2.2	3.8	5.1	2.0	2.8	2.3	2.7	3.9
5.2	Pre- and parallel manufacturability	4.9	3.8	1.0	1.2	3.4	1.8	2.6	3.4	2.1	2.6	2.0	1.8	2.7	1.6	4.2	1.9	7.9	5.7	4.1	5.0	5.7	3.2
6.5	Resistant to thermal deformation	7.8	3.0	5.9	3.1	5.5	7.8	5.2	2.1	4.8	1.8	1.4	1.7	4.5	5.7	2.6	4.7	2.7	2.7	2.8	2.7	3.0	4.5
5.6	Load-bearing capability	7.0	2.9	2.3	2.4	5.4	6.0	6.5	2.2	7.2	1.6	1.7	1.5	5.2	2.4	2.8	4.0	2.4	2.8	2.6	2.7	3.1	4.6
7.6	Health & safety	5.5	3.2	6.6	2.8	2.8	3.4	2.6	2.5	3.7	3.4	3.6	5.4	1.3	2.2	4.3	2.8	2.1	3.8	3.2	4.7	3.8	7.9
5.7	Perforation resistant	7.1	2.5	2.9	3.5	5.3	4.5	4.2	2.0	5.9	1.6	1.2	1.8	3.9	2.7	2.5	3.2	1.9	2.5	2.3	2.6	2.3	4.4
	Technical importance score	739.01	424.41	412.81	365.80	556.28	427.72	400.51	382.91	428.00	374.90	347.77	400.33	439.89	421.84	427.56	458.73	376.66	494.02	433.66	444.07	525.45	510.78
	Importance %	7.55%	4.33%	4.22%	3.74%	5.68%	4.37%	4.09%	3.91%	4.37%	3.83%	3.55%	4.09%	4.49%	4.31%	4.37%	4.68%	3.85%	5.04%	4.43%	4.53%	5.37%	5.22%
	Priorities rank	1	13	15	21	2	11	16	18	10	20	22	17	8	14	12	6	19	5	9	7	3	4

Figure 4. Filled out HoQ from survey feedback.

engineering characteristic that primarily affects effective thermal insulation the most is the thermal conductivity of the novel insulation material or concept, with a score of 8.9. Conversely, the thickness mainly affects space and volume efficiency, as expected, with a score of 7.2.

The ranking of the identified customers' requirements is also shown for the various needs, with effective thermal insulation being the most important. This is as expected since the primary function of an insulation system is to provide effective thermal insulation. It is followed by health and safety concerns, with ease of manufacturing and installation being the least important. For clarity, the ranking of the various requirements is presented in Figure 5, starting from the most important to the least important. A total of eighteen (18) functional requirements for novel insulation materials/concepts were identified in this study.

The findings from prioritising customers' requirements, which translate to insulation requirements, reflect fundamental engineering and physical principles. The main function of an insulation system is to resist heat flow; therefore, it is expected that the most crucial requirement is effective thermal insulation, which aligns well with the results presented in Figure 5. Health and safety are non-negotiable requirements, especially since some insulation materials (for example, certain foams) can be toxic and pose handling risks. As a result, health and safety rank very high in the prioritisation of the insulation requirements. Durability and fire resistance are closely ranked, with both representing two vital aspects of insulation. Durability is essential as it governs long-term performance degradation, which can significantly impact thermal behaviour over time and under real-world conditions. Insulation materials are placed between the annulus of liquid hydrogen tanks and are difficult to replace; thus, their lifespan is required to be similar to the tanks' lifespan. Fire resistance is highly ranked due to its importance to safety, particularly in high-risk environments like hydrogen systems, where leaks or accidents could cause fires or explosions. Following that, cost-effectiveness is considered as it influences feasibility at scale and market acceptance, since both initial costs and long-term savings matter, and insulation should be affordable. Mechanical properties, such as resistance to thermal deformation, load-bearing capacity, and perforation resistance, are of secondary importance but still necessary to maintain performance stability, structural integrity, and resistance to damage during installation. Economic and scalability considerations, which affect large-scale adoption, along with requirements like space efficiency, ease of maintenance, and adaptability to various tank shapes –though they influence practical implementation and system integration –

