International Journal of Hydrogen Energy 68 (2024) 159–169

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Uncertainty quantification in hydrogen tank exchange: Estimating maintenance costs for new aircraft concepts

Jennifer Ramm *, Ahmad Ali Pohya, Kai Wicke, Gerko Wende

German Aerospace Center (DLR), Institute of Maintenance, Repair and Overhaul, Hamburg, 21129, Germany

ARTICLE INFO

Keywords:
Hydrogen-powered aircraft
Life cycle cost analysis
Maintenance costs estimation
Uncertainty quantification
Dempster–Shafer theory of evidence
Global sensitivity analysis

ABSTRACT

The increasing demand for sustainable air mobility has led to the development of innovative aircraft designs, necessitating a balance between environmental responsibility and profitability. However, despite technological advancements, there is still limited understanding of the maintenance implications for hydrogen systems in aviation. The aim of this study is to estimate the maintenance costs of replacing the hydrogen storage system in an aircraft as part of its life cycle costs. To achieve this, we compared conventional and hydrogen-powered aircraft. As there is insufficient data for new aircraft concepts, typical probabilistic methods are not applicable. However, by combining global sensitivity analysis with Dempster–Shafer Theory of Evidence and discrete event simulation, it is possible to identify key uncertainties that impact maintenance costs and economic efficiency. This innovative framework offers an early estimate of maintenance costs under uncertainty, enhancing understanding and assisting in decision-making when integrating hydrogen storage systems and new aviation technologies.

1. Introduction

The demand for aviation has increased significantly, resulting in a rise in CO_2 and non-CO_2 emissions. To remain competitive and environmentally conscious, it is imperative to develop innovative solutions towards aircraft that have significantly reduced emissions. Promising alternative propulsion systems and energy sources are under development, with hydrogen emerging as a potential alternative fuel that could reduce emissions by 50% or more [1,2].

The first concepts for hydrogen-powered aircraft were already developed several decades ago and have been further developed in recent years [3–10]. Most of these studies focus on fundamental physics, current technology assessments, and their implications for aircraft design, cost, certification, and environmental considerations [11–13]. However, for hydrogen-powered aircraft concepts to succeed in the future, it is essential to focus not only on minimizing their environmental impact but also on establishing a viable business case for operators and manufacturers. A systematic process of concept selection and show stopper identification in early design phases is crucial to the development of such novel aircraft prototypes, particularly those focused on hydrogen use, in order to optimally allocate development resources. Therefore, various methodologies exist to facilitate early-stage cost assessments [14,15]. These methodologies use cost estimation relationships based on regression analysis of existing airline fleets and financial data. Some of these methods were adapted for alternative aircraft concepts. For instance, Hoelzen et al. [16] presented a method for estimating the change on the operating costs for a hydrogen-powered aircraft, with ranges in the overall result leading from a possible decrease to an increase in direct operating costs of up to 112%. A comparative study by Verstraete et al. [17] investigated the introduction of hydrogen as a fuel in hydrogen-powered aircraft compared to kerosene-powered aircraft, finding similar operating costs between both aircraft concepts. However, it should be noted that the exact method for calculating cost was not explained in detail in this study. Since hydrogen-powered aircraft usually incorporate an electric infrastructure, it is important to broaden the range of methods to encompass not only those focused on hydrogen-powered aircraft, but also those focused on hybrid-electric aircraft concepts. For example, Vercella et al. [18] introduced a technique to evaluate the impact of system electrification on the operational expenses of regional aircraft. This involved incorporating advancements in more-electric and all-electric aircraft technologies into the calculations. Similarly, Ploetner et al. [19] expanded a model by integrating battery characteristics into the assessment of operational costs for electric aircraft. Furthermore, Hoelzen et al. [20] modified a regression method to estimate the operational costs of hybrid-electric aircraft and explore the significance of batteries in such propulsion systems. Ahluwalia et al. [21] assessed the techno-economic feasibility of electric vertical take-off and landing air taxis with alternative powertrains, comparing battery, fuel cell, and hybrid powertrains for both multi-rotor and tilt-rotor crafts. By combining a detailed bottom-up approach with the necessary adaptations

* Corresponding author.
E-mail address: jennifer.ramm@dlr.de (J. Ramm).

https://doi.org/10.1016/j.ijhydene.2024.04.157
Received 18 December 2023; Received in revised form 3 April 2024; Accepted 14 April 2024
Available online 25 April 2024

Abbreviations

APU	Auxiliary Power Unit
APU+	fuel cell secondary power supply unit
BBA	Basic Belief Assignment
CoG	Centre of Gravity
DOC	Direct Operating Cost
DSTE	Dempster-Shafer Theory of Evidence
EIS	Entry Into Service
EXACT	Exploration of Electric Aircraft Concepts and Technologies
FC	Flight Cycle
FCS	Fuel Cell System
FH	Flight Hours
GSA	Global Sensitivity Analysis
LH2	Liquid Hydrogen
LHS	Latin Hypercube Sampling
LYFE	Lifecycle Cash Flow Environment
MCS	Monte-Carlo Simulation
MRO	Maintenance, Repair and Overhaul
NPV	Net Present Value
PtL	Power-to-Liquid
SCSA	Structural and Correlative Sensitivity Analysis

for hydrogen-powered vehicles, they can be evaluated with greater granularity over their entire life cycle. Therefore, Ramm et al. [22] presented a methodology to evaluate a new hybrid-electric hydrogen aircraft concept against conventional kerosene aircraft concepts in terms of economic and environmental impacts. The assessment employs a detailed and adapted discrete event simulation model, which is not based on a regression model.

All of these approaches include adjustments for new aircraft concepts, some of which only affect individual systems or are presented in an unclear manner. Therefore, despite their modified nature, they have a significant lack of transparency, which is why the usefulness of all the above methods is questionable, as they often make predictions that go beyond the available data. This can be problematic because uncertainties in the predictions are not taken into account, and final statements without consideration of uncertainties can potentially influence design decisions incorrectly. In the broader context of hydrogen use in aviation, the quantification of uncertainties has emerged as a critical aspect in assessing the viability of hydrogen as an alternative fuel source. For instance, Kim et al. [23] and Sabio et al. [24] have demonstrated the importance of considering demand uncertainty in hydrogen supply chains, emphasizing the impact of such uncertainties on network costs and strategic planning. Additionally, Lee et al. [25] utilized Monte Carlo simulations to conduct an uncertainty analysis for hydrogen production, underscoring the relevance of economic evaluations under uncertain conditions. Furthermore, the life cycle evaluation of hydrogen and other potential fuels for aircraft by Biçer and Dincer [26] emphasizes the necessity of considering environmental and cost factors in the transition to hydrogen-powered aviation.

