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Modeling the impact of sustainable aviation fuel properties on end-use performance and emissions in aircraft jet engines

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ABSTRACT

The present study supports the development and testing of alternative jet fuels by introducing a state-of-the-art mathematical model that enables for the first-time accurate estimations of the fuel consumption in jet engines via employing the collective impact of the most significant fuel properties. Based on literature data the matrix with fuel properties and end-use performances was constructed. The Best Multiple Linear Regression combined with quantitative analysis was employed in the modeling procedure. The developed Jet-model contains the effects of viscosity, density, and calorific content on fuel consumption, with p-values much below 1%. The coefficient of determination R-Square of 0,993 indicates a high accuracy, that in the validation procedure translated into the error of 0,21% against internal data and 0,68% in external data. The Jet-model was applied to simulate the end-use performance of commercial sustainable aviation fuels. The results show changes in fuel consumption relative to standard kerosene oscillating between −0,85% and +3,72% and reduction in carbon dioxide emissions that vary from −3,22% to +0,42% for selected fuels. The present study shows that Sustainable Aviation Fuels have the potential to outperform their fossil counterpart not only in terms of the environmental impact but also in fuel and energy consumption.

1. Introduction

Transportation grows dynamically while the sector increased its share of final energy consumption from 23% (1971) to 29% (2017) [1]. In 2018, the transport's energy consumption of about 2.8 Gtoe [2] was mainly relying on fossil-fuels (over 95% [3]) which corresponded to emissions of about 8.23 Gt of CO_2 [2]. The aviation sector was responsible for around 0.93 Gt of CO_2, 12% of the whole transport sector emissions. However, when comparing aviation to the total world anthropogenic CO_2 emissions of 33.51 Gt, it constitutes around 2.8% [2]. Aviation is the most difficult mode of transportation to be electrified, therefore, there is a strong need for liquid fuels even in the distant future [4].

In 2019, 363 billion liters of jet fuel were used in commercial flights, out of which significantly less than 1%, only 40 million liters, were Sustainable Aviation Fuels (SAF) [5]. According to the sustainable development scenario of IEA, SAF are expected to reach around 10% of aviation fuel demand by 2030 worldwide, which corresponds to 37 billion liters [6]. Therefore SAF production capacities need to increase significantly in the next decade.

SAF are certified under the ASTM D7566 standard, and currently, 7 conversion pathways are approved [7]: Fischer-Tropsch Synthesized Isoparaffinic Kerosene (FT-SPK), Hydroprocessed Esters and Fatty Acids (HEFA), Renewable Synthesized Iso-Paraffinic Kerosene (SIP), Synthetic Paraffinic Kerosene with Aromatics via Fischer−Tropsch (FT-SPK/A), Alcohol-To-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), Catalytic Hydrothermolysis Jet fuel (CHJ), Hydroprocessed Hydrocarbons - Synthesized Isoparaffinic Kerosene (HH-SPK or HC-HEFA).

1.1. Feedstocks and conversion pathways for sustainable aviation fuels production

The value chain of SAF begins with feedstocks, which are essential when thinking about the supply security of SAF end-products and their life-cycle environmental impact [8]. Not only quantities but also the type of feedstock is significant, as it affects the end-product composition and properties. P. Vozka et al. investigated the impact of feedstocks such as camelina, tallow, and

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mixed fat oils, on HEFA fuel composition and properties in blends with Jet-A1 at various concentrations [9]. The production of biokerosene using the macauba oils via catalytic deoxygenation was studied by L.N. Silva et al. [10]. The non-edible sunflower oil is an interesting feedstock for SAF production, X. Zhao et al. explored that option through catalytic cracking [11], the resulted carbon distribution was between C_7 and C_{43}, which is applicable for not only SAF production but also renewable gasoline, diesel and heavier fractions for marine engines. The production of SAF from non-edible soybean oil was investigated by I.H. Choi et al. in a single-step process [12], the results showed a jet-fuel range of hydrocarbons reaching up to 69.3% which included n-paraffins, isoparaffins, and aromatic compounds, all of them were oxygen-free. Lignocellulosic biomass could be converted via fast pyrolysis or hydrodeoxygenation (HDO) [13], currently both pathways are gaining momentum in downstream of SAF. The benefit of fast pyrolysis is that it has the potential to reduce the cost of SAF production, especially when utilizing straw as feedstock, J. Wang et al. produced C_8–C_{15} hydrocarbons that met the technical specifications of jet fuels [14]. Rice husk is an agricultural waste that could be utilized as a feedstock for SAF production through fast pyrolysis as demonstrated by Y.K. Chen et al. [15].

Microalgae are a potential feedstock for jet fuel production, M-O. P. Fortier et al. investigated the Life Cycle Assessment (LCA) of microalgae-based SAF made through the hydrothermal liquefaction (HTL) process [16]. Raw materials are certainly limited and the demand for alternative fuels is growing. Therefore, new possibilities such as waste plastics could play a significant role in the future. S. Tomasek et al. performed an experimental analysis of jet fuel production from waste polypropylene and polyethylene [17], whereas H. Tang et al. utilized polyethylene terephthalate (PET) wastes [18]. W. Mateo et al. showed that sulfonated activated carbon (SAC) is an efficient pyrolysis catalyst for the production of SAF (aromatics and C_9–C_{16} alkanes) from both biomass and plastic wastes [19]. An interesting pathway for military-grade renewable jet fuel production from catalytic microwave-induced degradation of plastics was presented by X. Zhang et al. [20]. Such a route allowed to achieve up to 63% carbon yield of plastics derived jet fuels [21].

