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Fuzzy Rule-based Comparison of Alternative Jet Fuels

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Abstract

In today's aviation alternative jet fuels play an increasingly important role. Their application incurs new engineering and environmental protection challenges. The key properties of their feasibility of integration are from technological point of view aging behavior and applicability as well as from environmental protection point of view the carbon footprint. During the comparison process experts can evaluate the above characteristics with linguistic variables. The application of linguistic variables always results in some degree of uncertainty – by their subjectivities. Fuzzy calculation methods are used to mathematically describe these uncertainties. The purpose of this study as a pilot project is to gain experience in developing a methodology of a multi-level fuzzy rule-based jet fuel qualification process.

Keywords

alternative jet fuels, applicability, storability, compatibility, carbon footprint, fuzzy decision

1 Introduction

The aviation industry takes an increasingly important place in world economy and generates 3.5% of the world's GDP. The aviation industry provides nearly 44.8 million workplaces and transports 4.5 billion passengers annually worldwide (ATAG, 2020). With the increase in the number of passengers and the amount of transported goods, the demand for aviation fuel is also expected to increase in the foreseeable future (Nygren et al., 2009). However, the aviation industry is currently responsible approximately 2.5% of all human-caused carbon-dioxide (CO_2) emissions, not including the amount of other greenhouse gases released into the atmosphere by burning kerosene (NO_x, CH_4, SO_2, etc.) (Klöwer et al., 2021). Moreover, kerosene as a fossil fuel, is an unsustainable solution for transportation in the long term due to the rapid decrease in the available supplies of fossil fuels. In recent decades, in addition to the traditional production of aviation fuels by crude oil refining, many other alternative methods are used, such as the conversion of coal, gases and biomass into fuel.

Zöldy et al. (2024) provided an overview of the "CogMob Conference 2022". The presentations at the conference covered broad areas of intelligent and sustainable mobility research, including the issue of advanced and alternative fuels. Cognitive mobility examines the intertwined combination of research areas such as mobility, transport, its management, vehicle manufacturing and related sciences (Zöldy and Baranyi, 2023).

Bagdi et al. (2023) presents the possible alternatives to traditional fuel, such as liquefied hydrogen, which are future technologies. This alternative fuel can play a significant role in meeting the energy needs of aviation. Experts consider it essential to focus on using renewable energy to produce hydrogen produced by water decomposition. According to ICAO, the use of hydrogen in propulsion will not have a significant impact on carbon dioxide reduction until 2050.

Alternative propulsion options and alternatives to jet fuel (e.g., liquefied natural gas and liquefied hydrogen) have been proposed, but have only been tested at the pilot-scale thus far. There are numerous unresolved technical issues associated with these alternatives; therefore, stabilizing international aviation CO_2 emissions at 2019 levels will likely require the use of drop-in sustainable aviation fuels (Prussi et al., 2021). By Virt and Zöldy (2022) why liquid fuels are needed in addition to the spreading electromobility were reviewed.

These alternative solutions can diversify the sources of aviation fuels, thus helping to improve the security of the fuel supply and/or reduce the environmental impact of the air transport. As long as the existing tens of thousands of

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conventional internal combustion engines (approximately 20–40 years) and those produced in the near future are still in operation, we need to align the properties of the developed propellants with the existing infrastructure and fuel systems to achieve sustainable aviation. However, different jet fuels perform differently in environmental, economic, storage and some other aspects. Although their environmental impact may be lower, they may present challenges in other considerations compared to traditional kerosene. Therefore, it could be difficult for users to choose the most suitable one when faced with multiple criteria. Alternative aviation fuels must meet a strict set of criteria that regulate the chemical and physical properties of kerosene in order to fully satisfy the requirements of civil and military aviation. Such requirements include:

- having a low environmental impact;
- being chemically and physically stable, not reacting with elements and equipment of the onboard fuel system;
- easily extractable and cost-effective resources being available for long-term use;
- heating value being at least equivalent to or higher than the fuel used previously;
- avoiding technology that requires a lot of energy or is harmful to the environment during its extraction, processing, and conversion;
- being suitable for adequate cooling of the aircraft engine, air conditioning system, and surfaces, as well as lubrication of certain equipment;
- not requiring significant modifications of the currently available aircraft fleet and the infrastructure necessary to service it (Óvári and Szegedi, 2010).

During the comparison of alternative fuel integration feasibility by the requirements mentioned above experts generally use so-called linguistic variables that have uncertainties. Szamosi and Pokorádi (2015) investigated the impact of subjectivities or intersubjectivities on expert opinion-based decisions. They recommended applying fuzzy assessment methods. The fuzzy set theory is a highly useful mathematical tool for quantifying seemingly immeasurable information and modelling the above-mentioned problem, especially since it is difficult to quantify.

There is considerable literature on fuzzy mathematics and its applications with a high number of books and papers. Laufer (2024) proposed a fuzzy logic-based risk calculation model, which can be used for risk level assessment.

