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Article

Development of a Method for Evaluating H2-Filling Stations

Bastian Nolte *, Dominik Gollnick, Armin Stein and Thomas Vietor

Institute for Engineering Design, Technische Universität Braunschweig, Hermann-Blenk Strasse 42, 38108 Braunschweig, Germany; ik@tu-braunschweig.de (D.G.); armin.stein@tu-braunschweig.de (A.S.); t.vietor@tu-braunschweig.de (T.V.)
* Correspondence: b.nolte@tu-braunschweig.de

Abstract: To expedite the development of the infrastructural expansion for hydrogen applications, the research project "THEWA" was founded. Within this project, the development of hydrogen-refueling stations is being advanced so that the hydrogen strategy for mobility in Germany can move forward. One development point of the project is to develop an evaluation model that recommends a concept for hydrogen-refueling stations for initial individual situations. In this work, an evaluation method is developed that provides an appropriate recommendation. For this purpose, basics, such as the general structure of hydrogen-refueling stations, their classification into functional areas, and already-existing evaluation methods for multi-criteria decisions, are shown. The method for the evaluation of hydrogen-refueling stations will be developed in a component-based manner, for which a selection of influencing factors of hydrogen-refueling stations will be explained and categorized. With the help of an expert workshop, these are scaled so that the result is an evaluation method based on an expert assessment and the consideration of individual customer requirements. In addition, the method is implemented in a tool so that it can be used more easily.

Keywords: hydrogen refueling; hydrogen mobility; hydrogen; hydrogen-refueling station

Citation: Nolte, B.; Gollnick, D.; Stein, A.; Vietor, T. Development of a Method for Evaluating H2-Filling Stations. *Hydrogen* **2024**, *5*, 851–871. https://doi.org/10.3390/hydrogen5040044

Academic Editor: Silvano Tosti

Received: 3 September 2024
Revised: 23 October 2024
Accepted: 5 November 2024
Published: 12 November 2024

1. Introduction

Hydrogen is a promising element for decarbonization. In order for a hydrogen strategy to be accepted by end users as quickly as possible, hydrogen infrastructure is essential [1]. For this reason, the development of a method for decision support for hydrogen-filling stations is advantageous, which accelerates the planning phase for the construction of hydrogen-filling stations and, thus, the expansion of filling stations, thereby laying the foundation for a functioning hydrogen strategy. There are currently almost 100 hydrogen-filling stations in Germany with a 700-bar refueling facility, which means that six million passenger cars can be refueled [2]. Commercial vehicles can currently refuel at six hydrogen-filling stations with 350 bars [2]. According to Hutmacher's maturity analysis, it is also clear that the development status of hydrogen-refueling stations is less advanced than that of vehicle storage technologies [3]. In order to catch up with this backlog in development, a more intensive examination of hydrogen-refueling stations is needed to accelerate the implementation of the hydrogen strategy.

In the following, an evaluation method is presented that accelerates the planning phase of hydrogen-refueling station expansion and serves as an initial guide for the concept selection of H2-refueling stations. The aim of this paper is to showcase a methodical approach to the early-phase concept development of hydrogen-refueling stations by utilizing real-world hydrogen-refueling station data, expert opinions, and giving the to-be designer the ability to prioritize certain characteristics over others. Finally, the software implementation of the method, as well as a case study, are presented.

2. State of the Art

This chapter reviews the state of the art in hydrogen-refueling station (HRS) operations, key technical concepts, and characteristics.

2.1. Hydrogen-Refueling Station Operation

The first hydrogen vehicles and trains are already in use, and there are already about 100 hydrogen-filling stations in Germany [4]. For the decarbonization of mobility to continue, an accelerated expansion of the H2 infrastructure is necessary so that H2 mobility offers are accepted by industry and society [5,6].

A basic structure of a hydrogen-filling station with central hydrogen production (off-site production) is given in Figure 1. Off-site production means that the hydrogen is produced centrally and delivered to the respective hydrogen-filling stations. For the filling station, the first step is therefore the gaseous or liquid delivery of the hydrogen to the filling station itself. The two types of delivery differ in their necessary compression and the components required for this. For example, a cryogenic pump is used to process liquid hydrogen, while a regular compressor is used for gaseous hydrogen. Delivery can generally be made by trucks (trailers) or by pipeline, which also have an impact on hydrogen conditioning. In a trailer, the hydrogen is transported at a higher pressure than in the pipeline, which means that in the case of pipeline delivery, compression must be carried out on site with a higher energy input [6,7]. On site, the hydrogen is compressed and temporarily stored in a buffer tank. The hydrogen is then conditioned, i.e., it is conditioned with the help of a refrigeration system and compressor according to the individual tank protocols. The actual refueling of the mobility vehicles takes place via the petrol pump and the dispenser [8].

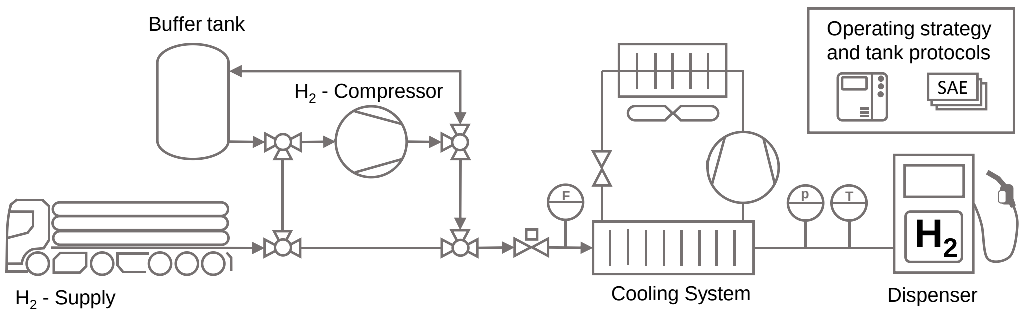


Figure 1. Schematic structure and mode of operation of a hydrogen-filling station [8].

2.2. Hydrogen-Refueling Station Concepts

Due to the increasing demand and the different hydrogen storage technologies in transport modes, the number of different requirements for hydrogen-filling stations is increasing. In order to be able to realize the different requirements, a wide variety of technical solution options exist, which, for example, influence energy efficiency or costs in different ways. This means that different concepts for filling stations are conceivable, which fulfill the respective requirements to varying degrees [8]. Not every concept is equally well suited to the initial individual situation, which is why the best individual concept must be found from the various concept options.