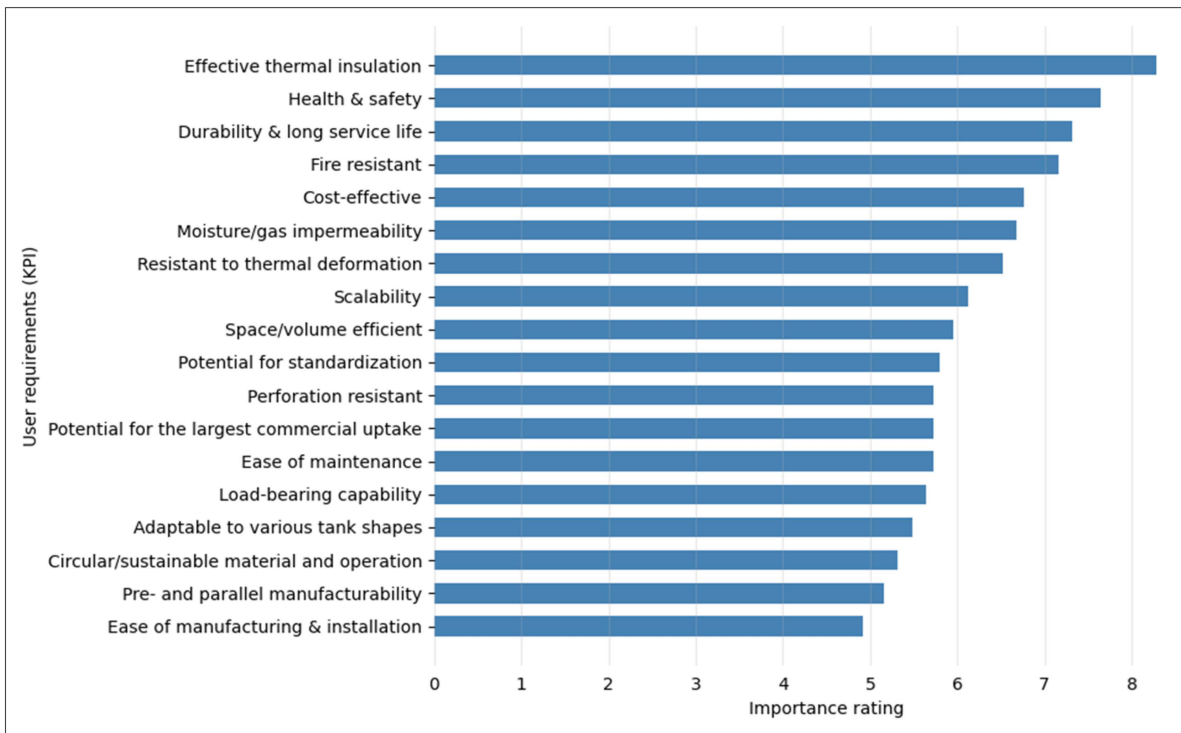


Figure 5. Relative importance ratings of identified insulation system functional requirements.

do not directly impact the intrinsic material performance, which is in agreement with their relatively lower ranking.

With respect to the engineering characteristics, it is shown in [Figure 4](#) that the material selection index, which is based on a combination of relevant material properties, is the most important technical feature influencing the performance of novel insulation materials and concepts across all customer requirements. For clarity, this is presented in [Figure 6](#). It is also important to note that the technical importance score for each engineering characteristic is assessed across all customer requirements. For example, although thermal conductivity has the greatest influence on effective thermal insulation, it ranks 14th across all customer requirements.

The material selection index is followed by the thickness of the insulation materials/concepts, as shown in [Figure 6](#). In this study, 22 engineering/design characteristics have been identified. Modifying these characteristics would influence users' perceptions of the functional requirements of novel insulation concepts. It should be noted that the ranked engineering characteristics provide the basis for making trade-offs when designing or selecting an insulation material or concept for a particular application. Thus, an engineering characteristic that substantially enhances one particular functional requirement may not necessarily rank high when compared with all functional requirements.

The ranking of engineering characteristics guides the selection of insulation materials and/or concepts based on different design priorities. For instance, in scenarios where thermal performance is prioritised, thermal conductivity and thickness are used as the criteria for choosing insulation materials. This is consistent with standard practice, which requires that thermal insulation be rated based on thermal conductivity and thickness. Therefore, thin materials with low thermal conductivity, such as multilayer insulation or vacuum insulation systems, are considered suitable in such situations. On the contrary, where cost is the priority, factors such as production cost and selling price are considered in the material selection. This leads to the use of low-cost materials such as polymeric foams despite their high thermal conductivity. Likewise, in situations where circular and sustainable materials and practices are given priority, materials and processes that result in minimal waste, have high recycling rates, and low environmental impact are the preferred choice, as shown in [Figure 4](#).