A new promising feedstock is CO_2, that together with hydrogen from renewable electricity could be fed into the FT reactor to produce liquid synthetic fuels, such technology was studied by D.H. König et al. [22]. Nevertheless, the price of Power-To-Liquid (PTL) SAF is still a big challenge, it is estimated that the approximate production cost is about 2.4 euro/liter [23]. When it comes to the ATJ pathway, K. Atsonios observed that the ATJ process has higher efficiency, and better carbon utilization than the FT pathway and opens a possibility to sell intermediate products such as olefins and alcohols, however, ATJ commercially is less competitive due to its higher CAPEX [24].

1.2. End-use of sustainable aviation fuels and policies

SAF reduce significantly not only the CO_2 emissions but also lead to lower soot formation as observed by M. Buffi et al. [25]. Moreover, jet fuel standard ASTM D1655 allows 0.3% mass concentration of sulfur in the fuel, which is much higher compared to road fuel standards (gasoline EN228, diesel EN590) that permit max. 0,001% mass of sulfur. This leads to the high emission of SO_x, which is particularly concerning for areas around airports. SAF either do not contain sulfur or have only trace amounts (much below 0.01% mass), this drastically reduces or even eliminates SO_x emissions, contributing to lower global aviation-induced mortality [26].

The performance and emissions of SAF could be tested experimentally or through thermodynamic simulations either on steady-state jet engine operation on a ground level or through flight conditions. When it comes to steady-state jet engine (constant speed and load of the engine) measurements, B Gawron et al. observed that the addition of 10% butanol to Jet-A1, causes a slight increase in FCmass (due to the lower LHV of butanol compared to Jet-A1), however, lowers tank-to-thrust (TTT) emissions of CO_2, CO and NO_x [27]. A higher concentration of butanol (25%) with Jet-A1 decreased the FCmass below the level of neat Jet-A1 as observed by C.J. Mendez et al. [28]. M. Noureldin et al. investigated the end-use performance of biodiesel blends with Jet-A1, the results show that the higher concentration of biodiesel the higher FCmass, however similarly like in the case of butanol, CO and NO_x emissions were lower compared to Jet-A1 [29]. Biodiesel as a Fatty Acid Methyl Ester (FAME) contains oxygen in its molecule which helps to achieve more complete combustion reducing the unburned hydrocarbons between 10% and 55% as observed by E. I. H. Tan and W.W. Liou [30]. Neat FAME (100% biodiesel) showed also FCmass improvement compared to Jet-A1 in micro gas turbine engine [31]. A similar trend of lower FCmass and increased thermal efficiency over Jet-A1 was observed by Z. Habib for soy methyl ester, canola methyl ester, recycled rapeseed methyl ester, and hog-fat biofuel tested in 30 kW gas turbine [32]. The results show also lower CO and NO emissions for tested biofuels. HEFA synthetic paraffinic kerosene is an ASTM certified drop-in SAF for standard Jet-A1, which both in blends with Jet-A1 but also as a neat fuel leads to reductions in FCmass, as well as lower CO, CO_2, and NO_x emissions [33]. Hybridization of powertrains in combination with alternative fuels brings a new level of opportunities for reduction of GHG emissions and enhancements of the performance. S. Seyam et al. investigated two hybrid aircraft propulsion systems (jet engine with fuel cells) powered by both standard kerosene and a blend of methane with hydrogen. A strong reduction of CO_2 emissions and better system performance despite increased engine weight was reported [34]. The flight procedures are another option to measure the end-use performance of alternative fuels. A good example is an “Alternative Aviation Fuel Experiment (AAFEX)” of NASA that examined the end-use performance and emissions of different feedstock type Fischer–Tropsch (FT) fuels [35]. Another real flight-based examination is F.D. Cox and G. A. Bobula's study that investigated the performance of the ATJ 50:50 blend with JP-8 (military jet fuel) on two aircrafts and reported no noticeable differences between the use of neat JP-8 and the ATJ/JP-8 blend [36]. As presented there are different options to measure the end-use performance of alternative fuels, however, repeatability and reliability of results are essential to observe the true effects of fuels over real flights. Therefore, International Civil Aviation Organization (ICAO) introduced a flight procedure called Landing and Take-Off Cycle (LTO) [37]. Additionally, the full life cycle assessment of SAF can help to understand better their real environmental impact, beyond the tank-to-thrust part [38].

Considering policy, regulations, and incentives, D. Chiaramonti et al. concluded that SAF are in a clear need of scaling up that is involved with very large investments in research and development, fuel certification, conversion technology piloting, and demonstration, and building of new biorefinery complexes. This all requires strong policy support including long-term stability in regulations. The authors highlighted that all barriers hampering market development need to be addressed and overcome [39]. Additionally, C. Panoutsou et al. investigated the policy gaps on the EU level, suggested policy interventions, mechanisms, and their added value to bring down the higher cost of SAF, distribute the feedstocks effectively while reducing the competition between aviation and other transport sectors such as on-road, and strengthen the coordination, cooperation and synergies within the whole value chain [40].

1.3. Fuel consumption models for the aviation sector

In the literature, there are studies focused on relations between fuel consumption and aircraft characteristics, flight structure, jet-engine class, and type of fuel. In terms of aircraft characteristics, J. E. Nettle and J. R. Lord patented a method and means to increase the aerodynamic efficiency of an airfoil designed for aircraft [41]. The weight of aircraft is essential when thinking of FC, and it is heavily affected by the amount of fuel that is loaded for the specific route. K. Abdelghanya et al. developed a model for aircraft optimal fuel management at each airport and specific route [42]. Flight altitude and speed as well as flight path or weather affect strongly FC, W. A. Khan et al. developed a self-organizing constructive neural network (CNN) for trip-specific fuel consumption estimation [43]. The jet engine plays a major role when thinking of FC, especially its max power and speed, as well as characteristics of the combustion chamber, compressor, and injectors. The mathematical model for FC estimation based on the shaft power off-takes was developed by D. Scholz et al. [44]. The optimizations of the combustion chamber, as well as compressor components can increase the energy efficiency and lower the FC as concluded by O. Balli and H. Caliskan [45]. The jet engine operation in terms of load factors affects its performance, C.T. Yucer made an energetic and exergetic analysis on a small scale jet engine at idle, two part loads, and full load conditions [46]. SAF differ from Jet-A1 in their composition, which affects the spray and droplet characteristics including droplet diameter and velocity [47]. Furthermore, the combustion efficiency and local emissions are affected by changes in fuel composition as observed by R. H. Sundararaj et al. [48]. This on a larger scale translates to changes in the FC and GHG emissions of SAF when compared to their fossil counterpart. K Lokesh et al. developed a life cycle GHG model, for “cradle-to-grave” environmental impact assessments of various SAF [49]. Additionally, based on thermodynamic modeling, M.Z. Sogut et al. investigated the performance of alternative jet fuels over various flight conditions [50].