Table 1 provides an overview of the hydrogen-filling station concepts considered in the "THEWA" project. These are based on the hydrogen-filling stations commonly found in the literature and on an in-house evaluation of relevant hydrogen-filling station components. Four different functional areas (supply, storage, conditioning, delivery) [9] were deliberately chosen to structure the H2-filling station so that the most important elements of an H2-filling station are taken into account, and the basic idea of the evaluation method table becomes clear. In general, filling stations are systems, so a system evaluation takes place. Well-known and -established assessment methods already exist for this purpose, which can be applied to hydrogen-filling stations in a modified or shortened form. Therefore, the following development of the evaluation method for H2-filling stations was based on a utility analysis, an Analytic Hierarchy Process (AHP), and a Quality Function Deployment (QFD).

Table 1. Components of the hydrogen-filling station concepts.

Concepts	Supply	Storage	Conditioning	Delivery
Concept 1	Gas trailer	(Trailer)+ CGH2 Tank	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 2	Pipeline	CGH2 Tank	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 3	Gas trailer	Trailer	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 4	Pipeline	-	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 5	Gas trailer	Main storage+ CGH2 Tank	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 6	Pipeline	Main storage+ CGH2 Tank	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 7	Gas trailer	Main storage	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 8	Pipeline	Main storage	Compressor+ Precooling+ Expansion valve	CGH2 350/700 bar
Concept 9	Fluid trailer	Cryotank LH2+ CGH2 Tank	Cryopump+ Heating+ Expansion valve	CGH2 350/700 bar

2.3. Hydrogen Fueling Station Charachterisation

In alignment with the objectives of this study, an extensive review of the scientific literature concerning the characterization of hydrogen-refueling stations (HRS) has been conducted. This investigation employed the following keywords: "Hydrogen Refuelling Station", "Hydrogen Refuelling Station characteristics", "Hydrogen Refuelling Station Parameters", "Hydrogen Refuelling Station Area", "Hydrogen Refuelling Station Capacity", and "Hydrogen Refuelling Station Cost". For each of these terms, the top-20 results (two pages) from the Google Scholar database were analyzed and assessed for their relevance to the topic. Upon analyzing the collected papers, it becomes evident that the primary focus of existing research on HRS pertains to techno-economic analyses of specific station concepts [10–17], the optimization of particular components or station designs through advanced simulation techniques [18], or the planning of HRS networks and infrastructure in anticipation of future hydrogen demand [19–22].

The selected studies revealed important characteristics of HRS, such as spatial requirements [12], refueling capacity [11–13], and the localized cost of hydrogen, along with storage and transport strategies [13–15,18]. However, no study was identified that specifically addressed the characterization of hydrogen-refueling stations for early-stage planning processes. Moreover, no methodology has been identified for the comprehensive comparison of refueling station concepts, nor for the integration of customer preferences into the early-stage design process.

2.4. Aims of the Paper

Based on the evaluation of the literature shown in Section 2.3, two aims can be formulated for this research paper:

Aim 1: Define a system or list of characteristics, which can be used to characterize HRS during the early development process.

Aim 2: Develop a method, which, based on the characteristics identified in **Aim 1**, supports the comparative analysis of different HRS concepts based on customer preferences.

The method to be developed will from now on be referenced as the THEWA method.

3. Methods

In response to the research questions, this chapter develops a method based on multi-criteria decision analysis (MCDA), identifies design criteria, categorizes hydrogen-refueling station (HRS) concepts based on the criteria, and applies customer weighting to the criteria, providing a structured framework for evaluating HRS designs. The result of this chapter is the development of the THEWA method.

3.1. Multi Criteria Decision Analysis Methods

Multi-criteria decision analysis (MCDA) refers to a set of techniques designed to evaluate complex decisions that involve multiple, often conflicting, criteria and has been increasingly applied in the design of technical systems. In engineering and system design, decision-makers are often faced with the challenge of selecting optimal solutions that balance a range of factors, such as cost, performance, reliability, and environmental impact. Prominent MCDA methods used in this context include the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Multi-Attribute Utility Theory (MAUT). The AHP [23] is widely used in technical system design for its ability to break down complex decision problems into simpler components, allowing engineers to compare criteria such as cost efficiency, energy consumption, and durability. The AHP's pairwise comparison process simplifies the evaluation of both qualitative and quantitative criteria, making it a popular choice in selecting technical solutions. However, it can be sensitive to the consistency of judgments and the subjective nature of pairwise comparisons [24]. TOPSIS ranks alternatives based on their proximity to an ideal solution and distance from the least desirable outcome and is particularly useful in the design of technical systems where quantitative data like system performance or energy consumption can be easily compared [25]. However, TOPSIS can struggle with high-dimensional problems and small changes in data can alter rankings [26]. MAUT is another useful approach in technical design, especially when decisions involve significant trade-offs or risk, as it allows decision-makers to model preferences through utility functions, but the need for extensive input makes it less practical in large-scale system design [27]. In the design of technical systems, a Likert scale is often employed to capture subjective preferences, particularly in situations where qualitative judgments about criteria such as user satisfaction or esthetic value must be integrated into the decision-making process. Likert scales, typically using a 5- or 7-point format, help quantify these subjective preferences, but care must be taken to avoid biases such as central tendency or the assumption of equal intervals between points on the scale [28]. In conclusion, MCDA methods play a crucial role in the design of technical systems, helping decision-makers to evaluate and balance multiple criteria, both qualitative and quantitative. Methods such as AHP and TOPSIS are particularly useful in technical design due to their simplicity and ability to handle diverse data, while MAUT and the Likert scale offer ways to integrate subjective preferences, albeit with some limitations related to complexity and bias.

Qin et al. developed an intelligent site-selection model for HRSs using a combination of the Analytic Hierarchy Process (AHP), fuzzy comprehensive evaluation (FCE), and artificial neural networks (ANN) [29]. This model was applied to identify optimal HRS locations in Shanghai, considering factors like hydrogen demand, economic development, and population density. Zheng et al. applied a multi-period hydrogen-refueling station location model that used demand forecasting and set covering models to plan HRS locations in the Jiading District, Shanghai [30]. This study highlighted the importance of balancing hydrogen demand with infrastructure growth over time to optimize refueling-station placement. Various reviews highlight the application of MCDA techniques for hydrogen supply chain optimization, incorporating methods like fuzzy AHP and data envelopment analysis (DEA). These approaches help in evaluating the best sourcing alternatives and siting locations for hydrogen-related infrastructures based on sustainability and economic performance [31].