Zlateva et al. (2011) suggested a three-level fuzzy approach for risk estimation from natural hazards in Bulgaria. The problem was determined as a multi-criterial task and the applied model evaluated several input variables, such as indicators for natural hazards and social vulnerability.

The main aims of this study are two-fold: on the one hand, to work out a two-level fuzzy rule-based qualifying method for comparison alternative jet fuels. On the other hand, as a pilot project, to gain experience in developing a methodology of a multi-level fuzzy rule-based fuel qualification process.

The paper's outline is as follows: Section 2 describes the alternative jet fuels. Section 3 shows the proposed two-level fuzzy rule-based qualifying method theoretically. Section 4 outlines the case studies. Finally, the research findings and future activity plans are summarized in Section 5.

2 Alternative jet fuels

Conventional gas turbine engine fuels are mixtures of hydrocarbons that mainly contain paraffins, isoparaffins, cycloparaffins and aromatic compounds. They are produced by distillation or cracking of crude oil.

Alternative jet fuels have been considered since the early days of gas turbine engines. Cryogenic fuels such as liquid hydrogen and synthetic coal-based fuels were studied in the 1950s and 1960s. Research of biomass conversion to fuel was conducted after the 1973 U.S. energy crisis at the dramatical increase of fuel prices. However, only petroleum-derived jet fuels have been found to be economically practical for widespread, routine use (Hilsenrath, 1989).

At the end of the 20th century, with the development of technology and the increase in demand for sustainable aviation fuels, the production of alternative jet fuel became more economically feasible and attractive to aviation industry members. Up to the present, there have been many developments and alternative solutions for the production of jet fuels. In recent decades, various renewable resources have also been researched. Their main advantages are the natural origin, do not produce excess carbon dioxide in the atmosphere, they are less harmful to the environment, and easily decomposed. According to the type of raw material used, five different groups of alternative fuels can be defined:

- derived from unconventional oil (oil sands, oil shale);
- derived synthetically from natural gas, coal, or combinations of coal and biomass via the FT-process;

- derived from renewable oils (biokerosene, hydroprocessed renewable jet – HRJ or hydrotreated vegetable oil – HVO);
- cryogenic gases (liquid hydrogen, liquid methane);
- derived from alcohols (Alcohol to Jet – AtJ) (Boichenko et al., 2013).

Among these are kerosene-like, so-called "drop in" fuels, which are liquid hydrocarbons whose main properties are approximately the same as conventional aircraft fuels, consequently they are compatible with most types of aircraft without significant changes in the fuel system design. The International Civil Aviation Organization (ICAO) distinguishes between alternative aviation fuels (AAF) and sustainable aviation fuels (SAF). AAFs are produced from raw materials other than petroleum (coal, natural gas, biomass, hydrogenated fats and oils). SAFs are AAFs that meet sustainability criteria. According to CORSIA's definition, SAFs must achieve a carbon footprint reduction of at least 10% compared to the 89 g CO_2 e/MJ of fossil fuels (Klöwer et al., 2021).

Synthetic fuels would make excellent drop-in fuels for aircraft and motor vehicles. However, the Fischer–Tropsch process requires much more energy than the final product contains, due to its low energy density. Depending on the raw material, synthetic fuels are usually divided into three groups:

- Coal to Liquid Fuel (CtL): coal-based liquid fuel;
- Gas to Liquid Fuel (GtL): a colorless, odorless fuel from natural gas and other gaseous hydrocarbons;
- Biomass to Liquid Fuel (BtL): biomass-based fuel (can be categorized according to the origin, production area of the raw material or the production technology generations) (Gupta et al., 2020).

Hydroprocessed Esters and Fatty Acids (HEFA) may be another alternative to the currently accepted aircraft propellants in the future. They are produced from used cooking fat, vegetable oil and animal tallow, and as by-products, water and propane gas are produced (Kandaramath Hari et al., 2015). Among the non-drop in fuels there are hydrogen, which can be produced from water by electrolysis, and paraffin hydrocarbons that appear as by-products during the extraction of crude oil and natural gas. In addition to hydrogen, the use of methane, propane and butane has also received attention due to their extremely high combustion heat and their long-term, industrial-scale extraction (Békési and Sári, 2021).

It can be seen that there are many types of alternative jet fuel, which have different advantages and disadvantages. In addition to safety, performance, applicability and economic considerations, alternative fuels must also meet strict certification and regulatory requirements, not to mention environmental considerations. Taking these into consideration, the industry is constantly researching and developing to offer sustainable and efficient alternative solutions for aviation.

3 Fuzzy rule-based qualifying method

The purpose of the proposed method is to help decision-makers in determining the suitability of alternative aircraft fuels, taking into account the subjective judgment of experts and the uncertainty of the linguistic variables used. The comparison does not take into account the cost difference of fuels. It compares fuels only from a technical point of view.