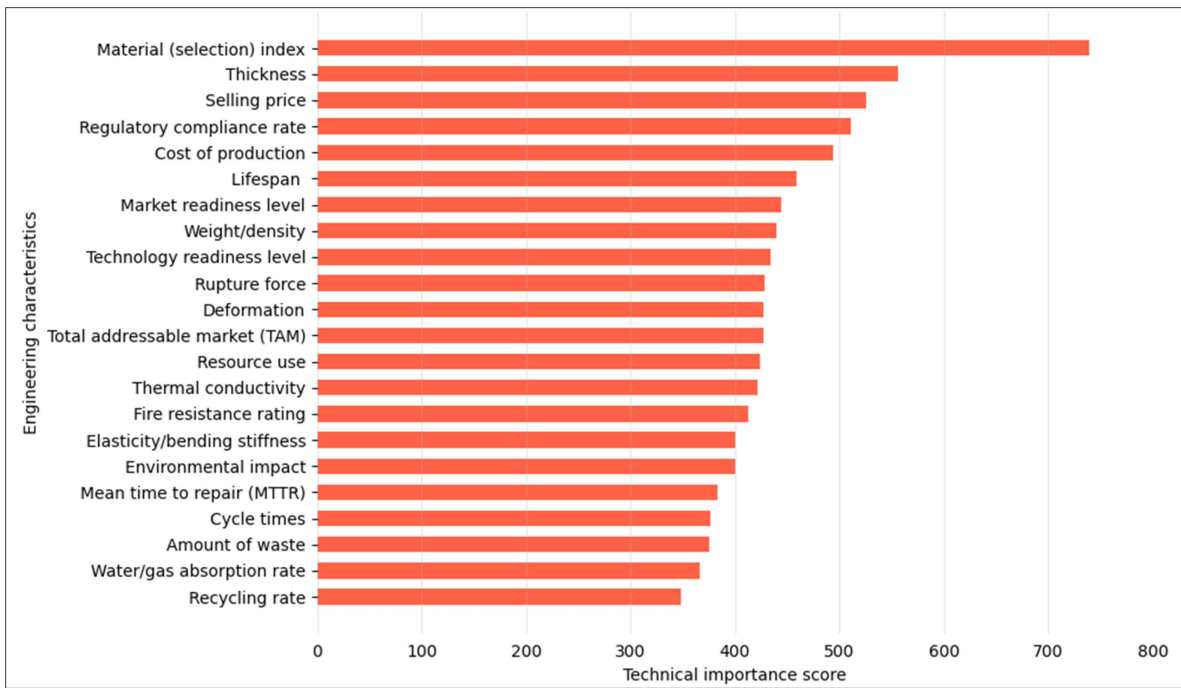


Figure 6. Technical importance ranking of proposed engineering characteristics across all functional requirements.

Moreover, the QFD results also indicate several inherent trade-offs due to the coupling of engineering characteristics and multiple customer requirements. For instance, selecting a material that has a high fire resistance rating not only ensures that the insulation system has high resistance to fire but also resistance to thermal deformation and compliance with health and safety regulations. However, this has a significant effect on cost-effectiveness since fire-resistant materials are also more expensive. This demonstrates that insulation system selection and design are fundamentally a multi-objective optimisation problem, where improvements in one area may require sacrifices in another.

3.3. Sustainability perspective

Although this study does not include a formal life cycle assessment, many of the customers' requirements and engineering characteristics inherently reflect sustainability-oriented outcomes and support sustainable design decisions for novel insulation concepts relevant to liquid hydrogen storage technologies. For instance, the emphasis on durability and long service life contributes to sustainability by reducing the frequency of material replacement and associated material consumption, thereby lowering lifecycle resource consumption and waste generation. Fire-resistant materials are more likely to remain intact and reusable after a fire event, especially for high-risk environments like those of liquid hydrogen. This ensures that materials are used longer, waste generation is reduced, and air pollution is avoided. The requirement for the use of circular/sustainable materials and operations supports the eco-design of novel insulation materials. At the same time, cost-effectiveness and scalability relate to resource efficiency in large-scale deployment. Additionally, requirements such as pre- and parallel manufacturability, ease of manufacturing, and ease of maintenance contribute to lower operational and production burdens.

Furthermore, the coupling of engineering characteristics to multiple customer requirements provides a framework that supports sustainable design decisions for liquid hydrogen storage technologies. The rating of each engineering characteristic in relation to each customer requirement has direct implications for sustainability performance. For instance, improved thermal insulation reduces heat ingress into liquid hydrogen storage systems, thereby minimising boil-off losses and associated energy consumption. This enhances overall system efficiency and reduces indirect environmental impacts due to hydrogen losses. To achieve this, the novel insulation material is selected or designed based on the engineering characteristics

that greatly influence the provision of effective thermal insulation. In this case, the thermal conductivity of the material is given more emphasis as depicted by the rating in Figure 4. Also, the requirement for circular/sustainable materials and operations, which aligns well with circular and sustainable design principles, is greatly impacted by the amount of waste generated during production, the recycling potential, and the environmental impact of the selected material. As these engineering characteristics play a crucial role, it is expected that processes and materials that generate less waste, have high recyclability potential, and low environmental burden are used. A similar trend applies to the other relations between customer requirements and engineering characteristics. From this perspective, the QFD framework adopted in this study can be interpreted as a preliminary decision-support tool that incorporates key sustainability-related criteria at the early design stage of novel insulation systems.

3.4. Sensitivity analysis

A one-at-a-time (OAT) sensitivity analysis was conducted by perturbing each customer requirement (CR) rating by $\pm 20\%$ while keeping others constant. The resulting variation in engineering characteristic (EC) scores was used to assess robustness. This is presented in Figure 7, where the bars represent the baseline technical scores of the EC, and the orange shadow band represents the minimum and maximum EC scores obtained due to perturbation of the CR ratings. The width of the band gives a direct measure of the sensitivity of each EC to variations in individual CR rating, with larger ranges indicating greater susceptibility to input variation.

Considering the width of the band, it can be observed that the EC scores are not highly susceptible to changes in the CR ratings. A summary of the sensitivity results is presented in Table 1, where the EC scores of the five highest and lowest EC are shown. Engineering characteristics with low relative ranges are considered robust, whereas those with higher values indicate greater sensitivity to input uncertainty. The complete table is attached in Appendix A3. As can be seen in the table, the highest relative range is approximately 7%. This shows that the results obtained are robust and not highly sensitive to CR ratings.