3.2. Identification of Design Criteria

In this chapter, the successive development of the evaluation method for hydrogen-refueling stations takes place. It starts with the development of suitable design criteria and ends with the decision-making process using the method. From the THEWA project, there are several requirements that the assessment method must fulfill. The first requirement is that the evaluation method is scalable and can be linked to mathematical optimization methods. This means that the result achieved by the evaluation method must be able to be improved by a subsequent optimization method if necessary. In addition, the evaluation method must be able to flexibly combine the different hydrogen-filling station concepts with the storage systems of the transport modes. In doing so, the method must cover the gaseous, liquid and chemical delivery of the hydrogen with gaseous delivery to the end user. Evaluation criteria serve to make an objective measurable and thus comparable [32]. The evaluation criteria should not be equated here with the basic requirements for hydrogen-filling stations. It can be assumed that every refueling station concept fulfills the basic requirements, which must be met by standards or legal requirements anyway. The evaluation criteria address objectives that are fulfilled to varying degrees by each concept and take into account possible wishes of the filling station planners. For attributes to be comparable, they must have an ordinal level of measurement so that they can be ranked [33]. If attributes have a nominal measurement level, they are not comparable and must be considered in advance in the system analysis. Attributes that can be measured nominally are thus used to define the characteristics of hydrogen-refueling stations [34]. The interrelationships of influencing factors, requirements and the system architecture are shown in Figure 2. System requirements for the hydrogen-filling station can be derived from the environmental influencing factors. The requirements in turn define the characteristics and properties of the filling station system or the filling-station architecture. For example, the following requirement for the hydrogen supply of an HRS can be derived from the usage-related influencing factor “distance HRS to hydrogen supplier”: “Realize minimum transport costs and times through suitable choice of location” [35].

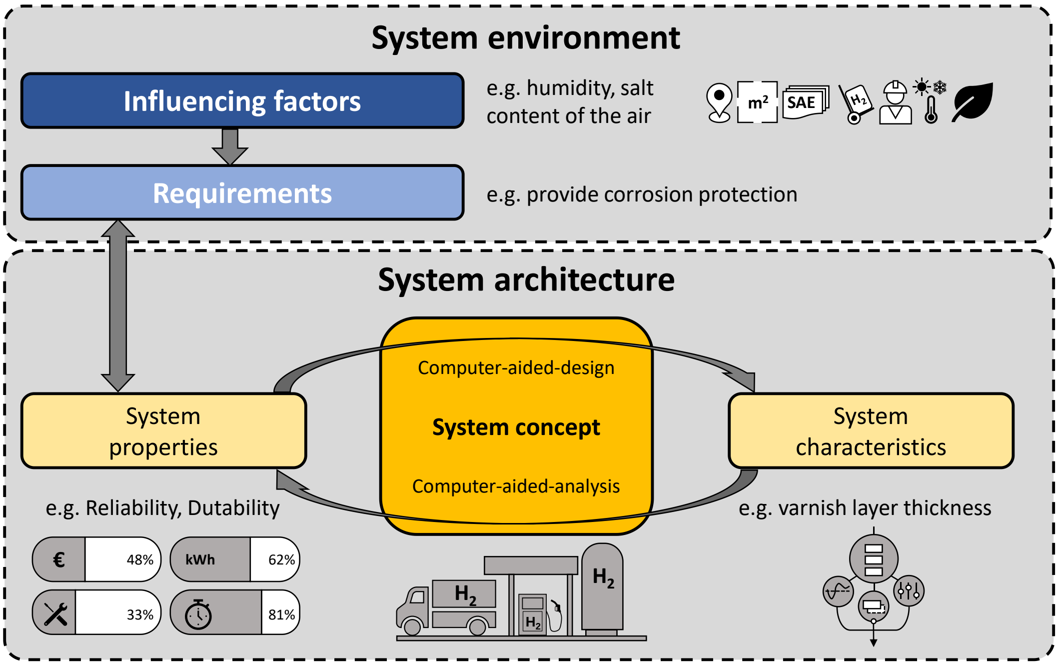


Figure 2. Relationship between system architecture, influencing factors, and requirements.

From these interrelationships, the influencing factors, the requirements for the hydrogen-filling station, and the filling station architecture itself, the criteria listed in Table 2 can be derived based on the characteristics-identified expert opinions from two workshops, in which, with the help of three experts (specialist areas: "Modelling and simulation in the field of hydrogen filling stations", "Thermal management of hydrogen filling station systems" and "Modelling and simulation of automotive fuel cells and fuel cell systems"), the most important characteristics of hydrogen-refueling stations were identified, categorized, and weighted, as shown in Appendix A. The criteria serve to highlight the possible needs of the filling station planner, so that he can weigh the criteria individually according to their relevance for the initial situation at hand.

Table 2. Differentiation of exclusion criteria and evaluation criteria.

Exclusion Criteria	Evaluation Criteria
Fueling-station area	Reliability
Handling capacity	Modularizability
Transport mode/Storage technology	Efficiency
Investments costs	Approval effort
Distance from H2 Source	Operational costs
H2 Demand	Working lifespan
Infrastructure connection	-
Average usage time	-

A subdivision of the criteria into exclusion criteria and evaluation criteria proves to be useful so that different scales can be used. The exclusion criteria describe the main parameters of HRS, while the individual wishes of HRS operators or HRS designers are described by the evaluation criteria. For the exclusion criteria, individual scales, such as the nominal scale or selection scale, can thus be used, while a uniform 5-point Likert scale is used for the evaluation criteria. The advantage of the Likert scale is that respondents can answer several questions using the same scale. This facilitates the survey and is additionally less time-consuming [36]. Exclusion criteria can be equated with the minimum requirements for the hydrogen-filling station and exclude other filling-station concepts from the outset, thereby reducing the complexity of the decision [32]. The evaluation criteria correspond to the desires, which have different degrees of intensity. Thus, the evaluation criteria only refer to the concepts that were not previously excluded by the exclusion criteria. The criteria must be evaluated with the help of experts so that a generally valid impact database of the individual components exists with regard to the criteria.

3.3. Categorization of Hydrogen-Refueling Stations

H2-filling stations are categorized by "T-shirt sizes", from XS to XXL, for easier communication. XS represents small stations, M for medium, and XL for large. These sizes are linked to specific areas in square meters, with six sizes commonly referenced in the literature [3,7,37,38]. Based on the evaluation of the different categorizations, T-shirt sizes from S to XL will be used for this method, according to the values shown in Table 3.

Table 3. Categorization of HRS based on station area.