The analysis is based on a hierarchical fuzzy inference (HFIS) system and considers three factors:

1. Aging behavior: refers to how long the fuel is able to maintain the properties necessary for proper operation and the extent to which its extraction and processing has been solved.
2. Compatibility: shows the extent to which the given fuel is compatible with the aircraft's fuel system and the technical requirements of the supply infrastructure.
3. Carbon footprint: represents the total emissions of all greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x) and generated during the life cycle of the fuel, projected by CO_2 equivalent/MJ (Boichenko et al., 2013).

To estimate the integration feasibility of given fuel firstly the applicability (as technological property) should be determined depend on aging behavior and compatibility. Then knowing integration feasibility can be estimated as a function of carbon footprint and applicability. This basic concept of HFIS is presented in Fig. 1.

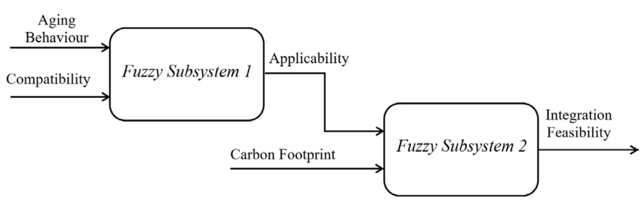

Fig. 1 Block diagram of HFIS

The definitions and membership function parameters of input and output parameters have been determined by opinions of experts. The definitions and membership function parameters of input variables are specified in Tables 1 to 3 by Eq. (1):

$$f\left(a,b,c,d\right)=\begin{cases}\dfrac{f-a}{b-a} & \text{if} \quad a\le f<b\\ 1 & \text{if} \quad b\le f\le c\\ 1-\dfrac{f-c}{d-c} & \text{if} \quad c<f\le d\\ 0 & \text{if} \quad \text{other}\end{cases}. \tag{1}$$

Table 1 Categories of aging behavior

Category	Definition	Parameters
Poor	They are difficult to store for a long time and require special conditions (e.g., low temperature, high pressure), or difficult to transport.	{0; 0; 0; 3}
Limited	Their storage and transport are complex, solved in the short term and requires special measures/equipment in the long term.	{0; 2.5; 2.5; 5}
Average	They can be stored relatively easily, but special attention must be paid to certain parameters (e.g., temperature, pressure).	{3; 5; 5;7}
Good	They are easy to store under normal conditions and require minimal additional measures.	{5; 7; 7; 10}
Excellent	They can be stored under the same conditions as kerosene, no special measures are required.	{7; 10; 10; 10}

Table 2 Categories of compatibility

Category	Definition	Parameters
Very low	They cannot be integrated into the fuel systems of currently used aircraft, a complete infrastructural transformation is required.	{0; 0; 0; 3}
Low	They are partially compatible with the current fuel systems, there is still a need to transform and develop the infrastructure. Modifications are difficult to integrate.	{0; 3; 3; 5}
Average	They are partially compatible with current fuel systems, but minor modifications are required for optimal operation.	{3; 5; 5; 7}
High	They can be relatively easily integrated into current fuel systems, they can be used effectively with minimal changes, which can be easily integrated into the system.	{5; 7; 7; 10}
Very high	They are fully compatible with current fuel systems and infrastructure without the need for major modifications.	{7; 10; 10; 10}

Table 3 Categories of carbon footprint

Category	Definition	Parameters
Low	Fuel has carbon neutrality	{0; 0; 0; 3.5}
Below average	Carbon footprint is much lower than that of kerosene	{0; 3.5; 3.5; 6}
Average	Carbon footprint is the same or slightly lower than that of kerosene	{3.5; 6; 6; 7.5}
High	Carbon footprint is higher than kerosene (>89 g CO_2 e/MJ)	{6; 7.5; 10; 10}

Figs. 2 to 4 show membership functions of input variables.

3.1 Estimation of applicability

The first fuzzy subsystem estimates the fuel Applicability depending on its aging behavior and Compatibility. The membership functions of Applicability categories are given in Fig. 5. Table 4 displays function parameters of