The studies showing the effect of alternative fuels are analyzing the impact of their chemical composition where respective performance in jet engines is estimated based on experimental campaigns or through thermodynamic analysis. Presently, there are no studies that investigated the direct effect of fuel properties on jet engine performance. Fig. 1 highlights the current knowledge gap that the present work is addressing (see Fig. 2).

1.4. Outline of the study - novelty

Addressing the knowledge gap highlighted in the previous section, the current work covers an important niche in fuel consumption models, related to the effect of fuel properties. The aim is to develop a state-of-the-art mathematical model that will enable instant, cost-free, and accurate estimations of FC in aircraft jet engines based on fuel properties exclusively. The proposed new approach is exceptionally important in the fuel development stage where available quantities of developed SAF are too low for experimental studies, but sufficient to measure their chemical and physical properties. Additionally, such a model offers an alternative route to expensive experimental jet engine tests including flight procedures as well as thermodynamic analysis that require specific knowledge and tools.

The outline of the present work is as follows:

- Section 2: Introduces a new approach and method in the development of an accurate mathematical model for fuel consumption estimations in aircraft jet engines with applicability to all kinds of liquid fuels.
- Section 3: Analyses the collected data in terms of fuel properties and their end-use performance as well as introduces the developed Jet-model and its validation results.
- Section 3.2: Applies the Jet-model for simulation of the end-use performance for five commercial (ASTM D7566 certified) SAF in the entire concentration spectrum with standard Jet-A1.

2. Methodology

There are various potential approaches for modeling the collective impact of fuel properties on jet engine performance, dependent on the desired applicability of the final outcomes. **The present study is aiming at the development of a new model that should: i) bridge accurately fuel properties with fuel consumption in jet engines, ii) be applicable to the whole fleet of its kind (regardless of the jet engine size and specification), iii) work well with all kinds of fuels (from single chemical compounds, through refinery streams to ready fuel products), and iv) represent the impacts from the end-use perspective.** To meet

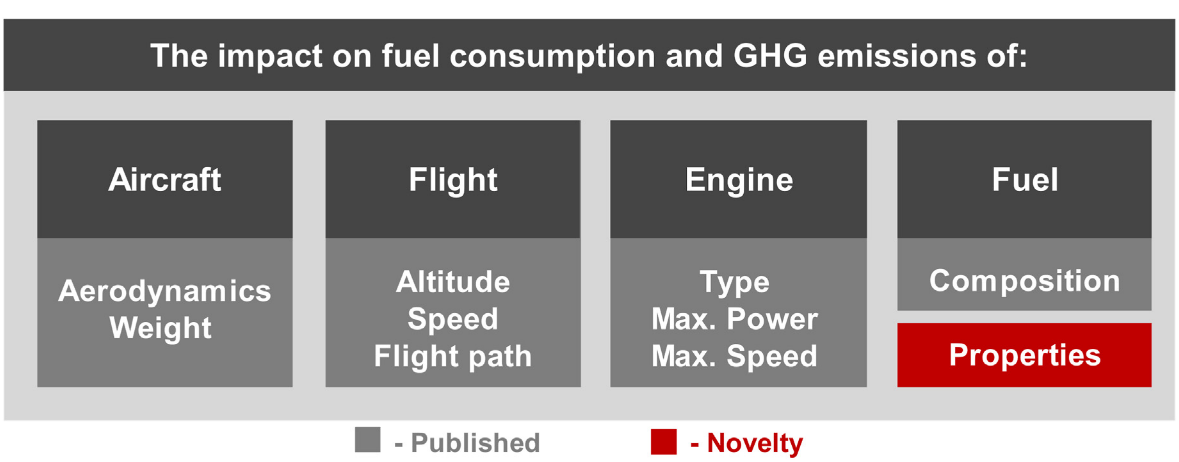

Fig. 1. The present paper's research in contrast to published studies. In the literature, there are published models and knowledge related to the effects of aircraft designs and weight, flight characteristics, engine type, and fuel composition. However, there are no models available that show the direct impact of jet fuel properties on the jet engine performance, which is the focus of the present paper.

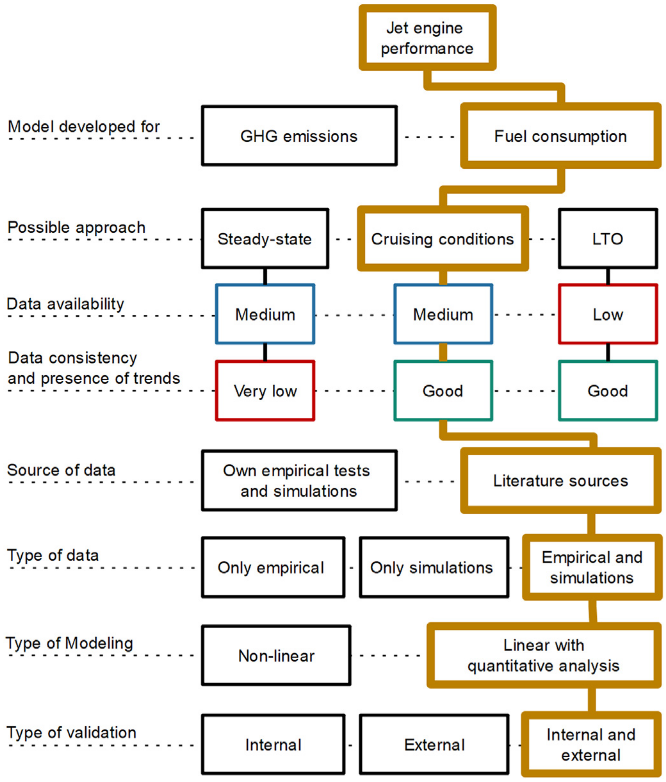

Fig. 2. Methodology pathway designed to develop a mathematical model that represents the impact of fuel properties on jet engine performance (yellow line).