S	M	L	XL
<200	<500	<800	>800

Hydrogen-refueling stations (HRS) are classified based on daily throughput. In [3] 200 kg/d is defined as the smallest, assigning it to size S, while [7] starts with size XS at 80 kg/d and sets size S at 212 kg/d. Sizes M and L have similar capacities. H2-Mobility specifies 4000 kg/d for XXL, a size not covered by [7]. In [38], future truck capacities are projected, assigning 938 kg/d to size XS and 30,000 kg/d to XXL. In [39], HRS is categorized into four sizes, starting with 500 kg/d for S and 3500 kg/d for XXL, differing slightly from [3] but maintaining similar overall scales. Based on the evaluation of the different categorizations, T-shirt sizes from S to XL will be used for this method, according to the values shown in Table 4.

Table 4. Categorization of HRS based on handling capacity.

S	M	L	XL
200	500	1000	4000

In [40], it is estimated that by 2030, an HRS handling 80 kg/d will cost €660,000, 212 kg/d will cost €970,000, 420 kg/d will cost €1,340,000, and 1000 kg/d will require €2,065,000. In [41] and [42] stations are categorized by the number of dispensers, with investments for gaseous delivery starting at €740,000 for 147 kg/d and rising to €2,850,000 for 2D stations. Liquid H2 stations start at 354 kg/d (€660,000) and reach €3,060,000 for 3533 kg/d [42]. An investment of €2,300,000 is expected for a 300 kg/d HRS (size S), €3,000,000 for 500 kg/d (size M), and €5 million for over 1000 kg/d according to [43]. Based on the evaluation of the different categorizations, T-shirt sizes from S to XL will be used for this method, according to the values shown in Table 5.

Table 5. Categorization of HRS based on investment costs.

	S	M	L and XL
Investment	2.3 Mio	3 Mio	<5 Mio
No. of Dispensers	1	2	3

Pipelines are most profitable for volumes over 70 t H2/d, according to [44], while liquid transport is cost-effective for 10 t H2/d over distances above 200 km. For shorter distances and volumes below 10 t H2/d, CGH2 trailers are more cost-effective [45]. In [46,47], it is suggested that liquid hydrogen is most cost-effective for distances of 300–400 km, while gaseous hydrogen is cheaper for shorter distances. Liquefying hydrogen is costly but reduces trailer needs for the same capacity [48]. Profitability depends on specific conditions, as noted in [49]. Table 6 summarizes the respective categories of delivery concept used for the THEWA method.

Table 6. Categorization of HRS based on delivery concept.

CGH2 Delivery	LH2 Delivery	Pipeline
<300 km	>300 km	
<10 t/d	<10 t/d	>10 t/d

The main criterion for selecting an HRS storage concept is available space. Cryogenic tanks are suitable for small spaces, offering higher hydrogen capacity, while trailer swaps require larger areas. For refueling needs up to 200 kg/d, low- or medium-pressure gaseous storage is recommended due to lower energy loss [50]. For over 200 kg/d with stable demand, liquid hydrogen storage using cryogenic tanks is advised, as economies of scale offset liquefaction energy loss [50]. High-pressure storage tanks are necessary for refueling at 700 bar, applicable for both CGH2 and LH2 [42,50]. Table 7 summarizes the respective categories for decision-making so that it is clear which storage components are recommended for which situational conditions.

Table 7. Categorization of HRS based on storage concept.

Medium-/Low-Pressure Storage	Fluid Storage	High-Pressure Storage
Main Storage, Trailer <200 kg H2 Uneven demand	Cryotank >200 kg H2 Even demand	CGH2 Tank At 700 bar fueling

Based on the state of the art and the collected data, decision tables were created, which showcase how the method selects certain design solutions for the inserted parameters. These decision tables are shown in Appendix B.

3.4. Customer Preference Weighting

The values assigned to the individual HRS components are derived from scientific sources, industry-based sources, and expert workshops (Appendix A). Pipeline supply requires greater approval efforts compared to pressurized gas and liquid trailers due to construction needs [40] but allows for early maintenance warnings via monitoring technologies, increasing reliability [48]. Cryogenic pumps are more reliable than gaseous hydrogen compressors (Appendix A), as compressors are more prone to failure [7]. In terms of operating costs, pipelines outperform trailer variants due to lower maintenance and the absence of fuel costs [44,48]. Cryogenic pumps, requiring less energy and maintenance, further reduce costs by eliminating the need for oil changes and thermal cooling systems [51].

The service life of pipelines is longer (40–80 years) compared to trailers (30 years) [42,48,52], with similar lifespans for both conditioning units. The scalability of liquid trailers is higher than pipelines, giving them an advantage in pairwise comparisons [41,53]. Liquid trailers also dominate pressurized gas trailers due to their ability to transport larger hydrogen volumes in both liquid and gaseous forms [46].

Regarding efficiency (Appendix A), pipelines offer the highest efficiency and lowest hydrogen transportation losses but require significant investment. With a weight of 0.56, pipelines rank highest in efficiency despite the boil-off losses in liquid hydrogen transport, where liquid trailers are outperformed by gas trailers. Cryogenic tanks, subject to up to 3% daily hydrogen vaporization, are outperformed by gaseous storage concepts [48]. However, cryogenic pumps are more energy-efficient than compressors, requiring just 10–20% of the energy due to the use of cryogenic LH2 (-253 °C) [51].

The numeric values derived for each HRS component are shown for the delivery concepts in Appendix C, for the storage concepts in Appendix D and for the conditioning concepts in Appendix E.

The criterion "petrol station area", for example, must be specified with absolute values in square meters. A possible classification here would be as follows: <150 m^2, <250 m^2, <400 m^2, <550 m^2, and >550 m^2. The 5-point Likert scale for the evaluation criteria is applied differently from an expert and user perspective and can be subdivided as follows in Table 8. This clearly shows that the experts evaluate the criteria in terms of their impact and the users evaluate the criteria in terms of importance.

Table 8. Views of the criteria assessment.

Expert View	User View
1 = very low reliability	5 = very important
2 = low reliability	4 = important
3 = medium reliability	3 = moderately important
4 = high reliability	2 = less important
5 = very high reliability	1 = not important

As in Table 9, the weightings of the individual components with regard to the criteria are denoted by x_{nm} (n = row, m = column). In this way, the individual filling-station components can be compared by experts with regard to the selected criteria.

Table 9. Weighting of the filling station components with regard to the criteria by experts.

Expert Evaluation	Criteria 1	Criteria 2
Component 1	x_{11}	x_{12}
Component 2	x_{21}	x_{22}
Sum	$\sum_{n=1}^{N} x_{n1}$	$\sum_{n=2}^{N} x_{n2}$

In order to show the relative strength of the individual component compared to the other components, a sum is formed for each criterion. By dividing the sum by the respective individual component weighting, a relative comparison of the components is possible (Table 10).