Additionally, the customer requirements (CR) were analysed using a tornado diagram (Figure 8) to quantify their aggregate influence on the EC scores. The total swing score range indicates the total impact of a CR on all ECs. The longer the bar, the higher the influence of that CR on the final engineering characteristics. As shown in Figure 8, durability and long service life, effective thermal insulation, cost-effectiveness, fire resistance, and health and safety drive the most change. Thus, the results obtained are highly sensitive to these customer requirements.

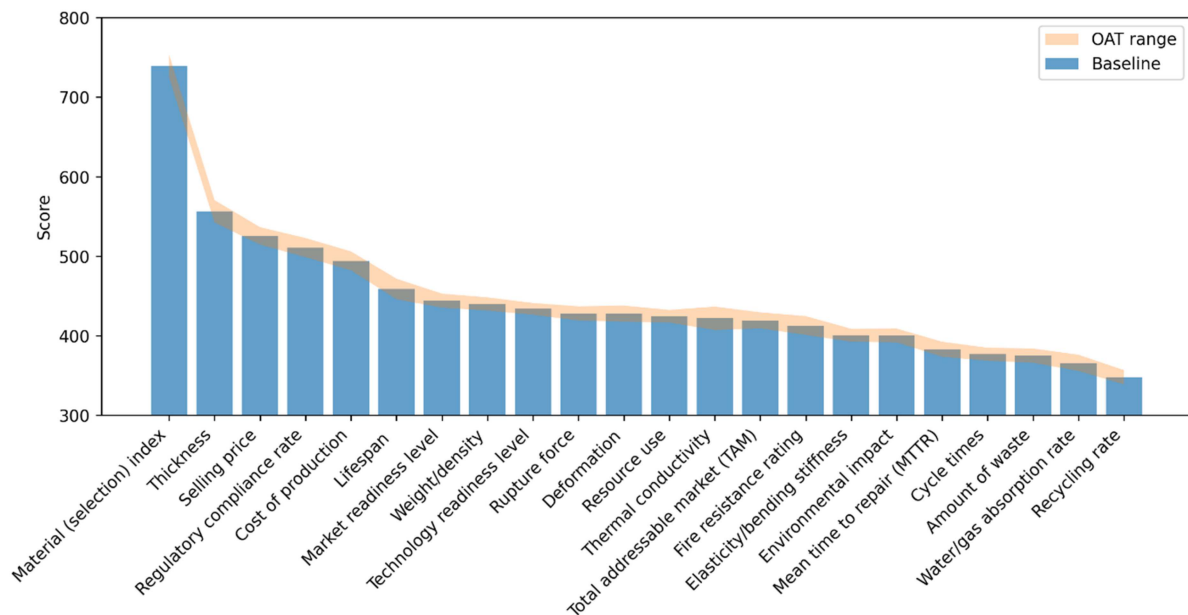
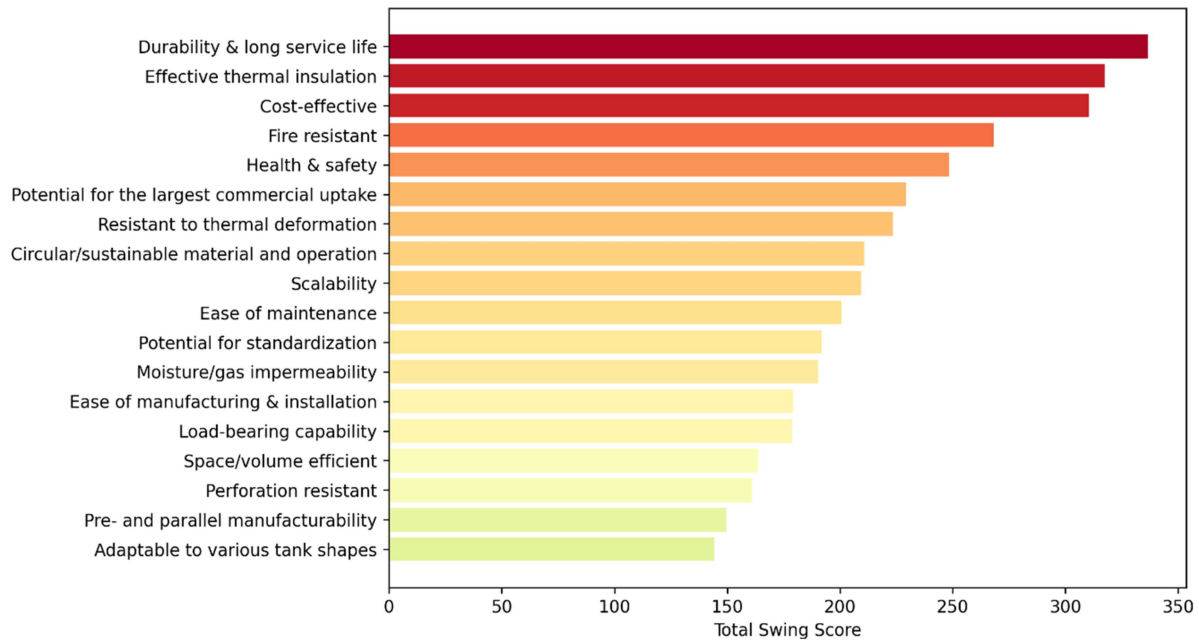


Figure 7. Engineering characteristics score with OAT sensitivity range.