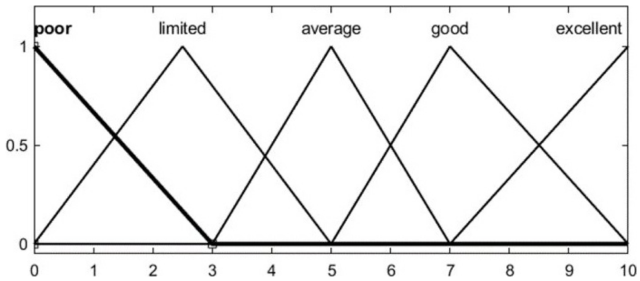

Fig. 2 Membership functions of aging behavior categories

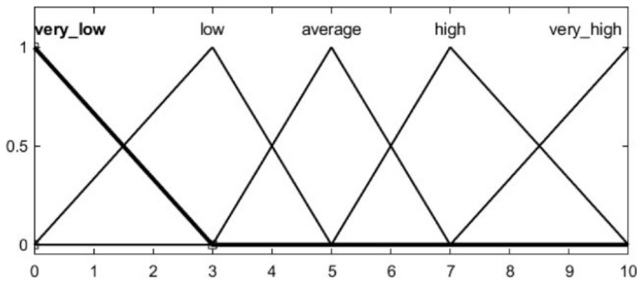

Fig. 3 Membership functions of categories of compatibility

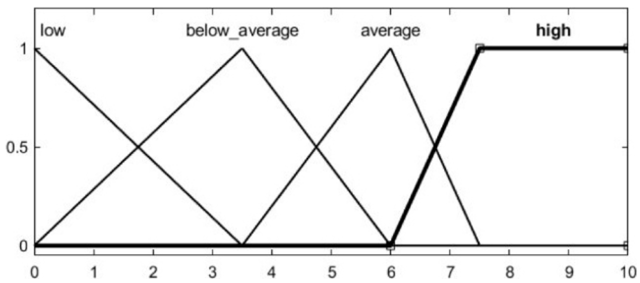

Fig. 4 Membership functions of carbon footprint categories

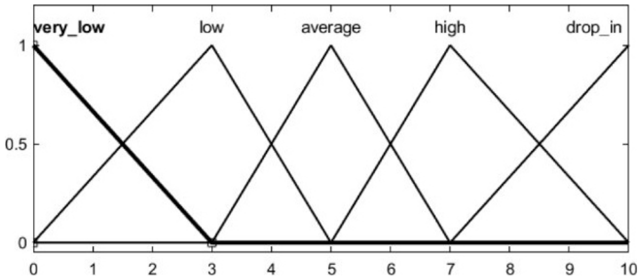

Fig. 5 Membership functions of applicability categories

Table 4 Function parameters of applicability categories

Category	Parameters
Very low	{0; 0; 0; 3}
Low	{0; 3; 3; 5}
Average	{3; 5; 5; 7}
High	{5; 7; 7; 10}
Drop in	{7; 10; 10; 10}

aging behavior categories. The rule base of applicability assessment is presented in Table 5. the output surface is shown in Fig. 6.

3.2 Estimation of integration feasibility

Using the second fuzzy subsystem the fuel integration feasibility can be estimated depending on its applicability and carbon footprint. The parameters of membership functions of integration feasibility categories are shown by Table 6 and Fig 7. Table 7 summarizes the rule base of Integration Feasibility assessment and its output surface is shown in Fig. 8.

Table 5 Applicability assessment matrix of the first fuzzy subsystem

		Aging behavior				
		Poor	Limited	Average	Good	Excellent
Compatibility	Very low	Very low	Very low	Very low	Low	Low
	Low	Very low	Very low	Low	Low	Low
	Average	Low	Low	Average	Average	Good
	High	Low	Low	Average	High	Drop in
	Very high	Low	Average	High	Drop in	Drop in

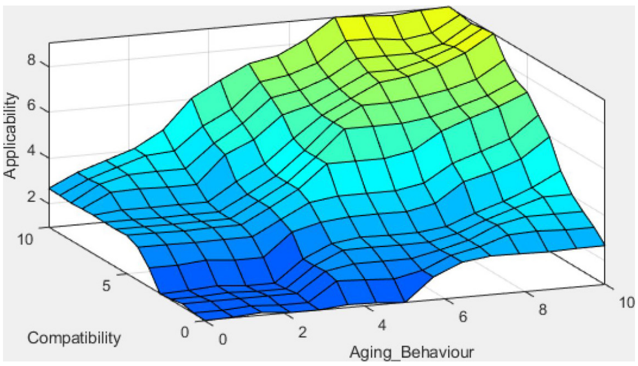

Fig. 6 Visualization of the output of the first fuzzy logic subsystems

Table 6 Function parameters of integration feasibility categories

Category	Parameters
Poor	{0; 0; 0; 3}
Limited	{0; 3; 3; 5}
Appropriate	{3; 5; 5; 7}
Good	{5; 7; 7; 10}
Excellent	{7; 10; 10; 10}

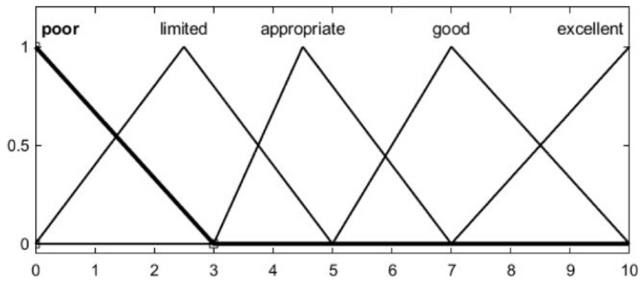

Fig. 7 Membership functions of integration feasibility categories

Table 7 Integration feasibility assessment matrix of the second fuzzy subsystem

		Carbon footprint			
		Low	Below average	Average	High
Applicability	Very low	Limited	Limited	Poor	Poor
	Low	Appropriate	Appropriate	Limited	Poor
	Average	Good	Good	Appropriate	Poor
	High	Excellent	Good	Appropriate	Poor
	Drop in	Excellent	Excellent	Good	Poor