Although several preliminary studies have been carried out on the design of aircraft and cryogenic tanks [27–29], little information is available on a comprehensive analysis of required maintenance activities. Nevertheless, detailed maintenance considerations are necessary to ensure safety [30], highlighting one of the most critical factors for the use of hydrogen in aviation. From an operational, safety and economic point of view, an important question is whether the hydrogen tanks need to be replaced during the lifetime of the aircraft and what impact this will have on economic efficiency. To answer this question, it is essential to conduct a comprehensive analysis of life cycle costs, including maintenance. Therefore, the objective of this study is to systematically estimate the impact of uncertainty in maintenance assumptions of a hydrogen tank exchange on maintenance costs and overall economic efficiency of a hydrogen-powered aircraft concept. For this purpose, we have investigated the effectiveness of the Dempster–Shafer Theory of Evidence (DSTE) approach by combining evidence gathered from expert interviews. This allows us to effectively address the uncertainties surrounding maintenance, resulting in more reliable cost estimates. Furthermore, we performed a Global Sensitivity Analysis (GSA) to quantify the impact of uncertainties within input variables on the estimated costs. This analysis helps to identify the key drivers of cost variation and to understand how changes in different parameters affect the overall cost estimate. By systematically varying input variables and observing their effects, we were able to identify critical factors to guide further investigation and refine design decisions.

This feasibility study serves as a demonstration of early life cycle cost estimation, considering uncertainties due to the early product development process, using a novel framework which combines DSTE and GSA. The results of this study contribute to the establishment of a comprehensive knowledge how uncertainties, such as those in maintenance, can be accounted for and how the associated boundary conditions affect economic assessments. More importantly, this information can be effectively fed back into the development process, facilitating informed decision making.

The remainder of this paper is structured as follows. Section 2 describes the novel framework of combining DSTE with GSA and how this framework is integrated into the discrete event life cycle simulation and economic evaluation methodology called LYFE (Lifecycle Cash Flow Environment). In Section 3 the use case of this study is explained in detail and in Section 4 the results are presented. First, the results of the expert interviews are analyzed according to DSTE, which then serve as input for the further calculations. Second, the overall economic efficiency results are described and a detailed cost breakdown is depicted and analyzed. The paper concludes with a summary and outlook in Section 5.

2. Method

This section describes the framework used for the early estimation of maintenance costs and overall economic efficiency. The framework itself is comprised of three elements: The use of DSTE as an alternative to conventional probabilistic methods (Section 2.1), the use of an appropriate GSA method that can handle the outputs of DSTE (Section 2.2), and the integration into the life cycle spanning discrete event simulation (Section 2.3).

2.1. Uncertainty quantification with evidence theory

Uncertainties are inevitable in simulations and predictions, and they can originate from a variety of sources, especially in multidisciplinary problems. While there is no universal definition of uncertainty [31], a common approach is to differentiate between *epistemic* and *aleatory* uncertainties [32]. If the uncertainty is considered to be reducible, for instance, when investing additional resources in research and development, it is considered to be *epistemic*. An example would be the final weight of an aircraft design when it is estimated in the early development stages. With more time passing and more sophisticated engineering techniques being employed, epistemic uncertainties can theoretically be reduced to a single, deterministic value. In contrast, *aleatory* uncertainties are non-reducible, often stemming from a physical variability or from an otherwise non-predictable domain. Examples for aleatory uncertainties include, but are not limited to, manufacturing tolerances, temperature fluctuations, or the expected fuel price in the future.

Different methods and theories exist for quantifying, propagating, and analyzing these uncertainties. The prevalent approach involves the use of probability theory, especially when large amounts of data for describing the uncertain parameters are available. However, due to the law of large numbers and central limit theorem, probabilistic concepts fall short when data are scarce. This is where the strengths of DSTE [33, 34] becomes apparent. This theory deals specifically with subjective uncertainty [35] and lack of knowledge [36], making it suitable for situations characterized by both limited empirical data and available expert knowledge. These abilities make DSTE suitable for applications in quantifying epistemic uncertainty. Whereas probability theory interprets uncertainty with one single measure, *i.e.*, probability, DSTE uses a two-valued interpretation. Here, the information (or evidence) about a hypothesis can be split into those parts that support it and those that contradict it. The supporting evidence is referred to as *Belief*, whereas those that do not contradict the hypothesis represent *Plausibility*. Since the probabilistic approaches are suitable for aleatory uncertainties and are well researched, in this study we focus on epistemic uncertainties and evidence theory.

In order to obtain the Belief and Plausibility measures for a hypothesis, a *Basic Belief Assignment (BBA)*, referred to as m, is needed first. In the context of scarce data, m is often obtained through expert elicitation in the form of systematic interviews. Consider a frame of discernment Ω. The BBA is formally defined as

$$m : 2^{\Omega} \rightarrow [0, 1] \tag{1}$$

if the following two requirements are met:

$$m(\emptyset) = 0 \tag{2}$$

$$\sum_{A \in 2^{\Omega}} m(A) = 1 \tag{3}$$

The Belief function Bel is now calculated as the sum of all masses of $B \in 2^{\Omega}$ which are a subset or are equal to A, *i.e.*,:

$$\mathrm{Bel}(A) = \sum_{\emptyset \neq B \subseteq A} m(B) \tag{4}$$

The complementary Plausibility function is formally defined as:

$$\mathrm{Pl}(A) = \sum_{B \cap A \neq \emptyset} m(B) \tag{5}$$

Based on the definitions of Belief and Plausibility, the methods of DSTE also include calculating uncertainty spaces (*i.e.*, complementary cumulative Belief and Plausibility functions) across the entire output domain (see Helton et al. [37,38] for further reading). While these can be useful, in the context of the present study, these steps are omitted as they require a very large sample size that is difficult to realize with the discrete event simulation. Furthermore, the evidence-based output uncertainty spaces are complex and difficult to interpret, rendering their use in the development process of hydrogen-based aircraft suboptimal. Instead, our process focuses on drawing samples from so-called *Belief spaces*, which are then fed to the Monte–Carlo Simulation (MCS) and subsequently to the GSA. This results in distributions and sensitivity indices that can be interpreted and fed back to technology developers and aircraft designers. The Belief spaces are constructed from the BBAs which are obtained from the expert interviews.

To achieve this, the first step is to design the interview process itself. It is advisable to conduct the interviews individually without revealing the answers from other experts to avoid potential bias. Furthermore, it is recommended to provide a brief explanation of the Belief-driven statements, ideally using an easy-to-understand example. This is important because DSTE is not widely used, and peers may find it challenging to grasp the concept of Belief [37,39,40]. During these interviews, experts are asked to provide one or more Belief values for one or more intervals of a specific uncertain parameter. In the subsequent step, these BBAs can be used to create Belief density functions for this parameter. A common method to calculate the Belief density function of a single expert statement involves dividing the BBA by the width of the chosen interval. In other words, the larger the interval, the lower the Belief density. Repeating this process for all BBAs results in a general Belief space for each uncertain input. To achieve a combined Belief, multiple expert statements can be combined using one of the many available combination rules provided by DSTE. Ultimately, these Belief spaces are transformed to cumulative density functions, from which samples are drawn using the Smirnov transformation [41]. All of these steps (including the aforementioned calculation of the output uncertainty) are automated in the used `dste` python package [42], which has been developed by DLR.

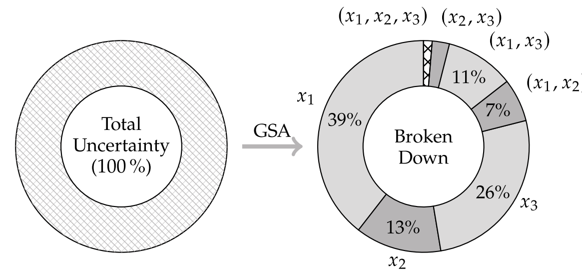


Fig. 1. Example of a breakdown of total uncertainty into its first, second, and third order effects for a function with three uncertain input parameters [45].