Table 1. Summary of sensitivity analysis results.

EC	Baseline score	Rank	Min score	Max score	Range	Relative range (%)
Thermal conductivity	421.84	13	407.10	436.57	29.48	6.99
Fire resistance rating	412.81	15	401.01	424.61	23.60	5.72
Lifespan	458.73	6	445.84	471.61	25.77	5.62
Water/gas absorption rate	365.80	21	355.59	376.00	20.40	5.58
Recycling rate	347.77	22	338.83	356.70	17.88	5.14
Market readiness level	444.07	7	435.26	452.88	17.62	3.97
Material (selection) index	739.01	1	724.91	753.12	28.22	3.82
Weight/density	439.89	8	431.61	448.17	16.56	3.76
Resource use	424.41	12	416.46	432.36	15.90	3.75
Technology readiness level	433.66	9	426.29	441.04	14.76	3.40

**Figure 8.** Customer requirements' influence on engineering characteristics score.

3.5. Description of reported functional requirements and engineering characteristics

The findings related to the customer requirements, which correspond to the KPIs of the novel insulation systems, and the engineering/design characteristics, are described in more detail in the following subsections.

3.5.1. Customer requirements

Based on the survey feedback, the following customer requirements were identified and are described in Table 2. Various aspects of the insulation system, including manufacturing, use, and marketability, were considered when defining these requirements. For brevity, the customers' requirements are presented in a table.

3.5.2. Engineering/design characteristics

The identified engineering characteristics, which are attributes that could be modified to influence the customer's perception of the novel insulation materials/concepts, are described in Table 3, along with recommendations for their improvement.

3.6. Implications of the study

This section highlights the study's implications. It is categorised into managerial and theoretical implications.

Table 2. Description of identified novel insulation materials/concepts requirements.

Insulation concept requirements (KPIs)	Description
Effective thermal insulation	Effective thermal insulation plays a pivotal role in reducing boil-off gas formation by minimizing heat transfer into the liquid hydrogen storage tank. Achieving dynamic thermal insulation is desirable as the ultimate goal (Jelle 2011).
Fire resistant	Fire resistance is crucial for safety, especially in high-risk environments where leaks or accidents can lead to fires or explosions. It describes the capacity of a material to maintain, for a specified period of time, particular mechanical resistance, tightness to smoke, and thermal insulation in fire conditions or high temperatures (Acuña-Pizano et al. 2022). Fume emission and the release of volatile organic compounds during a fire are other important factors to consider.
Durable and long service life	Novel insulation systems should retain their properties over time, even in harsh environmental conditions. Durable insulation ensures long-term efficiency (Berardi et al. 2020).
Cost-effective	The upfront costs and long-term savings associated with insulation systems are important, as the insulation has to be affordable. The life cycle cost analysis could be a suitable approach to monitor the efficiency and cost of insulation materials or concepts (Hauschild, Rosenbaum, and Olsen 2018).
Ease of manufacture & installation	Novel insulation systems should not be very challenging to manufacture, considering their design, cost, and other requirements. Additionally, they need sufficient rigidity to be installed easily. Moreover, quality control during the construction phase is another crucial aspect that can influence the performance of the insulation material/concept (Fesi 2010).
Sustainable/circular materials & operation	The sustainability, recyclability, and ecological footprint of insulation systems are significant. Choosing environmentally friendly insulation materials or concepts is essential for long-term sustainability (Füchsl, Rheude, and Röder 2022).
Potential for standardisation	The potential for standardising novel insulation materials and concepts ensures they are produced with consistent quality and are comparable to other similar materials and concepts. This guarantees the safety, interoperability, and compatibility of the insulation material/concept produced (Farrell and Saloner 1985).
Adaptable to various tank shapes	Insulation systems should be capable of adapting to a range of potentially complex tank geometries and accommodate design variations in tank shape without compromising the insulation performance (Drube et al. 2024).
Ease of maintenance	The maintainability of insulation systems impacts the tank's long-term viability. If the insulation deteriorates over time or gets damaged, it should be easy to repair without significantly disrupting the tank's operation. Inspection, maintenance, repair, and replacement procedures should be simple, economical, and safe (Campari et al. 2025).
Load-bearing capability	This entails the ability of insulation systems to withstand external loads exerted on them. These loads can include mechanical stresses on the insulation material or concept during transportation, installation, and operation. They may also include mechanical stress from the tank structure, external pressure, or its own weight (Dye et al. 2014).
Scalability	The scalability of a novel insulation material or concept pertains to the feasibility of translating the novel insulation system from laboratory-scale development to commercial-scale production while maintaining its performance (Putnik et al. 2013).
Potential for the largest commercial uptake	This provides a measure of the time required for the maximum commercial adoption of the novel insulation material or concept within a given transition period (LOMARTOV 2025).
Moisture/gas impermeability	Moisture/gas present in insulation materials can reduce their thermal resistance and durability (Hung Anh and Pásztor 2021) (Khan et al. 2024). High moisture/gas impermeability is required for durable insulation systems. Additionally, considering the cryogenic nature of LH ₂ , the insulation material/concept should demonstrate resilience against freeze-thaw cycles.
Health & safety	Insulation material/concept should meet health and safety standards, as some materials are hazardous to human health (Muir 1976) (Levin and Purdom 1983). Consequently, insulation material's/concept's potential for off-gassing, emissions, or adverse effects should be taken into consideration.
Perforation robustness	The perforation robustness of novel insulation concepts entails resistance to damage when exposed to localised stress during installation, operation, or maintenance (Jelle 2011; VIPA International 1983).
Space/volume efficient	This involves providing high thermal resistance while taking up minimal space. This is especially important because the volumetric energy density of LH ₂ is low (Klopott, Popek, and Urbanyi-Popiolek 2023).
Pre- and parallel manufacturability	This is crucial for the large-scale production of insulation systems. It could be used as an indication of the level of process automation and could help to shorten product development cycle (Fesi 2010).
Resistant to thermal deformation	Insulation systems should be able to maintain their integrity despite the stresses induced by thermal expansion and contractions. This is important as LH ₂ tanks undergo significant thermal cycles during filling, storage, and discharge (Shi et al. 2023).