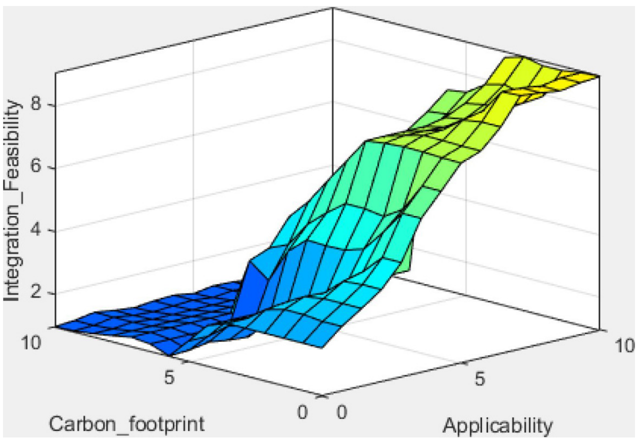

Fig. 8 Visualization of the output of the second fuzzy logic subsystems

4 Case studies

In order to illustrate the model's operation, some perceptive examples are presented from among the types of alternative aircraft fuels currently under development. In the model, the values of specific fuel properties were defined based on the expertise of specialists that had been working on this field for years. After entering the data into the model, the authors can rank the listed examples.

During fuzzy rule-based qualification centroid defuzzification method was used. For qualification of alternative jet fuels experts have characterized their above-mentioned factors by the categories defined in Section 3. Table 8 outlines average values of the considered factors as input data and results of qualifying process.

4.1 Fischer-Tropsch Synthetic Paraffinic Kerosene

Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) is a type of synthetic aviation fuel produced through the Fischer-Tropsch process, which involves the conversion of carbon monoxide and hydrogen gases into liquid hydrocarbons. The FT-SPK may only be used as a blend with conventional jet fuel from crude oil with a maximum blending ratio of up to 50%. FT-SPK has favorable storability characteristics, remaining in a liquid state at standard temperatures and pressures. It can be stored without major modifications using existing jet fuel infrastructure, requiring minimal adjustments to aircraft to make it compatible (Kumabe et al., 2010). Fig. 9. shows the estimation of Integration Feasibility of FT-SPK.

4.2 Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene

Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK). This type of biofuel is made from vegetable oils, animal fats, or microalgae oils, which are deoxygenated and hydroprocessed. Owing to these methods, this fuel is highly compatible with the current aircraft fuel systems. However, HEFA-SPK is a type of aviation fuel that is prone to degradation over time. This degradation is primarily due to oxidative processes and the presence of microbial communities. Therefore, its storability is limited (Bacosa et al., 2010). Unfortunately, at present, HEFA-SPK must be blended up to 50% with conventional kerosene, because it does