those criteria, the research was divided into the four major steps aiming at the development of a correct methodology:

1. **Selection of the approach.** In this stage, the decision should be taken about what kind of jet-engine performance data will be selected for further analysis. In general, there are three options: steady-state points for jet-engine operation, specific flight conditions, or full flight cycle. All of those options could be either experimental or simulation results.
2. **Data collection and representation.** After the decision of what kind of data needs to be acquired, an extensive literature review has to follow to find sufficient quantities of essential data for further analysis. Subsequently, data collected from literature need to be properly represented to allow direct comparison of measurements coming from different sources. In general, there are two options such as absolute values or relative changes.
3. **Development of the matrix.** Once the data is ready, the modeling matrix has to be constructed with a proper length and a good amount of initial independent variables. Additionally, a portion of the data should be extracted from the matrix for external validation.
4. **Modeling and validation.** The core part of this work is modeling, where an appropriate method such as linear or non-linear, has to be selected. The modeling should be enriched with quantitative analysis, to have confidence in the significance of the final independent variables. Once the model is ready, it should be validated both against the internal data (used for model development) but also external data (the data that the model has never seen).

The following figure reveals the chosen methodology path across various aspects (yellow line), whereas subsequent sections will look more into the details and motivation behind the chosen path.

2.1. Selection of the approach

In this section, the focus is paid to the limitations and opportunities related to possible problem approaches. In general, fuels can be tested in the steady-state turbine operation, during the specific flight conditions (take-off, climb, cruise, approach, landing), or over the entire aircraft flight cycle. All of those options are possible to investigate based on either real experimental testing or simulations using for example zero-dimensional (0D) thermodynamic models.

2.1.1. Limitations of the steady-state analysis

In steady-state analysis (SSA), tests are performed under fixed conditions of the engine operation, usually given by the engine speed and load. The main drawback of such an approach is a lack of transient conditions when the engine switches from one steady-state point to another, which is a natural way of operation during the flight. Additionally, when comparing the test results of SSA from various laboratories and sources, it could be noticed that the influence of a test engine used at a specific laboratory is greater than the influence of fuel and its properties. Moreover, relations for the engine thrust produced by the tested group of fuels at one specific steady-state point differ from another steady-state point (for example at higher rotations per minute (RPM) of the jet turbine). Those factors make it very difficult to find trends for modeling when combining the data points from different sources. In Appendix B, the results of engine performance under the SSA of jet engine operating with various SAF are presented (Table 3 and Fig. 11). The data from three independent sources (source X [51], Source Y [52], and Source Z [53]) were gathered, where tests on real jet engines under 60,000 RPM were performed. The outcomes indicate no clear trends between fuel properties and jet engine performance. In some cases, different sources show even contrary behavior. Therefore, the SSA approach was not selected for further modeling.

2.1.2. Aircraft cruising conditions - selected approach

As presented above, there are various limitations associated with SSA. The two remaining options are specific flight conditions or a full flight cycle. Much more applicable option, to reveal the performance in end-use, is a result of fuel consumption from a regular flight test, in which the aircraft spends most of its time in cruising conditions: power about 82% [54], altitude 10000 m–14000 m, speed of 0.8 Mach (980 km/h) [55], turbine inlet air temperature between $-50^{\circ}C$ to $-31^{\circ}C$, and air mass flow between 1.3 kg/s to 4.5 kg/s [56]. The phases of a regular flight are presented in Fig. 3.

The sources of data discussed in a subsequent section, give either full LTO cycle results with the specification of FC for each phase take-off (100% power), Climb (85% power), Approach (30% power), Idle (7% power), or typically the outcomes of FC for cruising conditions. There is a small difference between the climb phase which operates with 85% of power and the cruise with 82% of the power. It has been decided to take to the matrix primarily cruise conditions, but when they were not reported in the literature, then climb conditions were taken to increase the number of observations for modeling and validation procedure. Nevertheless, most of the data sources reported outcomes for cruise conditions.

2.2. Data

Ten sources of data were selected for analysis and modeling (A

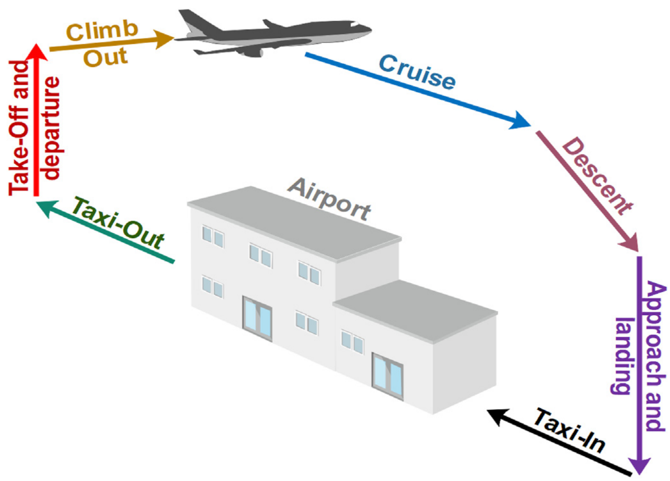

Fig. 3. Phases of the regular flight with a typical commercial aircraft.