2.2. Global sensitivity analysis

Despite receiving increasing attention in recent years, there is still a lack of a widespread adoption of GSA. Generally speaking, GSA serves multiple purposes [43–45]:

- *Obtaining scientific insights* regarding the potentially complex problem at hand, *i.e.*, identifying and understanding parameter causalities and their interaction [46].
- *Reducing complexity* by removing non-influential factors from a system or fixing non-influential uncertainties to their most likely value [47].
- *Decision support* in the context of product development and uncertainty quantification, *i.e.*, future efforts can be guided quantitatively to the most relevant uncertainties [48,49].

In the context of the present study, the main added value of GSA lies in its decision support aspect. In other words, we utilized GSA to identify the most influential uncertainties in order to direct future research and development in the context of hydrogen aircraft. To achieve this, GSA involves using the total output uncertainty, measured, for example, by the variance of a MCS and breaks it down to its constituent input uncertainties. This process is schematically depicted in Fig. 1, where the breakdown illustrates the primary effects x_i, the secondary effects (x_i, x_j), and the tertiary effects (x_i, x_j, x_k), which are usually neglected [32].

It should be noted that a number of different GSA techniques exist, each differing fundamentally in how they interpret sensitivity, the types of sensitivities they provide, their ability to quantify parameter dependence, and their support for given-data situations. The latter aspect is of utmost importance in the context of the evidence-based sampling approach. Therefore, the so-called Structural and Correlative Sensitivity Analysis (SCSA) method for GSA was chosen for this framework [50]. The SCSA provides the direct influence of each input uncertainty (*i.e.*, the primary effect), their interaction (*i.e.*, the secondary effect), and a correlative term quantifying the sensitivity of each parameter considering their dependency.

For clarity, it should be noted that a high primary sensitivity index S_1 for a particular uncertain input, *e.g.*, $S_1(x_3) = 0.7$, indicates that a

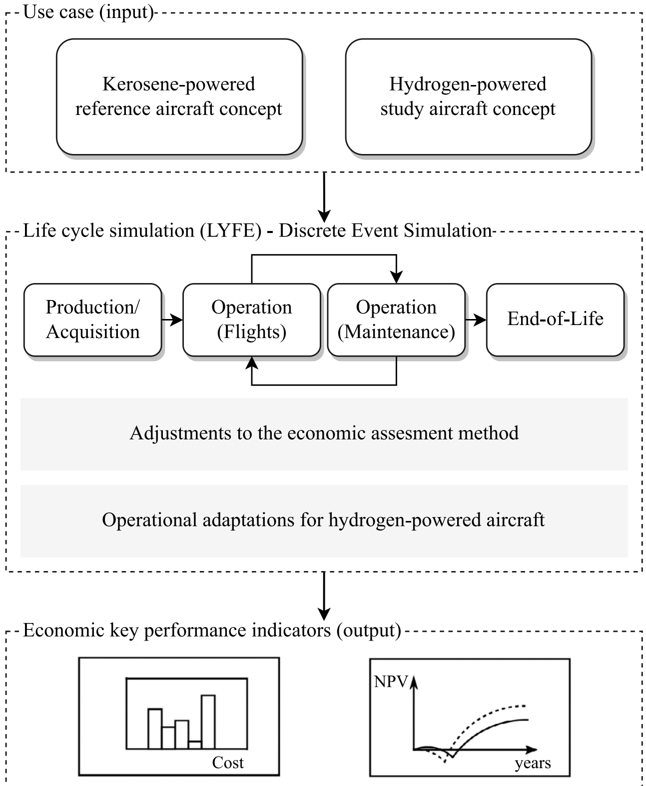


Fig. 2. Structure of LYFE (Lifecycle Cash Flow Environment) [22,51,52].

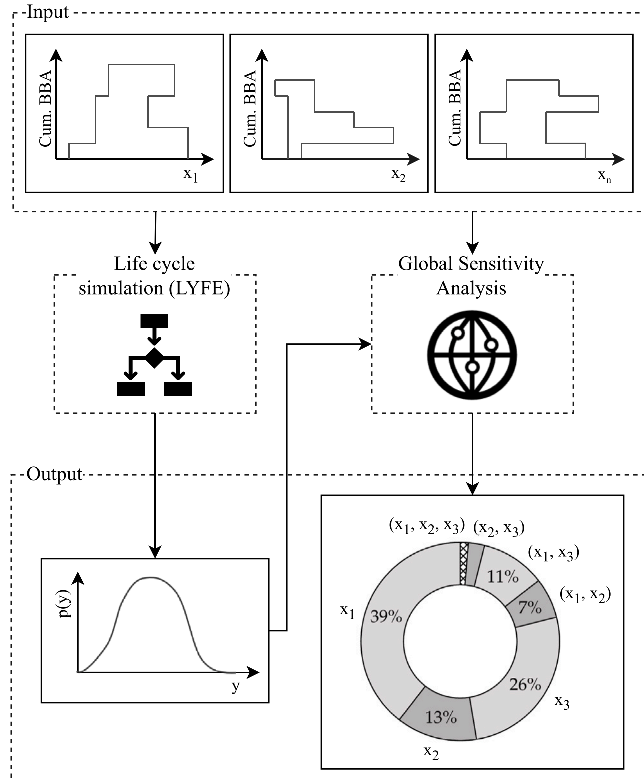


Fig. 3. Framework integration of Dempster–Shafer Theory of Evidence combined with Global Sensitivity Analysis into LYFE's discrete event simulation.

large portion of the output uncertainty (*e.g.*, variance) can be reduced if said parameter were to be fixed. A high secondary sensitivity index S_2 for two parameters, *e.g.*, $S_2(x_2, x_3) = 0.6$, indicates a large non-linear effect when both parameters are considered simultaneously. This indicates that the sensitivity of the combined parameters is higher than the sum of the individual sensitivities. The correlative term, which can be either positive or negative, quantifies the impact of the correlation itself. However, in this study the input parameters are assumed to be independent, meaning the correlative term is not evaluated.