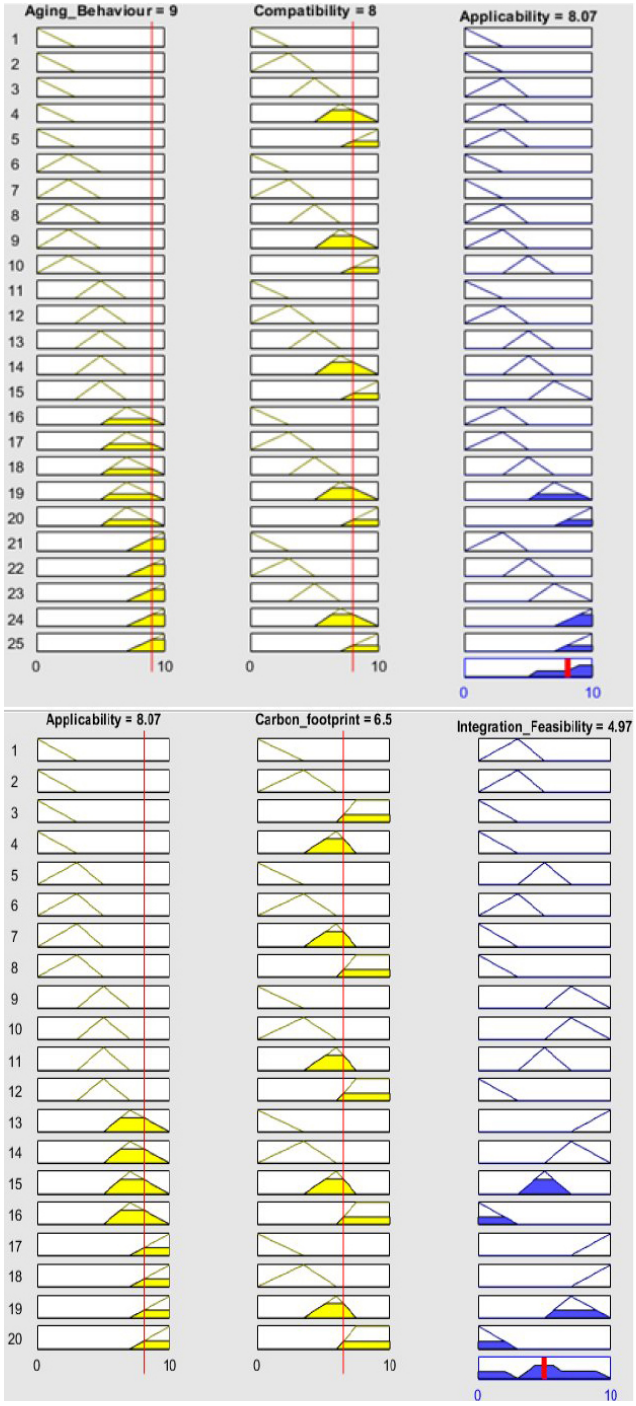

Fig. 9 Applicability and integration feasibility estimation of Fischer-Tropsch Synthetic Paraffinic Kerosene

Table 8 Input and output data of case studies

Fuel	Aging behavior	Compatibility	Applicability	Carbon footprint	Integration feasibility
FT-SPK	9.0	8.0	8.07	6.5	4.97
HEFA-SPK	7.0	5.5	5.88	3.0	7.42
LNG	4.0	3.0	2.34	5.5	1.62
LH2	3.0	2.0	1.06	1.0	3.37

not contain some less environmentally favorable components (e.g., sulphur) which allow seals to swell in engines and prevent fuel leaks. The carbon footprint of HEFA-SPK varies between 15–62 g CO_2 e/MJ depending on the feedstock used (Pavlenko and Searle, 2021). Therefore, it has significant potential for reducing lifecycle greenhouse gas emissions compared to conventional jet fuels (Seber et al., 2014). Fig. 10 demonstrates the estimation of Integration Feasibility of HEFA-SPK.

4.3 Liquefied natural gas

Another option is liquefied natural gas (LNG). LNG is a cryogenic fuel and its boiling temperature at standard atmospheric pressure is 112 K. Technical challenges such as low energy density (MJ/m^3) and thermal stability at standard atmospheric conditions have limited the research and development efforts due to hurdles in implementation, such as necessity of aircraft modification, storage, transportation and energy storage density. Despite these challenges, the use of LNG as a jet fuel is a promising area of research, with potential for further development and integration with renewable energy sources (Roberts et al., 2015). LNG is based on natural gas and generally has lower emissions compared to traditional fossil fuels. However, it is the production and liquefaction that generate the most GHG emission, followed by natural gas exploration and separation, and exportation and transportation. These factors give the LNG a slightly lower carbon footprint than the Jet-A1 has (Abrahams et al., 2015).

This table confirms that given the low aging behavior and the Compatibility, currently the LNG has poor integration feasibility (1.6). Fig. 11. shows the estimation of Integration Feasibility of LNG.

4.4 Liquefied hydrogen

Liquefied hydrogen (LH_2) is one of the most promising alternative fuels for aviation in the long run. Its direct greenhouse gas emission is very low, because hydrogen combustion produces only water vapor and does not emit any carbon dioxide. However, the overall carbon footprint depends on the production method, but in case of "blue" or "green" hydrogen it is also minimal. Yet, the extremely low temperature (10–21 K) needed for hydrogen storage makes the necessary infrastructure complex and energy-intensive. Unfortunately, the practical implementation in aviation would require significant advancements in technology and infrastructure development (Aziz, 2021).