Table 10. Relative concept assessment based on the expert assessment.

Concept Evaluation	Criteria 1	Criteria 2
Concept 1	$y_{11} = \frac{x_{11}}{\sum_{n=1}^{N} x_{n1}}$	$y_{12} = \frac{x_{12}}{\sum_{n=1}^{N} x_{n2}}$
Concept 2	$y_{21} = \frac{x_{21}}{\sum_{n=1}^{N} x_{n1}}$	$y_{22} = \frac{x_{22}}{\sum_{n=1}^{N} x_{n2}}$

Thus, y represents the relative weighting and x the absolute weighting of the components. Up to this step, the method consists of an expert-based evaluation. In the next step, the users evaluate the criteria and receive an order of the filling station concepts, which is best suited for their individual concerns. The users thus evaluate the individual criteria according to their relevance, so that the individual criteria receive an individual weighting. The criteria weighting by the user is referred to as x'_m, as shown in Table 11.

Table 11. User prioritization by the users themselves.

User Evaluation	Criteria 1	Criteria 2
	x'_{11}	x'_{12}
	x'_{21}	x'_{22}

For the combination of the expert weighting and the user weighting, which results in a concept recommendation that is as objective as possible, the individual criterion weightings x'_m must be multiplied by the relative component criterion weights y_{nm} for each criterion. The sum of this multiplication results in the new variable z_{nm}, which gives the total weight for the selected components. The sum of z_{nm} gives the total weight (z_{1m}, z_{2m}, …z_{nm}) per concept, as shown in Table 12.

Table 12. Final result of the concept evaluation.

Result	Criteria 1	Criteria 2	Sum
Concept 1	$z_{11} = y_{11} \cdot x'_{11}$	$z_{12} = y_{12} \cdot x'_{12}$	$\sum_{n=1}^{N} z_{1m}$
Concept 2	$z_{21} = y_{21} \cdot x'_{21}$	$z_{22} = y_{22} \cdot x'_{22}$	$\sum_{n=1}^{N} z_{2m}$

The final totals of the individual concepts are compared and ranked. The concept with the highest total is the recommendation for the hydrogen-filling-station concept.

3.5. Detailed Method Description

The step-by-step, schematic overview of the method is shown in Figure 3. In the first step, the basic parameters are determined using the relationship triangle between filling-station area, hydrogen capacity, and investment amount. Based on these data, the filling-station category can be determined in the T-shirt sizes S, M, L, and XL. If the determined H2-filling-station capacity is less than or equal to 20 kg, a mobile HRS is recommended. If the filling-station capacity is greater than 20 kg, the delivery concepts that cannot meet the requirements of the given initial situation are excluded using the initial data and the categories formed.

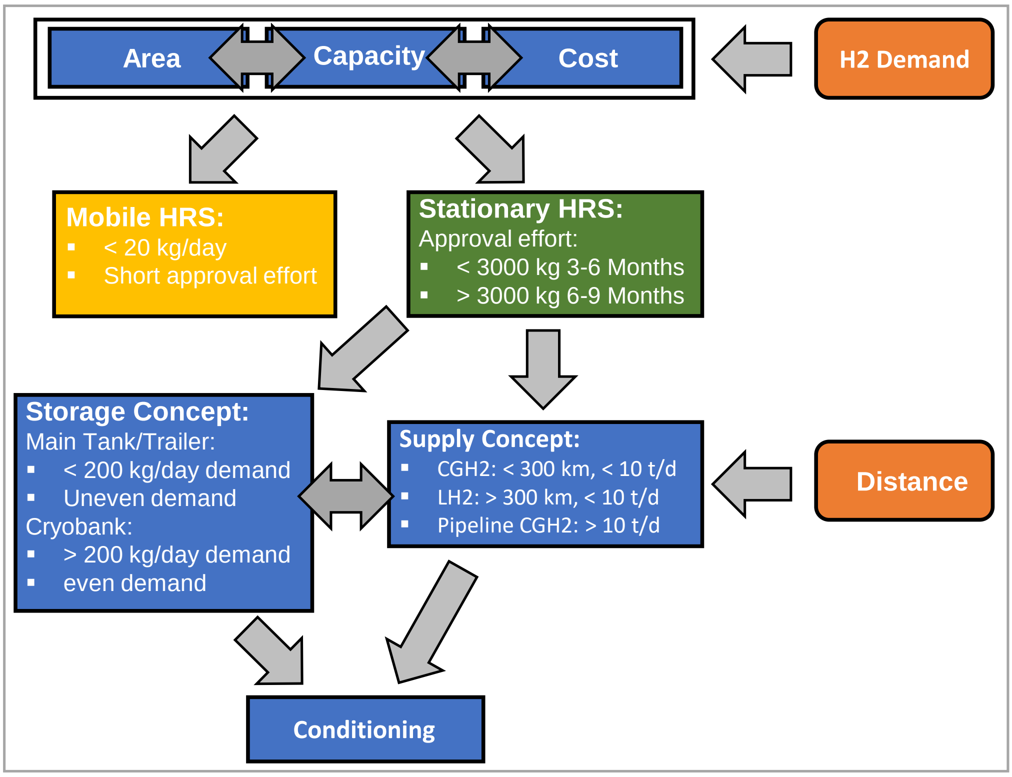


Figure 3. Schematic overview of the steps of the devised method.

The influencing factors of the infrastructural conditions (source distance, liquid delivery, gaseous delivery, pipeline infrastructure) are also taken into account. If one of these influencing factors is given by the user input, these influencing factors are used to check whether a further delivery concept can be ruled out. Based on the delivery concept and the hydrogen capacity, the feasible storage concepts are then also determined by means of an exclusion procedure. The selection of the storage concepts is based on the relevant t-shirt category and the supply concept. The conditioning concept is determined with the help of the delivery and storage concepts that are further considered.

4. Tool Implementation and Case Study

This chapter describes the implementation of the THEWA method in the form of a VBA tool and the testing of this tool based on a case study.