2.3. Integration into discrete event simulation

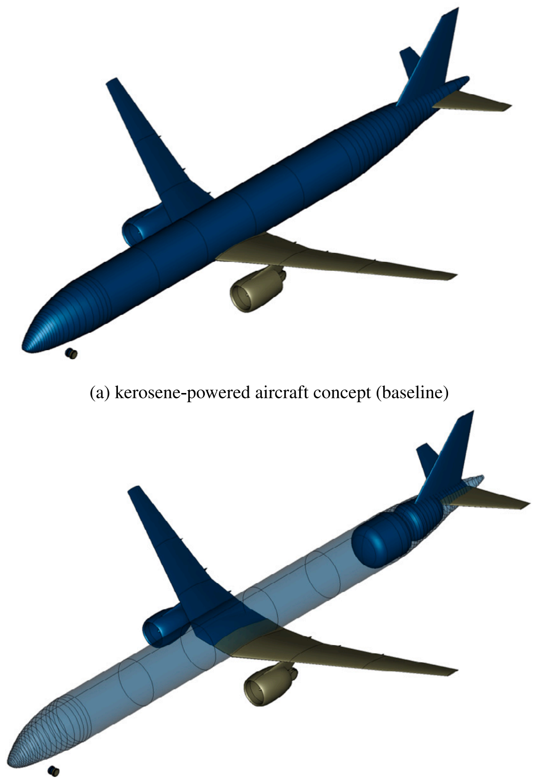
This study used the Lifecycle Cash Flow Environment (LYFE) method, a framework developed by DLR for event-based life cycle simulation [51,52]. LYFE is an object-oriented framework specifically designed for the economic evaluation of aircraft within a scientific context. It models the entire life cycle of an aircraft, from production through operation and maintenance to end-of-life, using discrete event simulation. This approach not only provides insights into the operational procedures of the aircraft but also enables a comprehensive assessment of its overall economic efficiency. The basic structure of LYFE, along with enhancements for hydrogen-powered aircraft by Ramm et al. [22], is depicted in Fig. 2.

In the context of this model, we present a framework for quantifying uncertainty in the life cycle cost-benefit assessment of novel aircraft technologies, as shown in Fig. 3. Initially, uncertain variables in the input parameter domain are modeled using Dempster–Shafer Theory of Evidence, as discussed in Section 2.1. This involves deriving BBAs spaces from expert interviews, from which samples are drawn using a quasi-random scheme such as Latin Hypercube Sampling (LHS). These samples are then processed through the discrete event simulation of LYFE.

The simulation is executed repeatedly in a Monte Carlo setup, with each iteration incorporating a new set of samples. This process continues until convergence criteria are met, culminating in a distribution of economic outputs. While the statistical moments of this distribution can be analyzed to define uncertainty measures, our framework takes a further step by implementing GSA, as outlined in Section 2.2. Here, the GSA method is applied to the output distribution and the input samples. By examining the input–output space and calculating conditional variances, we are able to decompose the output uncertainty into sensitivity measures for the uncertain input parameters. These measures are subsequently analyzed, providing valuable insights for decision-making and guiding future efforts to reduce uncertainty.

3. Use case

In this study, we used two different aircraft concepts as case studies [22]: a conventional kerosene-powered aircraft concept (referred to as the baseline) and a hydrogen-powered aircraft concept (referred to as the study aircraft) (as illustrated in Fig. 4). Both concepts were developed as part of the DLR research project EXACT (Exploration of Electric Aircraft Concepts and Technologies), with an anticipated Entry Into Service (EIS) in the year 2040. The baseline concept is derived from a modified A321neo with advanced wing-design, improved turbofan engines, and technology advancements expected by 2040 (see Ref. [22] for a more detailed description). The hydrogen-powered concept is developed based on the conventional design. It features two Liquid Hydrogen (LH_2) tanks located behind the cabin at the unpressurized rear of the fuselage. Integrating the tanks in the rear provides structural advantages by enabling a nearly spherical shape for the LH_2 tanks, which reduces mass and extends the dormancy period of the tank until hydrogen venting is required due to pressure build-up. Despite minimal impact on wetted area of the fuselage, the integration



(a) kerosene-powered aircraft concept (baseline)

(b) hydrogen-powered aircraft concept (study aircraft)

Fig. 4. Aircraft concept use cases based on Ramm [22].

necessitates a larger horizontal tail plane and results in a shifted Centre of Gravity (CoG) position. This study aircraft concept uses a direct combustion of hydrogen in the engines as primary propulsion system. It is important to note that when using direct hydrogen combustion efficiency drops significantly under off-design conditions. Therefore, a hybrid system is utilized, incorporating a redundant megawatt-scale Fuel Cell System (FCS) as described in Schroeder et al. [53]. This FCS serves as a fuel cell secondary power supply unit (APU+). The conventional Auxiliary Power Unit (APU), typically a compact gas turbine engine located at the rear of an aircraft, generates electrical and pneumatic power (bleed air) for various functions. These include starting the main engines, providing electrical and pneumatic power as redundancy for the main engines in case of failure and providing electrical and pneumatic power during ground operations when the main engines are not in operation. The APU+ in this case is powering all on-board systems during ground and flight operations enabling a bleed-less engine. It also provides power for the electric taxiing system in the landing gear and the assisted idle system. For added reliability, a ram air turbine and multiple generators driven by the main engines are incorporated, consistent with the baseline concept. Table 1 shows the top-level aircraft characteristics of both aircraft concepts according to Ramm et al. [22].

The incorporation of hydrogen in aircraft design represents a radically new concept that introduces various challenges. One example is the question of how to design the aircraft taking into account weight distribution, tank design and integration as well as possible necessary changes in the subsystem. Another critical aspect is determining the necessary modifications during the potential operation of an LH_2 aircraft. This includes adapting ground operations and, most importantly, ensuring operational safety both initially and in the long term. One approach to address this point is to ensure safety during operation, *e.g.* through regular maintenance or replacement of components. However, the practical realization of maintenance for novel systems, such as those involving hydrogen, remains unclear. A few studies exist, which are analyzing maintenance requirements for hydrogen in aviation. For example, Hoff et al. [54] examined the Maintenance, Repair and Overhaul (MRO) perspective of on-board hydrogen systems, particularly fuel cells. This analysis, including a literature review and comparison with the automotive sector, shows that extensive MRO activities may be required to meet the needs of the aviation sector. Meissner et al. [30] analyzed the impact of a hydrogen-based auxiliary power system on scheduled maintenance to comply with existing regulations and ensure an airworthy condition. In addition, they carried out a comparative study with a conventional fuel storage system to quantify the estimated changes in maintenance effort. However, due to the current lack of information and data on the operation of hydrogen tanks in aircraft, these considerations introduce a number of uncertainties. One crucial aspect, from an operational, ecological and from an economic point of view, is determining if the hydrogen tank needs to be replaced during the lifetime of an aircraft [22]. To better understand the uncertainties connected with a potential tank replacement and its impact on the maintenance costs and overall profitability of aircraft, we utilized a combination of DSTE, LYFE, MCS and GSA (as described in Section 2). Therefore, the event *LH_2 Tank Exchange* event serves as the central maintenance event, which is defined by a number of uncertain variables. Meanwhile, no uncertainties are considered for all other parameters such as fuel price, downtime, maintenance events, etc., although it is recognized that these parameters are also subject to high uncertainties.

Table 1
Overview of top-level aircraft characteristics from Ramm et al. [22].

	Unit	Aircraft cases	
		Ref.	*LH_2*
Maximum take-off weight	t	81.3	82.1
Operating Empty Weight	t	47.6	54.8
Fuselage length	m	46.9	53.3
LH_2 Tank Mass	kg	–	2685, 1822
Maximum LH_2 Tank Volume	m^3	–	37, 20
Gravimetric Index of LH_2 Tank	%	–	46, 41

A maintenance event, such as the LH_2 tank exchange, is characterized by four different parameters: *interval*, *downtime*, *material costs* and *labor costs*. The interval describes the time a tank can remain in an aircraft before it needs to be replaced, due to *e.g.* fatigue or leakage. The downtime defines the time how long the aircraft has to stay on ground for replacement. The goal of every airline is to keep this downtime as low as possible, because no flights can take place during this time and therefore no revenues can be generated. Since no repair of the hydrogen tank is considered in this study, the material costs correspond to the acquisition costs for a new tank. The labor costs describe the man-hours required for the exchange, *i.e.*, opening the respective section in the rear of the aircraft, removing the old tank, inserting the new tank, closing the aircraft and perform tests. To quantify these uncertain input parameters, seven expert interviews were conducted, as described in Section 2.1. Information about the experts and their affiliation can be found in Table B.1 in the Appendix.