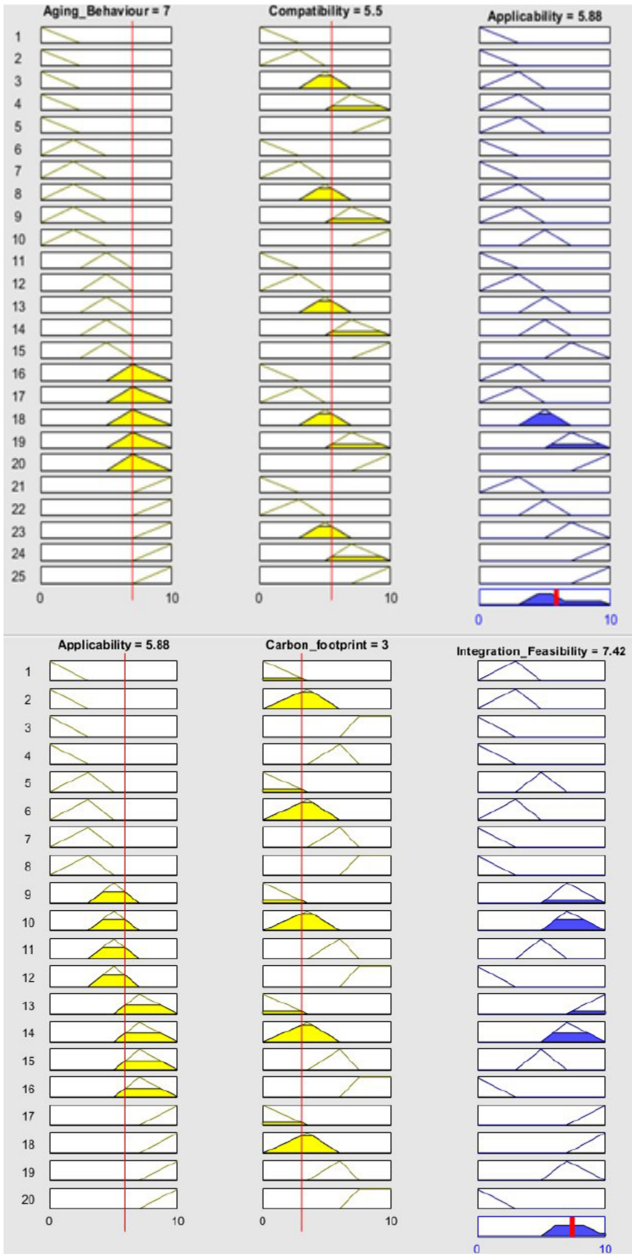

Fig. 10 Applicability and integration feasibility estimation of hydroprocessed esters and Fatty Acids Synthetic Paraffinic Kerosene

In the case of LH_2 the low carbon footprint value offsets the low applicability to some extent, therefore the integration feasibility is 3.25, which is within the limits of the limited and appropriate category. Fig. 12. shows the estimation of Integration Feasibility of LH_2.

4.5 Discussion

Out of the examples presented above, it seems that HEFA-SPK has the highest integration feasibility, followed by FT-SPK, LH_2 and LNG. This result is based on the fact that,

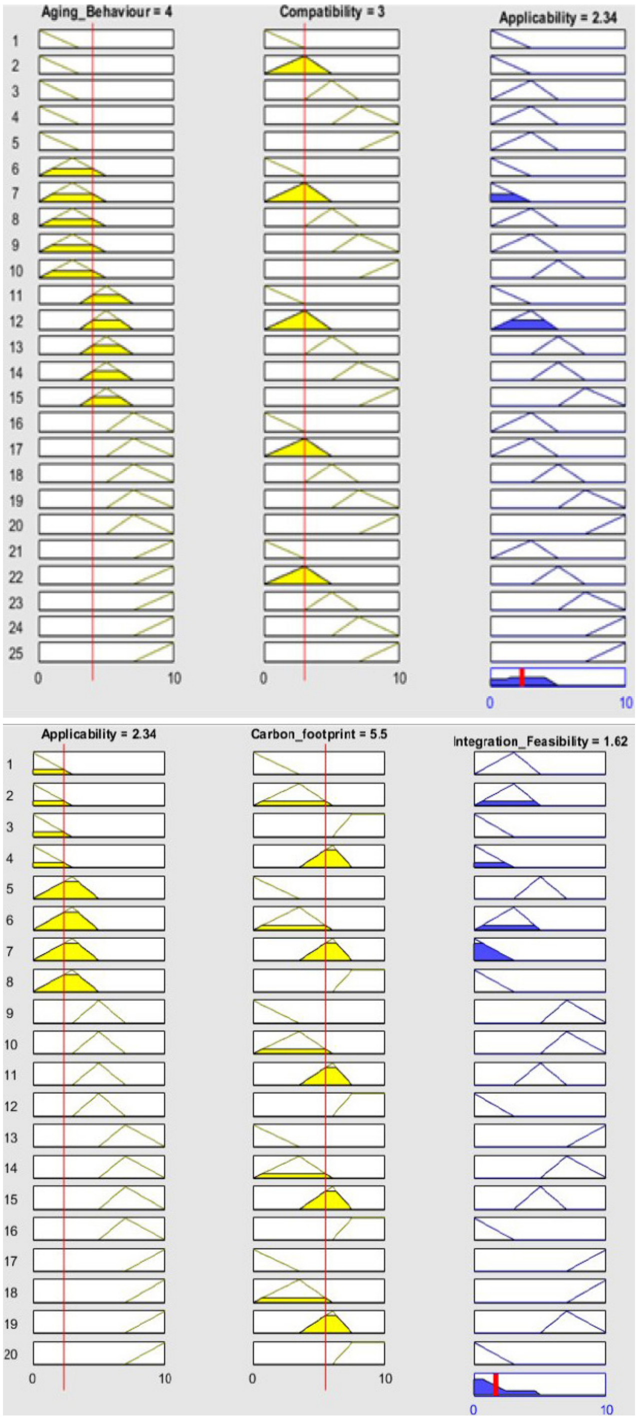

Fig. 11 Applicability and integration feasibility estimation of liquefied natural gas