[49], B [54], C [57], D [58], E [55], F [59], G [60], H [61], I [56], J [62]) that together gave 69 observations. They include results from experimental tests of real jet engines (TRS-18-046-1, 250-C18 B, F-404-400, T-56-A15, CF-700, CFM56-7B) powered by various SAF, and also simulation studies based on 0D thermodynamics. The most common software used for such analysis are Pythia and Hermes developed by Cranfield University. In both cases, the performance analysis is based on the principles of mass conversation, energy conversation, and special conditions. The model of the turbine is built based on blocks that represent compressors, combustors, turbines, etc. [63,64]. Both software are running on a 0D gas turbine performance code called "Turbomatch" developed in 1967 [65]. The difference between HERMES and PYTHIA, is that the HERMES code has the option to calculate engine power setting and performance during all flight phases (take-off, climb, descent, landing, taxi, deviation mission) - the entire landing-take-off (LTO) flight cycle. Pythia allows simulation during specific conditions, such as cruising, for example. Another software is a commercial GasTurb, which operates in 0D-thermodynamics and can simulate both steady-state and transient behavior [66]. More details are summarized in Appendix A and Appendix C.

2.3. Modeling and validation procedure

When SAF is blended with JET-A1, the resulting new blend has different fuel properties than SAF or JET-A1 separately. This new blend also performs differently in the jet engine. In the modeling part, a novel Jet-model will be developed, that will allow accurate estimations of jet fuel consumption, based on a known set of fuel properties. Fig. 4 represents the modeling problem, where the letters "γ, ζ, η, μ" represent fuel properties such as density, viscosity, calorific content, etc., whereas fuel consumption is represented by "FC".

In the modeling stage, multiple input parameters (independent variables) are represented by fuel properties, whereas a single output parameter (dependent variable) is represented by fuel consumption. All parameters (fuel properties and fuel consumption) are given as relative changes (in %) to standard fuel (Jet-A1), in order to make the model more uniform and allow the comparison of data coming from various sources (various jet engines, various fuels, different measurement equipment, etc.). In real life, fuel properties influence energy conversion processes collectively, and very often they are interrelated as well. Therefore, modeling takes into consideration the common impact of various fuel properties.

The modeling problem consists of multiple input and single output relation, and the chosen modeling approach is linear. Therefore, stepwise Best Multi-Linear Regression (BMLR) was selected as a modeling technique, and it could be expressed by the following equation:

$$y(x) = \varphi_1(x) \cdot \beta_1 + \cdots + \varphi_n(x) \cdot \beta_n + \epsilon(x) \quad (1)$$

where, y - dependent variable, x - independent variable, $\varphi_i(x)$ - explanatory variable, β_i parameter of explanatory variable, $\epsilon(x)$ - error.

The modeling criteria for a BMLR are aiming at the highest R-Square for the model that incorporates a combination of parameters while each of them has a significance level below 5% (P-value ≥ 0.05). The modeling is executed in a step-by-step iterative manner targeting to construct the most accurate regression model. This is achieved by incorporating statistical significance testing, in which independent variables are added or removed after each iteration. The modeling begins with no variables in the model, subsequently, each possible variable is added to the model, and the

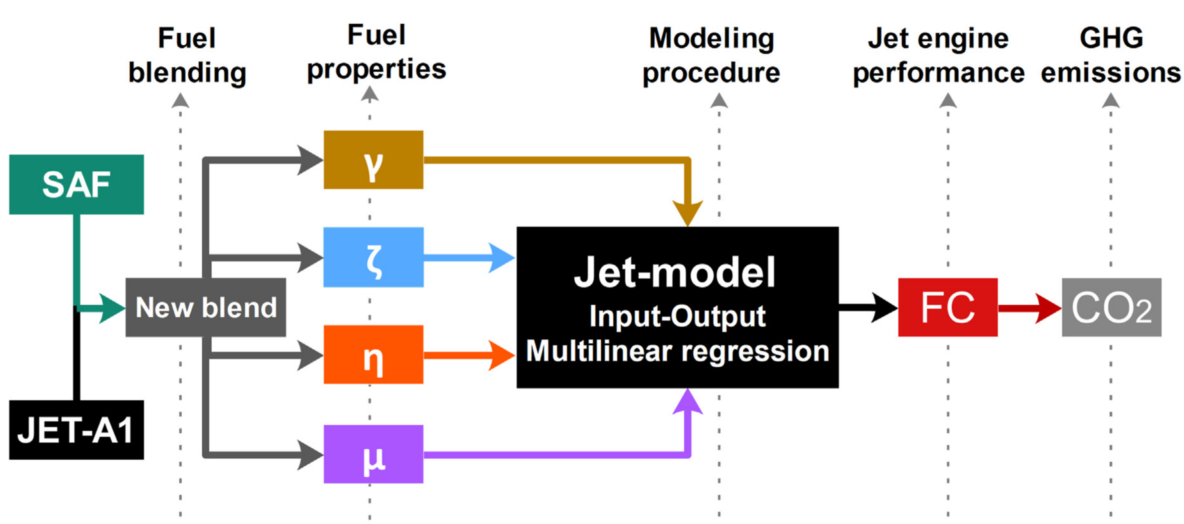

Fig. 4. The modeling approach. Letters "γ, ζ, η, μ" represent fuel properties such as density, viscosity, calorific content, etc. The fuel consumption (FC) relative to jet-A1 is estimated based on the Jet-model that uses fuel properties as inputs. The carbon dioxide emissions are subsequently calculated based on the carbon content of the fuel and the results of FC.

statistical significance test is performed (calculation of the p-value). If the variable has a p-value greater than 0.05, it is rejected from the model. After adding the first most significant explanatory variable, another is added and statistical significance is again tested. The process is continued with other parameters until the model is completed. This specific iteration is known as forward stepwise regression. The final model has the highest possible R-square and includes possibly the most significant explanatory variables. More about the quantitative analysis (T-test, and P-value) is provided at the end of the present chapter.