4. Results

To analyze whether an early estimation of uncertainties in maintenance costs and overall economic efficiency of new aircraft types is possible by combining DSTE and GSA using LYFE, first, the results of the expert interviews are presented (Section 4.1). Subsequently, the overall results of economic efficiency (Section 4.2) and overall costs (Section 4.3) are shown and analyzed in more detail. All results are presented in 2022-USD, assuming a 20-year lifetime from an operator's perspective for both aircraft concepts. The flight plan for both concepts is based on an expected route network for the hydrogen aircraft design,

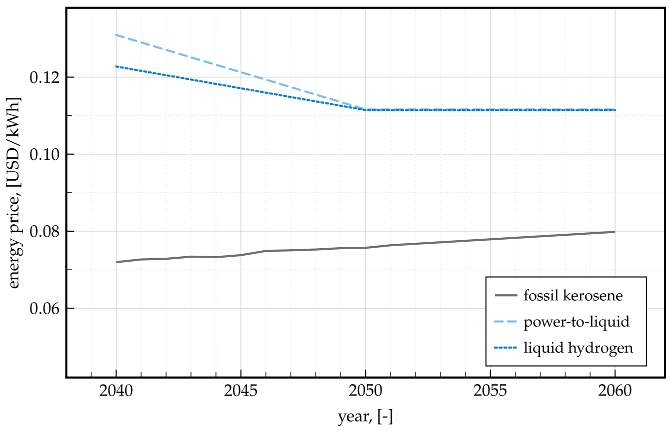


Fig. 5. Energy price assumptions of this study for fossil kerosene, PtL and LH_2 from Refs. [22,55].

reflecting realistic airline operations. This is based on the methodology described in Kuehlen et al. [56] using operational assumptions and data as described in Ramm et al. [22]. The maintenance plan for the kerosene-powered aircraft concept is based on the A321neo maintenance schedule from Aircraft Commerce [57]. The maintenance schedule for the study concept was derived using the A321neo schedule as a reference. It is assumed that the required changes are solely due to adaptations in maintenance activities necessitated by the LH_2 tank and delivery system, as well as the APU+ system, based on Refs. [58–61] as described in Ramm et al. [22]. Within this study, it is assumed, that the baseline aircraft is powered by synthetic kerosene produced via the PtL pathway. The energy carrier prices for PtL, LH_2 and fossil kerosene are illustrated in Fig. 5. The fossil kerosene price is based on the reference forecast of future jet fuel price trends through 2050 from the U.S. Energy Information Administration [55], with a linear extrapolation through 2060. The prices for PtL and LH_2 are derived on the mid projection presented in Ramm et al. [22].

4.1. Expert interviews for uncertainty quantification

Table 2 displays the experts' BBA for each parameter of the LH_2 tank exchange event. To mitigate potential bias from individual experts, we set the minimum number of experts statements for each parameter to three. However, since only two expert opinions were available for the *material costs* parameter, we supplemented this with information from a literature search. Mottschall et al. [62] published a report by the German Federal Environment Agency that discussed different sensitivities to assess the costs of different energy supply options for transport, including the costs for LH_2 refueling systems. It is assumed that 100% of this expert opinion is evenly distributed between the minimum and maximum values presented, as no further information is provided. Houchins et al. [63] presented the results of a cost analysis for a hydrogen storage system for the US Department of Energy. In this study, ranges for cost assumptions are treated with the same assumption that 100% of expert opinion is evenly distributed between the minimum and maximum values presented. Hoelzen et al. [16] assumed a fixed value for the LH_2 tank price for their studies, derived from Mottchall et al. [62]. This means that 100% of the expert opinion is based on this fixed value. To combine it with the other expert beliefs, the Dirac delta function is used to transform this value into an infinitesimally small range. Since this expert belief is based on another study we assumed a weighting of 30% compared to all other statements. Unfortunately, there is a lack of literature for the *Man-hours* and *Downtime* parameter considering the specific requirements of using an LH_2 tank inside an aircraft, which highlights their complex nature and the many factors involved. To address this gap, we rely on

Table 2
Overview of expert Belief per parameter of LH_2 tank exchange.

Experts	Parameter			
	Interval	*Downtime*	*Material costs*	*Man-hours*
H.M.	●	●		●
P.S.	●	●		
R.M.	●	●		
S.F.		●	●	
C.K.	●	●		●
T.B.	●	●		●
D.S.			●	
[16]			●	
[62]			●	
[63]			●	
Sum	5	6	5	3

expert opinions from those well-versed in maintenance intricacies and parameter delineations. Furthermore, since hydrogen aircraft are not yet operational, empirical data on these parameters is still unavailable. Regarding the parameter *Interval*, we decided that using expert BBAs is more precise than extrapolating mean time between failures values from dissimilar applications.

In general, all BBA of the different parameters are within the following ranges:

- *Interval*: 5,600–80,000 Flight Hours (FH), which is equal to 2–28 years within this use case
- *Downtime*: 48–960 h, this corresponds to 2–40 days
- *Material costs*: 2022-USD 500,000–6,500,000
- *Man-hours*: 96–3,600 h

In the top part of Fig. 6, the BBAs derived from the expert interviews for each uncertain parameter (interval, downtime, material costs and man-hours) of the LH_2 tank exchange event are shown. The abscissa depicts the range of the input uncertainty, while the ordinate represents the cumulative BBAs. The horizontal and vertical lines indicate the width of the stated interval and resulting combined Belief, respectively. The corresponding samples are shown in the bottom row as histograms, in which the frequency of the different values over the sample space is shown. To achieve this, LHS was used to draw 1,200 samples for each parameter from the density spaces. It is important to note that DSTE is best used when little or no data is available. Using the transformation from a cumulative density function to samples, a cumulative BBA for a parameter can be the basis for a large number of samples.

The distribution of the parameter *interval* shows that the highest confidence among experts was between 14,000FH (≈ 5 years) and 22,000FH (≈ 8 years), resulting in the highest number of samples in this range. The ranges from 5,600FH (≈ 2 years) to 14,000FH and 22,000FH to 42,000FH (≈ 15 years) are almost equally distributed, with a little less belief considering a dent at 35,000FH (≈ 12.5 years). The belief in an interval from 42,000FH to 80,000FH (≈ 28 years) is much less present among the experts, resulting in very few samples. The sample distribution of the *downtime* parameter is similar to the interval. The range from 48 h to 600 h shows an almost equal distribution of the results, while the belief in a downtime higher than 600 h is almost non-existent. The distribution of the belief in *material costs* shows a strong fluctuation, which is due to the fact that the opinions of the experts are more divergent than for the other parameters. The highest number of samples resulting from the highest expert belief for the *man-hour* parameter is between 96 h and 200 h, while the belief in longer man-hours is comparatively small.