3.6.1. Managerial implications

The results obtained in this study have several implications for engineers and decision-makers in selecting and designing insulation materials. Firstly, the results imply that decisions based on thermal performance cannot be made in isolation. Other parameters like fire resistance, health and safety, durability, and cost have significant constraints that need to be satisfied and can be more important than thermal considerations, especially in regulated environments like those of liquid hydrogen. Secondly, the identification of trade-offs among thermal performance, mechanical properties, and cost implies that decisions need to be

Table 3. Description of design features that relate to and influence the insulation system requirements.

Engineering characteristics	Description
Material (selection) index	Material index is a powerful tool in materials selection and engineering design. It represents a combination of relevant material properties that need to be optimised or constrained to ensure that the selected material meets the targeted design objective (Ashby, Bréchet, and Cebon 2002).
Resource use	This measures how much and how efficiently materials, energy, labour, and equipment are used in producing insulation materials or concepts. Efficient resource utilisation ensures optimal resource use to achieve production outcomes (Kalnæs and Jelle 2014; Resalati et al. 2021).
Fire resistance rating	Fire resistance rating of an insulation system indicates the period during which it can withstand a standard fire resistance test (Rizzo 2023). It assesses how quickly fire can spread and the amount of smoke produced as a result.
Moisture/gas absorption rate	This refers to the time required for an insulation material to absorb a certain amount of moisture/gas under specific conditions. Moisture content in insulation materials can increase their thermal conductivity and reduce their durability (Hung Anh and Pásztor 2021; Khan et al. 2024). Hence, the moisture/gas absorption rate of insulation materials should be minimal.
Thermal conductivity	Thermal conductivity is a primary property of an insulation material and needs to be analysed to determine whether a typical material can be used as an insulator. To qualify as a thermal insulator, a material's thermal conductivity should be below $0.1 \text{ W.m}^{-1}.\text{K}^{-1}$ (Ali, Issa, and Elshaer 2024).
Thickness	Optimising insulation thickness is crucial for reducing heat transfer (Sahu et al. 2015). Therefore, it is important to determine the optimal insulation thickness that balances overall insulation costs and heat transfer/boil-off reduction (Zhang et al. 2019). Given the volume requirement of LH_2 storage, it is preferable to use an insulation system that is as thin as possible.
Deformation	The amount of deformation gives a measure of the change in the shape or size of the insulation material or concept due to an applied load—mechanical or thermal, as the case may be. This characteristic is especially critical, given the constant thermal load cycles to which liquid hydrogen tank insulation is subjected (Arpacı 2001).
Elasticity/bending stiffness	The elasticity of an insulation refers to its ability to return to its original shape after deformation. The bending stiffness indicates the resistance of the insulation to bending when a load is applied (Kakani 2004). Both properties are particularly relevant when customising insulation for different tank shapes.
Mean time to repair (MTTR)	MTTR measures the average time taken to repair a product system after failure (IBM). The quicker an insulation system can be fixed, the better. Therefore, a low MTTR value is preferred.
Rupture force	The rupture force of an insulation system is the force that results in a significant failure in the system (Kakani 2004). Novel insulation concepts must maintain adequate resistance to mechanical stress during construction and usage, especially under vacuum conditions.
Amount of waste	This represents the amount of non-recyclable waste, as well as recyclable waste that remains unrecycled, generated throughout the entire life cycle of the insulation material/concept. It is desirable to eliminate or minimise waste to the lowest possible level (European Parliament and Council of the European Union 2008).
Recycling rate	The recycling rate shows the percentage of waste that can be recycled. It is determined by how much waste is recycled compared to the total amount of waste (EEA 2024). A high recycling rate means less waste ends up in landfills and more resources are conserved.
Environmental impact	Potential impact, whether adverse or beneficial, on the natural environment, resource availability, and human health, caused by human activities (Zelm, Hennequin, and Huijbregts 2025). The materials and operations used for novel insulation concepts should be environmentally friendly and sustainable.
Weight/density	Higher-density insulation materials tend to provide better insulation due to increased resistance to heat transfer (Petcu et al. 2023). However, some exceptions have been reported where unusual behaviour was observed (Hung Anh and Pásztor 2021). This may not be the case for new and advanced insulation material or concept, but it could serve as a basis for the design and development of a novel insulation system. Furthermore, lightweighting may be a critical element in applications where weight is a decisive factor, such as transportation.
Total addressable market (TAM)	TAM is the total revenue potential for a product in a specific market. It represents the maximum possible demand if the product were to gain 100% of the market share (Meabe 2024). TAM analysis is an essential step in market research that helps guide market entry by identifying opportunities for innovation and growth.
Lifespan	Lifespan or service life of an insulation system is the period during which the insulation can maintain the necessary level of insulation until its thermal resistance drops below a required minimum (ISO 2011). Ideally, the lifespan of insulation materials should be designed to match the lifetime of the storage tank itself.
Cycle time	Cycle time is a key manufacturing parameter that measures the time required to complete a production process from start to finish. This includes the time spent working on a product as well as the waiting period in between steps. Shorter cycle times correspond to faster production rates (SixSigma 2024).
Cost of production	This reflects all the costs associated with manufacturing the insulation system. It plays a significant role in determining the profitability and competitiveness of the novel insulation system. The cost of production should be minimised as much as practicably feasible (Božiček et al. 2024).
Technology readiness level	This is employed to evaluate the maturity level of a technology to ensure it can be used safely by trained and intended users in the envisaged commercial or non-commercial user environment (Hasenauer and Weber, 2015). It is determined by assessing if the criteria that define each level are met.
Selling price	The selling price is the final cost at which the insulation system is sold to a customer (MBN, n.d.). It is expected to remain within a range considered affordable by prevailing market standards.
Regulatory compliance rate	This metric evaluates the extent to which products meet regulatory standards. It is calculated as the ratio of instances where a product complies with specific regulations to the total number of applicable regulatory requirements. It is recommended to aim for a high percentage of compliance with regulatory requirements (KPI Depot).
Market readiness level	Market readiness level measures the maturity of a given need in the market, taking potential obstacles into account (Hasenauer and Weber, 2015). This is achieved by verifying whether the predefined criteria used to describe the level are met (Schildorfer, Walter, and Hasenauer 2017).