Referring to Fig. 4, the Equation [1] could be expressed as follows:

$$\alpha_{JET} = a_{\gamma} \cdot \gamma(X_{SAF}) + a_{\zeta} \cdot \zeta(X_{SAF}) + a_{\eta} \cdot \eta(X_{SAF}) + a_{\mu} \cdot \mu(X_{SAF}) \tag{2}$$

where, α_{JET} - relative change of fuel consumption [% change in reference to l/hr], X_{SAF} - SAF's volumetric concentration in the blend with standard Jet-A1, $\gamma(X_{SAF})$, $\zeta(X_{SAF})$, $\eta(X_{SAF})$, $\mu(X_{SAF})$ - relative change of fuel property γ, ζ, η, μ [% change relative to standard JET-A1], $a_{\gamma}^{\zeta,\eta,\mu}$ - coefficients of property γ, ζ, η, μ.

As mentioned before, all variables (dependent and independent) are represented as relative changes to standard Jet-A1 (in %), and they are calculated in the following way:

$$\gamma(X_{SAF}) = (\gamma_{SAF} - \gamma_{Jet-A1}) \Big/ \gamma_{Jet-A1} \cdot 100\% \tag{3}$$

where, $\gamma_{SAF}(X_{SAF})$ - the value of specific fuel property [γ] for alternative fuel blend dependent on concentration of SAF [X_{SAF}], γ_{JET-A1} - value of specific fuel property [γ] for standard Jet-A1, γ_{SAF} - value of specific fuel property [γ] for neat SAF.

The least-squares method is used to approximate the solution during the regression analysis in the modeling stage [67] - Eq. (4).

$$J_{\theta} = \sum_{x=1}^{N} \epsilon^2 = \sum_{x=1}^{N} (y(x) - \varphi^T(x) \cdot \theta) \tag{4}$$

where, J_{θ} - least-squares objective function.

The carbon dioxide CO_2 emissions are calculated based on the outputs of fuel consumption, density and carbon content in the fuel. The coefficient (44.December 01, 0107) is a molar mass relation between carbon dioxide and carbon. Eq. (5) represents the calculation methodology.

$$\delta = \alpha_{JET_{ABS}} \cdot \rho \cdot z \cdot \frac{44.01}{12.0107} \tag{5}$$

where, δ - CO_2 emissions [g/km], $\alpha_{JET_{ABS}}$ - absolute value of fuel consumption [l/hr], ρ - density of the fuel [g/dm3], z - mass-based carbon content in the fuel [%], $\frac{44.01}{12.0107}$ - molar mass ratio between carbon dioxide (44.01 g/mol) and carbon (12.0107 g/mol).

The mass-based concentration of carbon in the jet fuel can be calculated in the following way:

$$z = (X \cdot z_{SAF} \cdot \rho_{SAF} + (1 - SAF) \cdot z_{Jet-A1} \cdot \rho_{Jet-A1}) / \rho \tag{6}$$

where, X - volumetric fraction (concentration) of alternative fuel [%], ρ_{SAF} - density of net SAF [g/dm3], ρ_{Jet-A1} - density of net Jet-A1 [g/dm3], z_{SAF} - carbon content in SAF [%], z_{Jet-A1} - carbon content in Jet-A1 [%].

The energy consumption (EC) is calculated on a basis of FC and calorific content:

$$\epsilon = \alpha_{JET_{ABS}} \cdot LHV_{JET_{ABS}} \tag{7}$$

where, ϵ represents the energy consumption in [MJ/hr] and $LHV_{JET_{ABS}}$ is a lower heating value of a jet fuel expressed in [MJ/L].

The model's accuracy is characterized and controlled by the coefficient of determination (R-square) and standard error during modeling. The validation procedure is executed against the data used for modeling - internal validation, and the data that were not taken into the modeling process - an external validation (based on multiple independent sources). Additionally, quantitative analyses are incorporated in the modeling process to ensure that all independent variables that were selected in the final model are statistically significant, meaning that their p-value has to be lower than the significance level. The p-value is a data-based measure that oscillates between 0 and 1 and represents the probability of observing the results outside the range of statistical significance. Therefore, the lower p-values, the less interrelated independent variables in the model are, which ensures that each of them has its unique and particularly important impact. This in consequence leads to more accurate and stronger models. The p-value is calculated based on the t-value (the result of the Student's t-test - statistical hypothesis test) and probability density function (PDF) explained more in detail by Y. Kroyan et al. [68], where a similar approach was successfully applied in the development of models representing the end-use performance of alternative fuels in light-duty road transportation.

3. Results and discussion

This section focuses on:

1. Investigation of the collected data, with special attention on characteristics of analyzed fuels and correlations between their properties and fuel consumption in jet engines.
2. Analysis of data in terms of jet engine performance measures including volumetric FC, mass-based FC, energy consumption, and carbon dioxide emissions.
3. Internal and external validation of developed Jet-model.
4. Application of Jet-model in the simulation of performance and emissions for five ASTM D7566 fuels.

3.1. Modeling results and discussion

In the first stage of analysis, the individual relations between fuel properties and fuel consumption were investigated. Selected sources of data reported fuel properties such as viscosity, density, LHV mass, and volume-based, carbon and hydrogen content for each SAF that was tested, together with the engine performance outcomes. Fig. 5 shows the variation of fuel consumption versus the change of each fuel property (parameters are expressed as percentage changes relative to the standard Jet-A1).