4.2. Overall economic efficiency

Based on these samplings the MCS and a subsequent analysis in form of a GSA of the economic key performance indicators was performed.

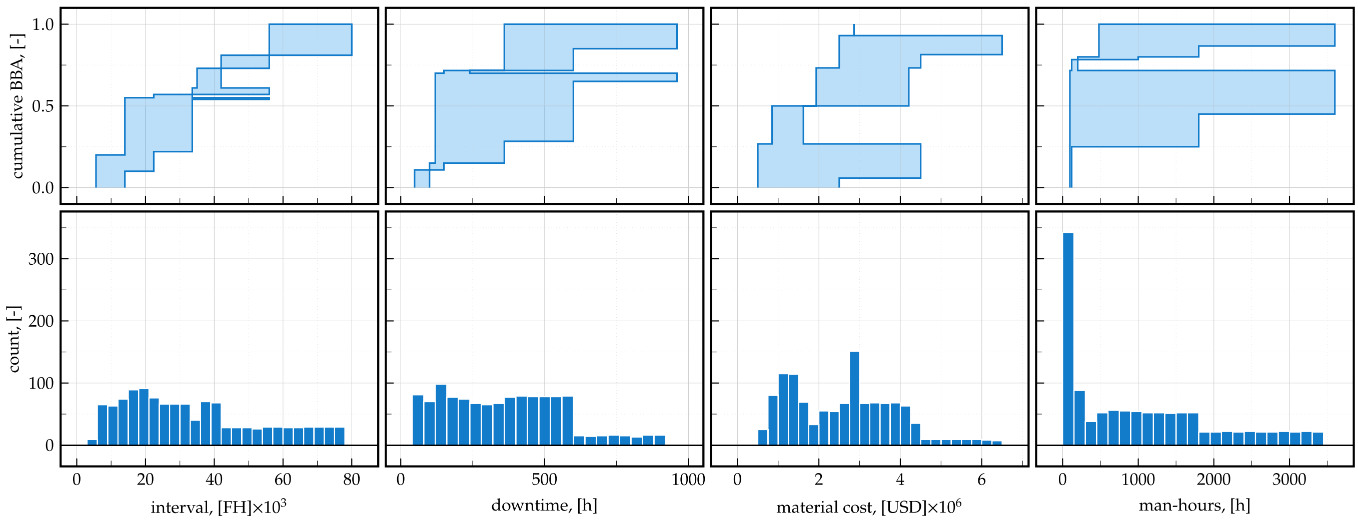
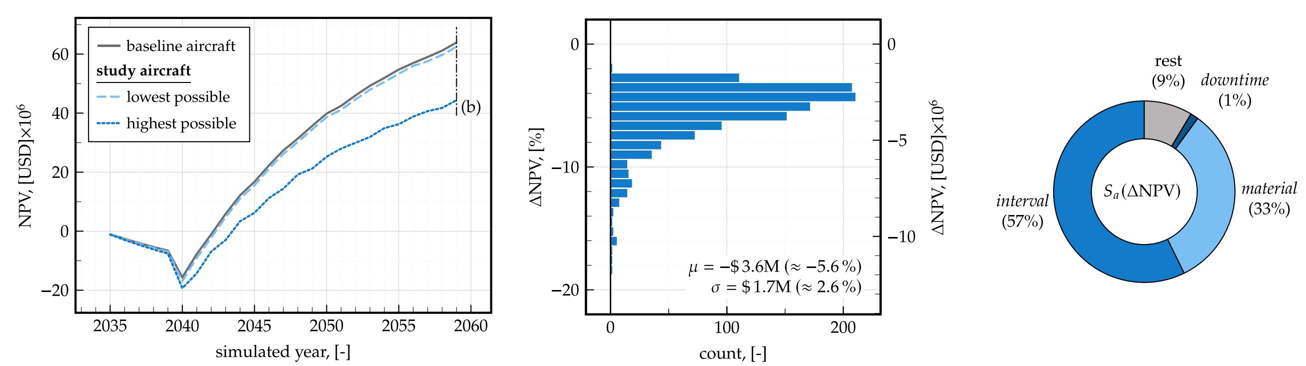


Fig. 6. Belief spaces derived from expert interviews (top) and resulting sample spaces (bottom) for each investigated input uncertainty.



(a) progression over lifetime for with lowest and highest possible values for the hydrogen (study) aircraft, compared to the baseline

(b) histogram and key statistics of ΔNPV values at the end of the simulation

(c) sensitivity index S_a (without correlation) breaking down the ΔNPV uncertainty

Fig. 7. Overall economic results of the study aircraft when compared to the baseline in terms of NPV.

In Fig. 7 the overall economic efficiency as NPV is presented. The NPV is a widely used in investment, accounting for the annual cash flow CF_t (revenue - cost) and the time value of money (using the discount rate r) [51]. The NPV is defined as:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} \tag{6}$$

Fig. 7(a) shows the NPV progression over the lifetime of the baseline aircraft and the two extreme cases of the hydrogen-powered study aircraft, where all values for the LH_2 tank exchange assume either the highest or the lowest possible value. Thus, it can be seen, that the economic profitability of the study aircraft has a wide range from being almost as profitable as the baseline aircraft up to a decrease of profitability of 30%. Additionally, it is notable that the curve of the NPV of the study aircraft with the highest possible parameters does not show a smooth curve but an inconsistent trend. This irregularity is attributed to the frequent LH_2 tank exchanges, occurring every second year, combined with the longest possible downtime and the highest estimated costs for materials and personnel. Fig. 7(b) displays the results of the MCS in form of a histogram, along with key statistics of ΔNPV values (study compared to baseline) at the end of the simulation. The probability density for the different results indicates that a decrease in NPV for the study aircraft is more likely to fall within the range of 2%–10%. The mean value μ is $\approx -5.6\%$, with a standard deviation σ of $\approx$ 2.6%. In the third part of the figure (Fig. 7(c)), the result of the GSA indicates, that the result dispersion is for 57% due to the uncertainty in the input for the *interval*, 33% due to the uncertainty in the *material costs*, 1% due to the uncertainty in the *downtime* and 9% due to the uncertainty in the *man-hours* as well as due to secondary effects. Consequently, reducing the uncertainty in the maintenance interval would lead to the most significant reduction in the dispersion of the NPV results.

4.3. Direct operating cost breakdown

Since the tank replacement event is a maintenance activity that only incurs costs without generating revenue for the operator, Fig. 8 presents a detailed cost breakdown for the study concept. This breakdown compares the lowest and highest possible values for the LH_2 tank exchange against the baseline.