made based on multiple parameters and not a single parameter. For example, materials that have low thermal conductivity can have inferior mechanical properties and higher costs. Therefore, decisions need to be made based on balancing multiple parameters. Hence, the selection and design of insulation material and/or concept should be based on stakeholder priorities. For instance, in cost-based scenarios, economic factors can be more important than thermal performance, while in safety-critical contexts, durability and fire resistance can be more important than thermal performance. This implies that early project decisions need to be based on defining priority criteria that can satisfy the requirements of the insulation material. Furthermore, practical aspects such as ease of installation, adaptability to different shapes, and pre- and parallel manufacturing are crucial in real-world implementation. Even though certain materials might exhibit promising characteristics in theory, they might still fail in practical applications due to installation difficulties. Finally, it is worth noting that the proposed QFD framework is potentially useful as a decision-support tool that can aid practitioners in evaluating insulation material and/or concept alternatives under various conditions and constraints, enhancing transparency and consistency in material choices.

3.6.2. Theoretical implications

This study adds to the existing knowledge on Quality Function Deployment (QFD) in several ways. Firstly, it develops an application-oriented QFD framework particularly tailored for insulation material selection and design. The framework is enhanced by including an extensive range of customer requirements, including thermal performance, fire safety, durability, mechanical integrity, economic feasibility, sustainability, manufacturability, and maintainability. This expands the use of QFD beyond conventional product planning to an engineering problem that deals with several factors. Secondly, by including sensitivity in the QFD framework, it provides a methodological contribution by demonstrating how QFD results might be affected by various stakeholder priorities in evaluating the ranking of various engineering characteristics. Lastly, the inherent trade-offs among competing requirements also serve to further clarify the role and importance of QFD as a multi-objective decision-support tool rather than just a prioritisation technique. This further enhances its potential for engineering decision problems.

Ultimately, the study has demonstrated that the selection of appropriate insulation materials requires a comprehensive evaluation of associated performance criteria. In addition, QFD, when combined with engineering interpretation and sensitivity analysis, has the potential to be invaluable in supporting complex decisions.

3.7. Limitations of the study

While this study provides useful insights into the functional requirements for novel insulation materials/concepts for LH₂ storage tank applications, certain limitations may have influenced the findings.

- The limited sample size may restrict the generalisability of the results.
- The outcomes, which are mainly based on an academic viewpoint, might not fully reflect the perspectives of industry practitioners. As a result, opinions could vary among different schools of thought. Therefore, the results should be seen as suggestive rather than universally applicable.

Nonetheless, the study serves as a reference framework outlining the requirements and features that new insulation systems are expected to satisfy.