When it comes to the density, based on 10 different sources, a very clear trend could be observed. In general, when density increases fuel consumption decreases. LHV volume-based and carbon content show a similar influence on FC as density. The opposite impact represents LHV mass-based and hydrogen content, where the higher their values, the higher fuel consumption. In Fig. 5, viscosity at −20 °C shows no clear correlations with fuel consumption. Nevertheless, fuel properties are interrelated and affect jet-engine performance collectively, therefore, their combined effect needs to be considered. The performance of the jet engine is commonly represented by the volumetric fuel consumption (FCvol), expressed in liters per unit of time. This is a convenient way of translating such performance into costs, as Jet fuels are traded on a volumetric basis. However, another possibility is a mass-based fuel consumption (FCmass) expressed in kg per unit of time or energy consumption (EC), which shows the magnitude of megajoules (MJ) that a given powertrain consumes per unit of time for

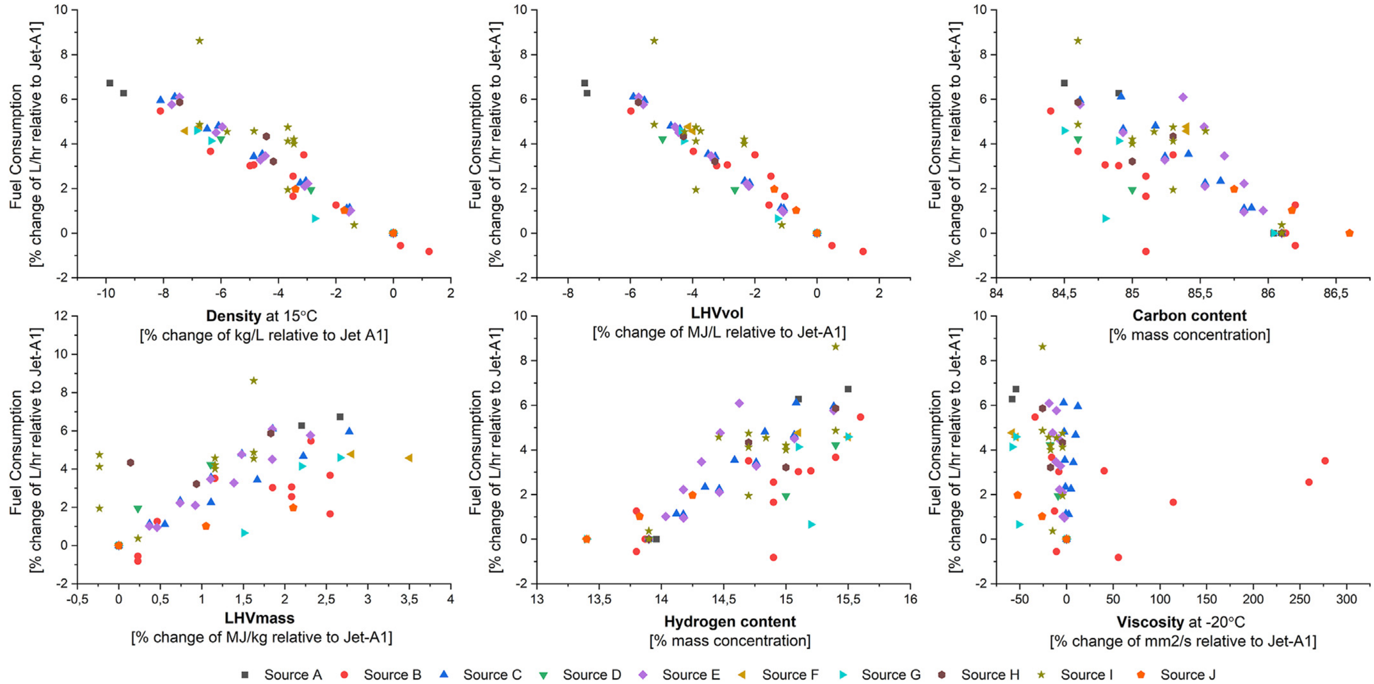

Fig. 5. The change of jet fuel properties vs change of fuel consumption in jet engine, based on the data from 10 selected sources (A [49], B [54], C [57], D [58], E [55], F [59], G [60], H [61], I [56], J [62]). It could be noticed that the growth of density, LHVvol and carbon content of the jet fuel reduces the fuel consumption in jet engines. The opposite effects are observed when increasing values of LHVmass and hydrogen content.

the specific fuel. The fourth option is emissions of carbon dioxide expressed as a mass of CO_2 per unit of time.

Fig. 6 represents all 4 above-mentioned options for the representation of the performance, based on the raw data coming from 10 selected sources. The FCvol of SAF is in a vast majority of cases higher than for Jet-A1. Based on the raw data the average value of FCvol for all tested SAF is 3,43% higher than FCvol of jet-A1, with the lowest value of −0,81% for the synthetic kerosene made via catalytic hydro-thermolysis with hydrogenation (HDO-SK) - result simulated with thermodynamic modeling of a typical two-spool turbofan in a 0D approach, and the GasTurb software [54]. The highest value of FCvol equal to +8,62% was measured experimentally on a TRS-18-046-1 jet engine for synthetic paraffinic kerosene (SPK) [56]. However, this value is exceptionally high when looking at Fig. 6. Moreover, the same jet engine (TRS-18-046-1) running on the same fuel SPK was tested in source H [61], and the result was +5,86% higher FCvol (compared to Jet-A1), which is more in the line with pure SPK fuel behavior when compared to results from other sources.