The breakdown illustrates all cost parts that add up to the Direct Operating Cost (DOC): capital costs, flight costs (which includes crew costs, energy costs and fees) and maintenance costs. In the capital costs, the initial investment costs of the aircraft, along with insurance payments and other expenses incurred throughout its lifetime, are combined. The increase in capital costs of +6% between the baseline and the lowest possible study case is due to the change in aircraft architecture considering hydrogen combustion, a FCS, a hydrogen storage system and a hydrogen distribution system (as described in detail in Ramm et al. [22]). Meanwhile, the difference in capital cost of +9% between the lowest and highest possible study cases is due to uncertainties in the material costs of the LH_2 tank. Fig. 9 shows (a) the detailed result distribution of the Δcapital costs with a mean value

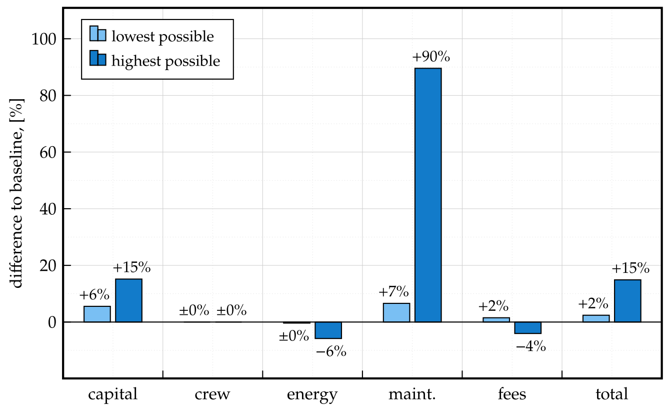
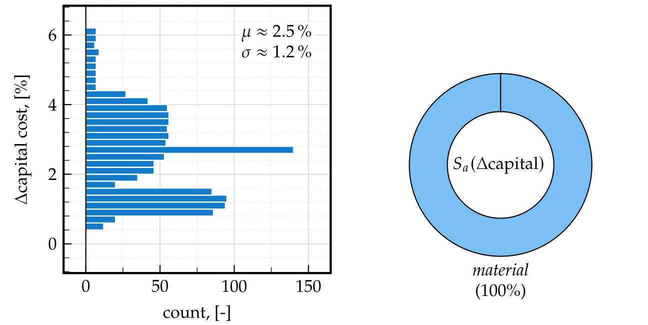
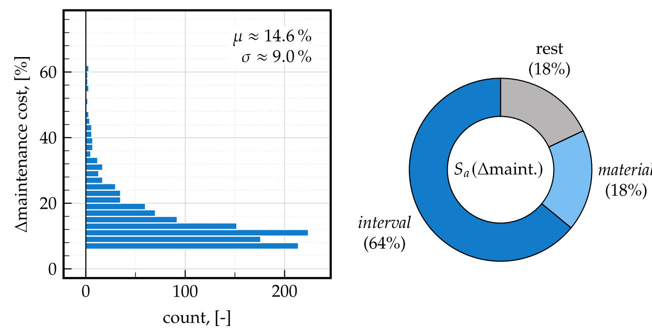


Fig. 8. Cost breakdown of the lowest and highest possible study case when compared to the baseline.



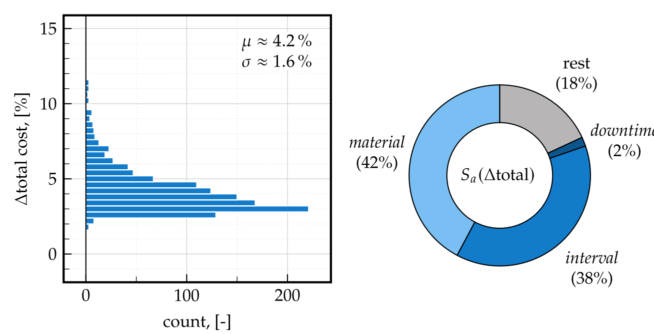
(a) histogram and key statistics (b) sensitivity index S_a

Fig. 9. Capital cost comparison between the study aircraft and baseline.



(a) histogram and key statistics (b) sensitivity index S_a

Fig. 10. Maintenance cost comparison between the study aircraft and baseline.



(a) histogram and key statistics (b) sensitivity index S_a

Fig. 11. DOC comparison between the study aircraft and baseline.

Table 3
Overview of operational results of the calculation.

	Aircraft cases		
	Ref.	*LH_2 low*	*LH_2 high*
LH_2 tank exchange events	0	0	9
Average FH per year	2990	2960	2800
Average FH/FC	1.75	1.74	1.74

μ of $\approx$ 2.5% and a standard deviation σ of $\approx$ 1.2% on the left, and (b) the sensitivity index S_a on the right. This figure confirms that the variability in *Δ*capital costs is solely due to the uncertainty in material costs.

The slight variations in flight cost, as shown in Fig. 8, are indirect consequences of the changes in maintenance downtime. The difference between the baseline and the lowest possible study case is (as well as for the capital costs) due to the change in aircraft concept. The fees increase by 2% due to a higher maximum take-off weight of the study aircraft, while the energy costs of the lowest possible study case remain approximately the same compared to the baseline. This consistency in energy costs is attributed to the fuel price assumptions shown in Fig. 5. It is important to note that this study did not focus on analyzing the impact of varying energy prices on total costs. Consequently, no sensitivity analysis was conducted in this regard, despite acknowledging the high degree of uncertainty associated with energy prices. The variation in energy costs between the lowest and highest possible study case is due to the fact that a higher amount of maintenance – due to more frequent events, longer downtime, or both – leads to fewer flights performed within the simulation. Table 3 shows the number of calculated LH_2 tank exchanges, the average FH per year and the FH/FC (Flight Cycle) ratio for the different use cases. It is observed, that due to the rise of LH_2 tank exchanges from zero to nine within the study cases, the FH per year drop by $\approx$ 5.5%. This drop indicates, that less flights are performed per year, resulting in a decrease of total energy costs and fees. Crew costs remain unchanged across all cases, as the crew cost modeling assumes a monthly crew cost payment and that all three aircraft concepts require the same number of crew to operate throughout the year.

The increase of 7% in maintenance costs between the baseline and the lowest possible study case arises from differences in the maintenance of the APU+, LH_2 tank inspections, and LH_2 delivery system as described in Ramm et al. [22]. Maintenance costs differences can be up to 83% between the lowest and highest study case. Fig. 10 shows (a) the *Δ*maintenance costs distribution of the MCS as a histogram with a mean value μ of $\approx$ 14.6% and a standard deviation σ of $\approx$ 9.0% on the left, and (b) the sensitivity index S_a as a result of the GSA on the right. The analysis reveals that 64% of the *Δ*maintenance costs dispersion is due to the uncertainties in the *interval*, 18% due to the uncertainties in *material costs* and for 18% due to the other parameters and secondary effects. Uncertainties in material costs have a smaller impact on maintenance costs than on the NPV. This is because material costs influence both capital costs and maintenance costs in the NPV.

The change in total DOC between the lowest and highest study case ranges from +2% and +15%. Fig. 11 shows (a) the distribution of the results of the MCS as a histogram with a mean value μ of $\approx$ 4.2% and a standard deviation σ of $\approx$ 1.6% on the left and (b) the sensitivity index S_a as the result of the GSA on the right. In terms of DOC dispersion, *material costs* have the highest impact at 42%, while the *interval* parameter has the second highest influence on the result dispersion at 38%. Material costs impact both capital and maintenance costs, which are considered together in the DOC, resulting in a greater influence of uncertainties on DOC from material costs. Additionally, it is important to note that DOC calculations do not take into account the time value of money or the concept of discounting future cash flows. This means that future cost have less impact on the NPV than on the DOC. This applies to the material costs but not the interval, which leads to the impact change from the DOC compared to the NPV. All second order sensitivity indices (using the non-correlated index S_a) covering ΔNPV, ΔDOC, ΔMaintenance costs, and ΔCapital costs can be found in Fig. C.1 in the appendix for completeness.