4. Conclusions and future works

This study evaluated the functional requirements of advanced insulation materials and concepts for use in liquid hydrogen storage tanks and, by extension, cryogenic systems. The first phase of the quality function deployment, known as the house of quality, was used to link the defined functional requirements with the identified design features. An expert survey based on purposive sampling was conducted to populate the HoQ, leading to the identification and definition of 18 functional requirements and 22 engineering characteristics, which were then ranked based on the respondents' perceived level of their importance. The findings indicate that, beyond thermal performance, factors such as durability, health and safety, cost,

fire resistance, and sustainability, among others, also influence the design of insulation systems and must be considered. This is especially critical for liquid hydrogen applications, given the significant thermal gradient and material behaviour when exposed to liquid hydrogen. Based on the identified functional requirements for novel insulation systems, it is inferred that no single insulation system fulfills all requirements. That notwithstanding, durability, effective thermal insulation, cost-effectiveness, fire resistance, and health and safety are the top drivers of the engineering characteristics of insulation materials and/or concepts. Consequently, the outcomes of this study enable informed decision-making regarding the prioritisation of insulation requirements and design features. Furthermore, it is important to emphasise that the conclusions of this study reflect the data provided by the respondents and the inferences drawn from them. It remains uncertain how these findings may evolve in the future.

Considering that the current study employed a simplified HoQ model, future research could investigate other aspects of the HoQ. The difficulty of achieving each feature could be factored into the analysis, and a competitive analysis could be conducted to evaluate competing products. Furthermore, subsequent studies employing a more diverse participant pool could enhance the robustness of these findings and extend the results to other phases of the Quality Function Deployment.

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Author contributions

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Disclosure statement

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Data availability statement

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Appendices

A1: Excerpt from the questionnaire for prioritising functional requirements

QUESTIONNAIRE: Quality Function Deployment

Dear All,

Thank you for taking the time to respond to this questionnaire. In this questionnaire, we kindly request you to:

- Rank the key performance indicators (regarded also as user requirements/specifications) according to your perceived relative importance of each KPIs with regards to insulation concept(s).
- Add any other KPI you consider necessary for insulation concept(s).
- Rank the relationship between the identified engineering characteristics and the KPIs (user requirements/specifications). This relationship is used to show the extent to which the engineering characteristics could technically relate to and influence the KPIs (user requirements).
- Add any other engineering characteristics/technical measures you consider necessary that, if modified, would affect the KPIs (user requirements).

When you submit this form, it will not automatically collect your details like name and email address unless you provide it yourself.

* Required

Prioritization of KPIs/user requirements *

Rank each key performance indicator/user requirement according to your perceived importance of each KPIs with regards to insulation concept(s).

	very low importance	low importance	moderate importance	high importance	very high importance
Effective thermal insulation	☐	☐	☐	☐	☐
Fire resistant	☐	☐	☐	☐	☐
Durability & long service life	☐	☐	☐	☐	☐
Cost-effective	☐	☐	☐	☐	☐
Ease of manufacturing & installation	☐	☐	☐	☐	☐
Sustainable/circular materials and operation	☐	☐	☐	☐	☐
Potential for standardization	☐	☐	☐	☐	☐

A2: Excerpt from the questionnaire for the relationship matrix

Rank the relationship between **market readiness level** and each KPI/user requirement. This relationship is used to show the extent to which the market readiness level could technically relate to and influence each KPIs. *

Market readiness level	no relation	very weak (relation)	weak (relation)	moderate (relation)	strong (relation)	very strong (relation)
Effective thermal insulation	☐	☐	☐	☐	☐	☐
Fire resistant	☐	☐	☐	☐	☐	☐
Durability & long service life	☐	☐	☐	☐	☐	☐
Cost effective	☐	☐	☐	☐	☐	☐
Ease of manufacturing & installation	☐	☐	☐	☐	☐	☐
Sustainable/circular materials & operation	☐	☐	☐	☐	☐	☐

A3: OAT sensitivity table showing results of sensitivity analysis

EC	Baseline score	Rank	Min score	Max score	Range	Relative range (%)
Thermal conductivity	421.84	13	407.10	436.57	29.48	6.99
Fire resistance rating	412.81	15	401.01	424.61	23.60	5.72
Lifespan	458.73	6	445.84	471.61	25.77	5.62
Water/gas absorption rate	365.80	21	355.59	376.00	20.40	5.58
Recycling rate	347.77	22	338.83	356.70	17.88	5.14
Thickness	556.28	2	542.17	570.39	28.22	5.07
Mean time to repair (MTTR)	382.91	18	373.44	392.39	18.94	4.95
Cost of production	494.02	5	482.12	505.92	23.80	4.82
Total addressable market (TAM)	419.28	14	409.20	429.35	20.14	4.80
Amount of waste	374.90	20	365.92	383.88	17.96	4.79
Deformation	427.72	11	417.55	437.89	20.34	4.76
Regulatory compliance rate	510.78	4	498.78	522.77	23.99	4.70
Cycle times	376.66	19	368.51	384.82	16.31	4.33
Environmental impact	400.33	17	391.69	408.96	17.28	4.32
Selling price	525.45	3	514.50	536.41	21.90	4.17
Rupture force	428.00	10	419.10	436.90	17.80	4.16
Elasticity/bending stiffness	400.51	16	392.37	408.65	16.28	4.06

EC	Baseline score	Rank	Min score	Max score	Range	Relative range (%)
Market readiness level	444.07	7	435.26	452.88	17.62	3.97
Material (selection) index	739.01	1	724.91	753.12	28.22	3.82
Weight/density	439.89	8	431.61	448.17	16.56	3.76
Resource use	424.41	12	416.46	432.36	15.90	3.75
Technology readiness level	433.66	9	426.29	441.04	14.76	3.40