To simplify the application of the method, it is recommended to implement it in a tool. Using Visual Basic for Application (VBA) allows for fast programming and user-friendly interface. The tool relies on two databases: one containing hydrogen-filling-station components and another with expert evaluations of these components. The user interface enables individual weighting of criteria on a 5-point Likert scale, after which the tool generates an ordered list of the best concepts. The result and input interfaces are shown in Appendices F and G, respectively. The tool's functionality was tested with a fictitious scenario for a hydrogen-filling station in Braunschweig. The station is located near a highway and will initially handle 150 kg H2/day, with the capacity to increase to 500 kg/day due to future hydrogen bus fleet operations. Vehicles to be refueled include cars, trucks, and buses, with a scalable design for future demand. The available space is 200–300 m^2, and gaseous hydrogen will be supplied from Salzgitter, 35 km away. Priorities for the planner are long service life, high reliability, and good modularity, while operating costs are secondary. Data are entered via the UserForm (Appendix G). The station's expected investment is approximately €0.85 million for an H2 capacity of 122 kg/day within the given space. A pressurized-gas trailer is initially recommended, with Concepts 1 to 4 evaluated. Concepts 1, 2, and 3 perform equally well in criteria like approval effort, efficiency, service life, and operating costs, while Concept 4 ranks lower. Concept 1 is the most modular and reliable. Concept 3 and 4 share characteristics, but Concept 3 is visually prioritized due to stronger performance. The evaluation of concepts is visualized in Appendix F. The input data for the tool are shown in Table 13.

Table 13. Case-study parameters.

Case-Study Parameters
Source distance: 35 km
H2 demand: Stable demand
Handling capacity: 150 kg H2 in future up to 500 kg H2 per day
Vehicle classes to be refueled: Buses, trucks, cars
Investment ceiling: Not given
Filling station use: Open ended planning
Filling station area: At least 200 m^2
Service life, reliability and modularizability are rated as very important
As little approval effort as possible
Efficiency is important
Operating costs secondary

5. Results

The result of this paper, the THEWA evaluation method and its software implementation, provides a novel approach in characterizing and planning HRS in the early development phase while addressing the challenge of accelerating hydrogen-refueling station (HRS) infrastructure development. This method provides a structured and scientifically grounded approach to the evaluation and selection of HRS concepts, incorporating both exclusion and evaluation criteria. These criteria were identified through literature review and an expert workshop with industry professionals, ensuring that the method reflects realistic decision-making scenarios.

The exclusion criteria, categorized by "T-shirt sizes", allow for the systematic elimination of unsuitable technical solutions based on key factors such as station area, handling capacity, transport mode, storage technology, investment costs, distance from the hydrogen source, demand, infrastructure connection, and average usage time. These categories help simplify the decision-making process by focusing on the most critical factors that impact HRS feasibility.

The evaluation criteria, including reliability, modularity, efficiency, approval effort, operational costs, and lifespan, were weighted based on expert input gathered during the workshop. The weighting process utilizes an adapted multi-criteria decision analysis (MCDA) method, ensuring that each criterion is appropriately valued in line with its importance. A 5-point Likert scale was employed for the evaluation, with a pre-set weighting scheme based on the expert input, which users can adjust according to their specific preferences.

This method was implemented into a tool using Excel's VBA programming, providing a user-friendly interface that integrates both exclusion and evaluation steps. The tool was validated using a case study of a hypothetical HRS-planning scenario. The tool successfully filtered unsuitable solutions and ranked the viable options based on user input, demonstrating the method's ability to provide a quick and accurate overview of possible technical solutions.

The case-study results aligned with the expectations set by the expert-defined criteria, confirming the tool's effectiveness and reliability in aiding the HRS-planning process. By accelerating the decision-making process and offering flexibility in the weighting of preferences, this tool contributes significantly to the efficient development of HRSs.

6. Discussion

The method proves to be a useful tool to accelerate the planning phase and to provide initial guidance for the construction of hydrogen-refueling stations. Due to the expert evaluation for the refueling-station components, the effort for the method is large but offers the advantage of scalability. This means that if further technical options for hydrogen-filling stations are developed, these can be implemented in the method's database. Furthermore, a flexible combination of hydrogen-refueling station systems and vehicle-side storage technologies is possible through the component evaluation. Thus, it fulfills the requirement of flexible combination possibilities set in the THEWA project. Likewise, it fulfills the requirement of taking into account gaseous, liquid, and chemical delivery. A disadvantage of this assessment method is the current dependence of the method on expert assessments. This means that the method is only applicable as soon as a representative number of experts from different disciplines weigh the components. Therefore, the goal is to collect data-based information from the components so that the method is independent of expert assessments in the future. If this succeeds, the method and the tool will be a good support for filling station operators to find the right filling-station concept for the planning phase of the individual project and thus also to accelerate the nationwide hydrogen-filling station expansion. According to [54], the influencing factors must completely cover the decision problem, which is why a more detailed analysis of the decision problem at hand must be carried out so that all relevant influencing factors have been considered. In particular, the allocation to the exclusion criteria and evaluation criteria must be taken into account. In the further development of the evaluation method, an optimized user tool will be developed, which will automatically generate a spider diagram for the presentation of the results.

7. Outlook

With the recommendation of a filling-station concept, a suitable guideline for the construction of an HRS could also be recommended. This would further simplify the planning phase and provide planning support from the conception phase through to completion of the filling station. The implementation of price indices in the size degression would be another exciting topic for student work. With the help of price indices, regional or temporal price differences can be taken into account. This would enable more accurate investment estimates, as price increases due to inflation in 2023 compared to 2019 could be taken into account, for example. Another topic is the extended review of the consistency of pairwise comparisons. A suitable method for this is the eigenvalue method, which is also used in the Analytic Hierarchy Process (AHP). There is potential for optimization in the graphical presentation of the results, in that it is possible to individually select which petrol station concepts are to be compared graphically. In this way, the tool can be made more user-friendly. The THEWA assessment tool can also be implemented as a petrol station configurator on a website. This makes it possible to make the THEWA assessment tool available to service station providers and offer customers an initial orientation aid. In this context, an integrated print function in the THEWA assessment tool would also be helpful. With the help of a button, the appropriate data sheet could be printed out directly or saved as a PDF so that the concept recommendation can be saved. Other infrastructure features could also be implemented in the tool. So far, pure hydrogen-filling stations have been considered, but H2-filling stations are often also integrated into conventional filling stations. These effects can be investigated through further work.