In summary, the results show that the uncertainties in the parameters *interval* and *material costs* have a significantly greater influence on the scatter of the MCS results than the *man-hours* and *downtime*. This observation does not imply that these latter parameters are irrelevant for estimating maintenance costs; rather, it suggests that their impact on cost predictions is less pronounced given the current state of knowledge. If the uncertainties in the *material costs* and the *interval* can be reduced through further research, the cost estimate focusing on the LH_2 tank replacement can be made more precise.

5. Conclusion and outlook

The objective of this study was to systematically assess the impact of uncertainties in maintenance assumptions for hydrogen tank replacement on the maintenance costs and overall economics of a hydrogen-powered aircraft concept compared to a conventional baseline aircraft. Using the Dempster–Shafer Theory of Evidence, we integrated insights from expert interviews to effectively address maintenance uncertainties and enhance the reliability of cost estimates. In addition, a global sensitivity analysis was performed to quantify the impact of uncertainties in input variables on the estimated economic results. This analysis not only facilitated the identification of key drivers of cost variation, but also highlighted how changes in various parameters affected the overall cost estimate. Therefore the discrete event life cycle simulation and economic evaluation methodology called LYFE (Lifecycle Cash Flow Environment) was employed.

In conclusion, the application of evidence theory proves to be a valid and effective method for translating expert beliefs into samples. The successful integration of Global Sensitivity Analysis with the Theory of Evidence in this context revealed its potential to significantly enhance economic analyses.

Specifically, the critical factors identified within the maintenance of the hydrogen tank exchange – namely, the *interval* and *material costs* – emerge as primary drivers of overall result variability.

Detailed findings include an increase in direct operating cost by $\approx$ 4.2% (μ) with a standard deviation of $\approx$ 1.6% (σ) between the baseline and the hydrogen study case. Additionally, maintenance costs increased by $\approx$ 14.6% (μ) with a standard deviation of $\approx$ 9% (σ), and the Net Present Value decreased by $\approx$ −5.6% (μ) with a standard deviation of $\approx$ 2.6% (σ). These values are attributed to the uncertainty range of parameters associated with the hydrogen tank replacement.

However, it is important to acknowledge the limitations of this feasibility study, which relied on a limited number of expert opinions and a single maintenance event. Additionally, the interviewed experts were exclusively from academia, which may introduce bias. To increase the study's robustness, it may be beneficial to include additional experts and perspectives from various industries and fields. Furthermore, more uncertain maintenance events or operational parameters could provide a more comprehensive and nuanced understanding of the operation of hydrogen-powered aircraft and refine the findings. For future research, it is recommended to prioritize the incorporation of a wider spectrum of uncertainties. This approach aims to enhance comprehension and facilitate more detailed design feedback.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the experts for their time and insights in the interviews, which contributed significantly to the depth and quality of this research.

Appendix A. Assumptions

- Two different aircraft concepts as case studies based on [22].
- Anticipated EIS for both aircraft concepts in the year 2040.
- The hydrogen concept has two LH_2 tanks located behind the cabin at the unpressurized rear of the fuselage.
- The *LH_2 Tank Exchange* event is the central maintenance event of the analysis, which is defined by a number of uncertain variables.
- No uncertainties are considered for all other parameters such as fuel price, downtime, maintenance events, etc., although it is recognized that these parameters are also subject to high uncertainties.
- A maintenance event, is characterized by four different parameters: *interval*, *downtime*, *material costs* and *labor costs*.
- All results are presented in 2022-USD.
- 20-year lifetime for the aircraft concepts from an operator's perspective for both aircraft concepts.
- The flight plan for both concepts is based on an expected route network for the hydrogen aircraft design, reflecting realistic airline operations based on Kuehlen et al. [56] using operational assumptions and data as described in Ramm et al. [22].
- The maintenance plan for the kerosene-powered aircraft concept is based on the A321neo maintenance schedule from Aircraft Commerce [57].
- The maintenance schedule for the study concept was derived using the A321neo schedule as a reference. It is assumed that the required changes are solely due to adaptations in maintenance activities necessitated by the LH_2 tank and delivery system, as well as the APU+ system, based on Refs. [58–61] as described in Ramm et al. [22].
- The baseline aircraft is powered by synthetic kerosene produced via the PtL pathway.
- The fossil kerosene price is based on the reference forecast of future jet fuel price trends through 2050 from the U.S. Energy Information Administration [55], with a linear extrapolation through 2060.
- The prices for PtL and LH_2 are derived on the mid projection presented in Ramm et al. [22].
- The crew cost modeling assumes a monthly crew cost payment.

Appendix B. Expert interviews

Table B.1
Overview of expert affiliation from interviews which were conducted in a time frame from August 2023 through November 2023.

Experts	DLR Institute of
H. Meyer	Maintenance, Repair and Overhaul
P. Sieb	Maintenance, Repair and Overhaul
R. Meissner	Maintenance, Repair and Overhaul
S. Freund	Lightweight Systems
C. Krombholz	Lightweight Systems
T. Burschyk	System Architectures in Aeronautics
D. Silberhorn	System Architectures in Aeronautics

Appendix C. Second order sensitivity indices

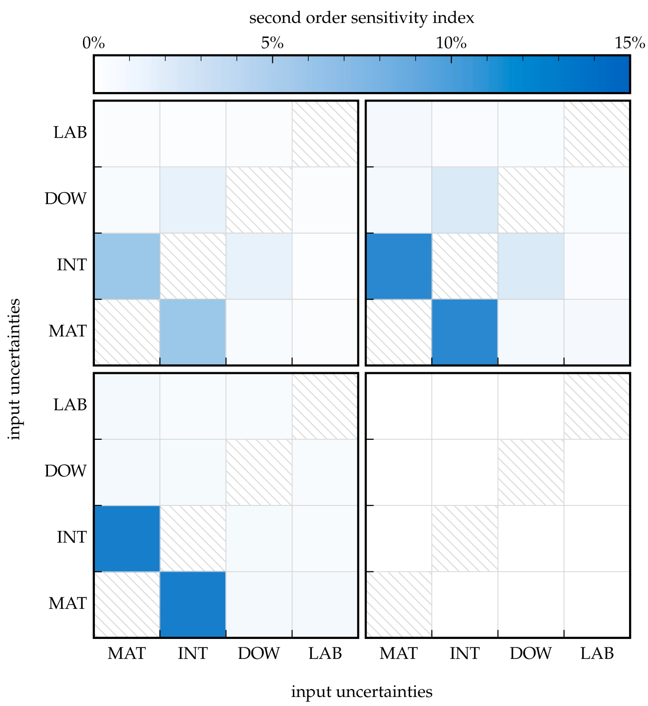


Fig. C.1. Second order sensitivity indices (using the non-correlated index S_a) covering ΔNPV (top left), ΔDOC (top right), ΔMaintenance costs (bottom left), and ΔCapital costs (bottom right).

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