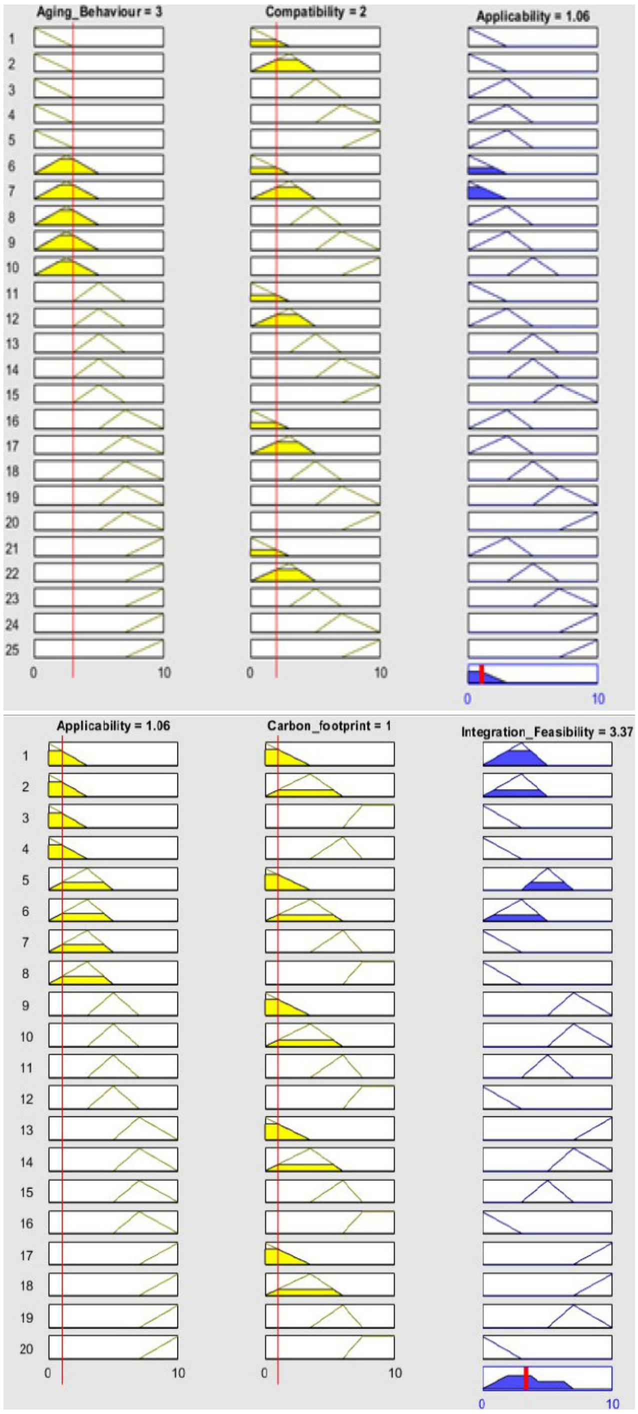

Fig. 12 Applicability and integration feasibility estimation of liquefied hydrogen calculation

among others, HEFA-SPK has a particularly low Carbon Footprint, moreover, the FT method is the closest to the traditional kerosene production process and is currently the most well-formed technology among the listed ones, however due to the high Carbon Footprint value it qualified only in second place. FT-SPK also performs well, whereas liquid hydrogen scores lower in these areas. This can be partly explained by the infrastructural and technical challenges associated with its introduction as an aviation fuel. Which leaves LNG as ranked last. These findings emphasize the importance of sustainable aviation fuels and the complex evaluation of different alternatives. Further, more specific results can be achieved by further breaking down the alternative fuel types according to specific feedstocks.

Through these examples, it can be seen that the developed model can provide a fairly accurate approximation to the relative ranking of alternative fuels according to their integration feasibility. The proposed method is suitable and reflects the general opinion of the experts in the field. However, several important factors, such as the cost, availability or heating value were not taken into consideration, which require further tuning.

5 Conclusions – future work

During the use of alternative fuels, many new problems arise, the subjective evaluation of which results in uncertainties. The developed fuzzy rule-based evaluation method examines these uncertainties well. The paper presented a hierarchical fuzzy rule-based qualifying method to comparison alternative jet fuels. The proposed method used as input parameters aging behavior; applicability; carbon footprint and estimated integration feasibility of valued jet fuel.

The authors' future work will be based on the experience gained during the development of the method and the opinions received from experts, focusing on developing a more complex methodology of a multi-level fuzzy rule-based jet fuel qualification process.

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