Author Contributions: Conceptualization, B.N.; Methodology, D.G. and A.S.; Software, D.G.; Investigation, D.G.; Writing—original draft, D.G.; Writing—review & editing, B.N. and A.S.; Supervision, B.N. and T.V.; Validation B.N.; Visualization, D.G. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: The publication of this paper has been funded by the TU Braunschweig Publication Fund.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: This work was conducted in the context of the project "THEWA" (Thermal Management of Hydrogen Refuelling Stations), which is funded by the funding initiative "Niedersächsisches Vorab" (Lower Saxony Advance) and the Lower Saxony Ministry of Science and Culture (MWK). THEWA receives industrial support from the companies Shell Oil Deutschland GmbH, Maximator GmbH, and MAN Truck & Bus SE (MAN) as well as TLK-Thermo GmbH.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Abbreviation	Meaning
HRS	Hydrogen refueling station
CGH2	Compressed Hydrogen
LCOH	Levelized Cost of Hydrogen
MCDA	Multi Criteria Decision Analysis
AHP	Analytic Hierarchy Process
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
MAUT	Multi-Attribute Utility Theory
ANN	Artificial Neural Networks
FCE	Fuzzy Comprehensive Evaluation
DEA	Data Envelopment Analysis
D	Dispenser
LH2	Liquid Hydrogen
VBA	Visual Basic for Applications

Appendix A —Summary of the Results of the Expert Workshop

Components	**Expert Evaluation**			
	Energy demand	**Efficiency**	**Reliability**	**Modularisiability**
Delivery:				
Pipeline	5 (very low)	3 (medium)	3 (medium)	3 (medium)
Fluid Trailer	4 (low)	1 (very high)	1 (very high)	2 (high)
Gas Trailer	5 (very low)	4 (low)	3 (medium)	2 (high)
Storage:				
CGH2 Tank	3 (medium)	2 (high)	2 (high)	2 (high)
Trailer	3 (medium)	2 (high)	2 (high)	3 (medium)
Main Storage CGH2 Tank	3 (medium)	2 (high)	3 (medium)	2 (high)
Cryotank LH2+CGH2 Tank	3 (medium)	3 (medium)	2 (high)	2 (high)
Conditioning:				
Compressor	1 (very high)	3 (medium)	3 (medium)	2 (high)
Cryopump and Expansionvalve	2 (high)	2 (high)	2 (high)	2 (high)

Appendix B —Decision Tables for Selecting Concepts Based on Input Parameters

Nr.	Periphery	Capacity	Transport distance	Selection
1	-	<10,000 kg	<300 km	Gastrailer
2	-	<10,000 kg	>300 km	Fluidtrailer
3	-	>10,000 kg	-	Pipeline
4	Gastrailer	<10,000 kg	<300 km	Gastrailer
5	Gastrailer	<10,000 kg	>300 km	Gastrailer
6	Gastrailer	>10,000 kg	-	Pipeline
7	Fluidtrailer	<10,000 kg	<300 km	Fluidtrailer
8	Fluidtrailer	<10,000 kg	>300 km	Fluidtrailer
9	Fluidtrailer	>10,000 kg	-	Pipeline
10	Pipeline	<10,000 kg	<300 km	Pipeline
11	Pipeline	<10,000 kg	>300 km	Pipeline
12	Pipeline	>10,000 kg	-	Pipeline

Transport Capacity	Transport distance		Storage Capacity	Demand		Decision
<10,000 kg	<300 km	CGH2	<200 kg	irregular	CGH2	CGH2
<10,000 kg	>300 km	LH2	>200 kg	regular	LH2	LH2
>10,000 kg	-	CGH2	<200 kg	irregular	CGH2	CGH2
>10,000 kg	-	CGH2	>200 kg	regular	LH2	CGH2
<10,000 kg	<300 km	CGH2	>200 kg	regular	LH2	CGH2
<10,000 kg	>300 km	LH2	<200 kg	irregular	CGH2	CGH2

	Decision Situation		Deciding Parameter
Area	-	-	**Area**
Area	Capacity	Cost	**Area**
Area	Capacity	-	**Area**
Area	-	Cost	**Area**
-	Capacity	Cost	**Capacity**
-	Capacity	-	**Capacity**
-	-	Cost	**Cost**

Appendix C —Paired Comparison of Delivery Concepts During the Workshop

Approval Effort

H2 Supply	Pipline	Fluid Trailer	Gas Trailer	Sum	Weight
Pipeline	1	2	1	4	0.44
Fluid Trailer	0	1	0	1	0.11
Gas Trailer	1	2	1	4	0.44
				9	1

Reliability

H2 Supply	Pipline	Fluid Trailer	Gas Trailer	Sum	Weight
Pipeline	1	0	1	2	0.22
Fluid Trailer	2	1	2	5	0.56
Gas Trailer	1	0	1	2	0.22
				9	1

Modularizability

H2 Supply	Pipline	Fluid Trailer	Gas Trailer	Sum	Weight
Pipeline	1	2	0	3	0.33
Fluid Trailer	0	1	0	1	0.11
Gas Trailer	2	2	1	5	0.56
				9	1

Efficiency

H2 Supply	Pipline	Fluid Trailer	Gas Trailer	Sum	Weight
Pipeline	1	0	2	4	0.33
Fluid Trailer	2	1	2	1	0.56
Gas Trailer	0	0	1	4	0.11
				9	1

Operational Costs

H2 Supply	Pipline	Fluid Trailer	Gas Trailer	Sum	Weight
Pipeline	1	0	1	2	0.22
Fluid Trailer	2	1	2	5	0.56
Gas Trailer	1	0	1	2	0.22
				9	1

Working lifespan

H2 Supply	Pipline	Fluid Trailer	Gas Trailer	Sum	Weight
Pipeline	1	0	1	2	0.22
Fluid Trailer	2	1	2	5	0.56
Gas Trailer	1	0	1	2	0.22
				9	1

Appendix D —Paired Comparison of Storage Concepts During the Workshop Approval Effort

H2 Storage	CGH2 Tank	Trailer	Main Storage CGH2 Tank	Cryotank LH2+CGH2 Tank	Weight
CGH2 Tank	1	1	1	1	**0.25**
Trailer	1	1	1	1	**0.25**
Main Storage CGH2 Tank	1	1	1	1	**0.25**
Cryotank LH2+CGH2 Tank	1	1	1	1	**0.25**
					1

Reliability

H2 Storage	CGH2 Tank	Trailer	Main Storage CGH2 Tank	Cryotank LH2+CGH2 Tank	Weight
CGH2 Tank	1	0	0	0	**0.0625**
Trailer	2	1	1	1	**0.3125**
Main Storage CGH2 Tank	2	1	1	1	**0.3125**
Cryotank LH2+CGH2 Tank	2	1	1	1	**0.3125**
					1

Modularizability

H2 Storage	CGH2 Tank	Trailer	Main Storage CGH2 Tank	Cryotank LH2+CGH2 Tank	Weight
CGH2 Tank	1	0	0	0	**0.0625**
Trailer	2	1	1	1	**0.3125**
Main Storage CGH2 Tank	2	1	1	1	**0.3125**
Cryotank LH2+CGH2 Tank	2	1	1	1	**0.3125**
					1

Efficiency

H2 Storage	CGH2 Tank	Trailer	Main Storage CGH2 Tank	Cryotank LH2+CGH2 Tank	Weight
CGH2 Tank	1	1	1	2	**0.3125**
Trailer	1	1	1	2	**0.3125**
Main Storage CGH2 Tank	1	1	1	2	**0.3125**
Cryotank LH2+CGH2 Tank	0	0	0	1	**0.0625**
					1

Operational Costs

H2 Storage	CGH2 Tank	Trailer	Main Storage CGH2 Tank	Cryotank LH2+CGH2 Tank	Weight
CGH2 Tank	1	1	1	1	**0.25**
Trailer	1	1	1	1	**0.25**
Main Storage CGH2 Tank	1	1	1	1	**0.25**
Cryotank LH2+CGH2 Tank	1	1	1	1	**0.25**
					1

Working lifespan

H2 Storage	CGH2 Tank	Trailer	Main Storage CGH2 Tank	Cryotank LH2+CGH2 Tank	Weight
CGH2 Tank	1	1	1	1	**0.25**
Trailer	1	1	1	1	**0.25**
Main Storage CGH2 Tank	1	1	1	1	**0.25**
Cryotank LH2+CGH2 Tank	1	1	1	1	**0.25**
					1

Appendix E —Paired Comparison of Conditioning Concepts During the Workshop Approval Effort

H2 Conditioning	Pipline	Fluid Trailer	Sum	Weight
Compressor	1	1	**2**	**0.5**
Cryopump and Expansionvalve	1	1	**2**	**0.5**
			4	**1**

Reliability

H2 Conditioning	Pipline	Fluid Trailer	Sum	Weight
Compressor	1	0	**1**	**0.25**
Cryopump and Expansionvalve	2	1	**3**	**0.75**
			4	**1**

Modularizability

H2 Conditioning	Pipline	Fluid Trailer	Sum	Weight
Compressor	1	1	**2**	**0.5**
Cryopump and Expansionvalve	1	1	**2**	**0.5**
			4	**1**

Efficiency

H2 Conditioning	Pipline	Fluid Trailer	Sum	Weight
Compressor	1	0	**1**	**0.25**
Cryopump and Expansionvalve	2	1	**3**	**0.75**
			4	**1**

Operational Cost

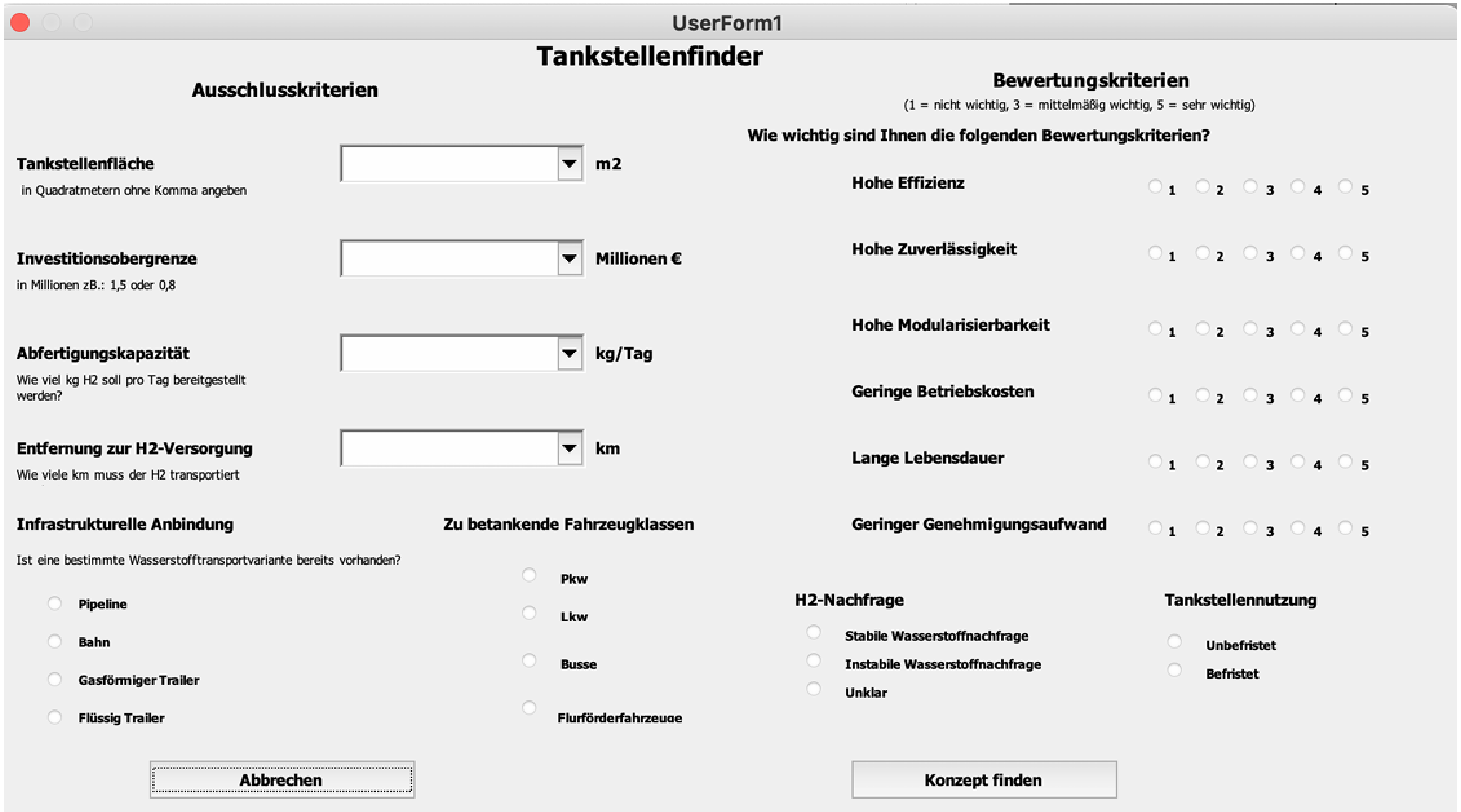
H2 Conditioning	Pipline	Fluid Trailer	Sum	Weight
Compressor	1	0	**1**	**0.25**
Cryopump and Expansionvalve	2	1	**3**	**0.75**
			4	**1**

Working lifespan

H2 Conditioning	Pipline	Fluid Trailer	Sum	Weight
Compressor	1	1	**2**	**0.5**
Cryopump and Expansionvalve	1	1	**2**	**0.5**
			4	**1**

Appendix F —Result Interface of the Software Implementation

Appendix G —Input Interface of the Software Implementation



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