The average energy consumption for SAF (+0015%) is almost identical to Jet-A1. The lowest EC of −2,03% is observed for a 50% blend of Camelina-based SPK in JP-8 fuel tested experimentally in the jet engine (CF-700) [56]. The highest EC of +2,94% is for the SPK in TRS-18-046-1, which had also the highest FCvol and FCmass. Otherwise, when it comes to FCmass, in the vast majority of SAF cases, it is lower than for Jet-A1. The average FCmass for tested SAF is −1,31%, with the lowest value of −3,8% for Jatropha SPK tested in source A [49]. The strong benefit of SAF is tank-to-thrust (TTT) CO_2 emission, which in most cases is lower compared to Jet-A1. The average value of CO_2 reduction is −2,32%, with the lowest of −5,52% for J-SPK tested in source A [49]. As could be noticed, the changes in fuel properties and performance of SAF compared to Jet-A1 are not very big. One of the main drivers is the ASTM certification, which sets very strict requirements for fuel properties, and even in the case of very compatible fuels such as SPK/A, the blending wall is still 50% volume-based with Jet-A1.

The green color boxes in Fig. 6 represent simulation data, whereas the orange color means experimental jet-engine tests. For modeling, there are taken in majority of simulation data, whereas for validation only real jet engine test outcomes - three different sources (more details in Appendix C). This type of distribution is motivated by the low availability of data from tests on real jet engines powered by SAF. Therefore, it is of higher value to dedicate most of the empirical data to external validation. In total, there were 69 rows of data for modeling, which were split between 70% for model development (48 rows - 7 sources) and 30% for model validation (21 rows - 3 sources).

The results of performed modeling are summarized in Table 1. The variables that turned out to be the most significant are density, LHVmass, and viscosity, which together describe the performance of alternative fuels such as SAF in jet engines with a very high accuracy, represented by the R-square value of 0,993. The p-values of all independent variables are notably lower than the significance level of 5%, which means that each final parameter (viscosity, density, and LHVmass) has a unique and very important effect on fuel consumption in jet engines. When it comes to LHVmass and density, they directly affect the energy content supplied to the jet engine for conversion into thrust. However, the role of fuel viscosity is very important as well, it ensures proper atomization of the fuel and its droplet evaporation at low temperatures, which in turn sustains the continuous combustion during jet-engine operation. Too high viscosity is disadvantageous for fine enough atomization of the fuel, that in consequence has a negative impact on the performance.

The final version of the Jet-model is represented by the following equation.

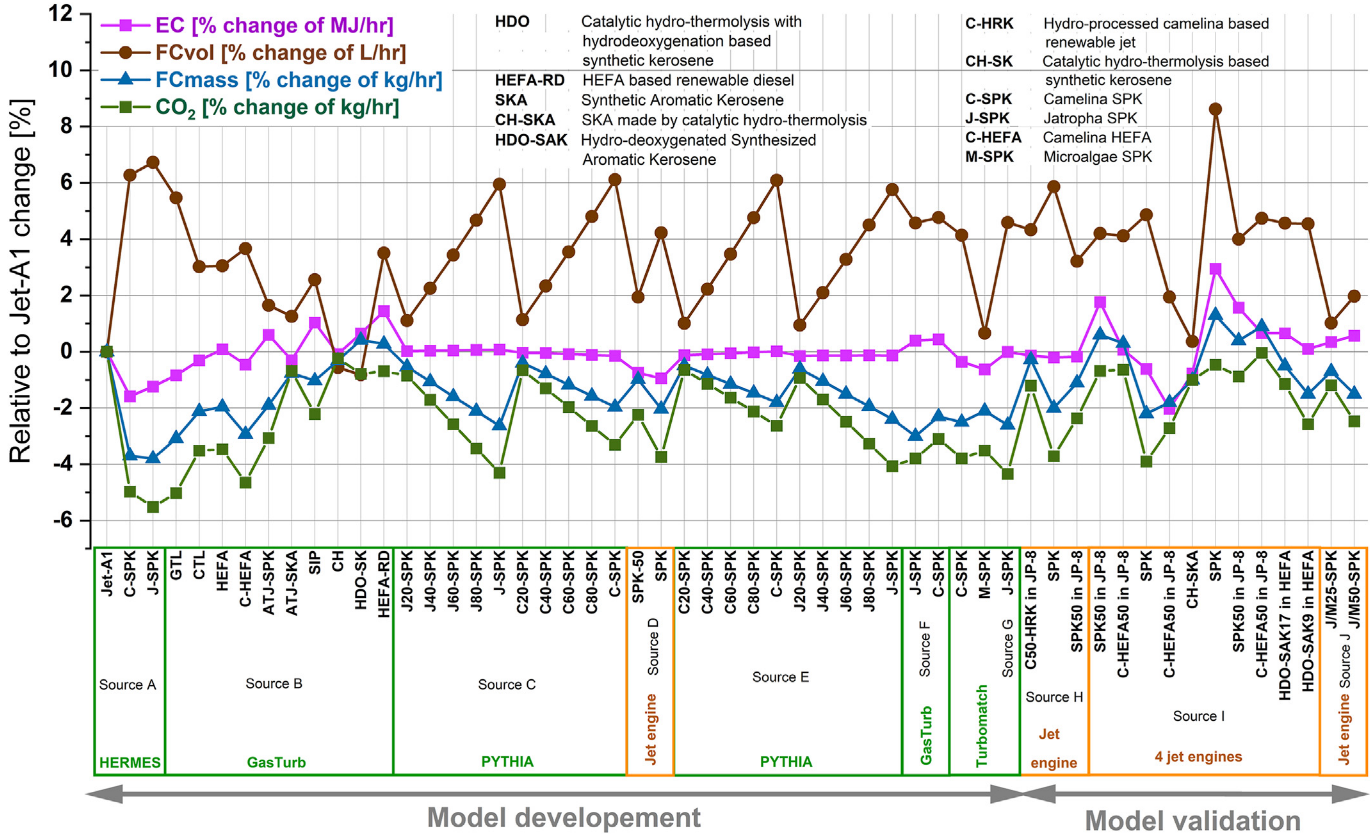

Fig. 6. The jet engine performance represented by FCvol, FCmass, EC, and TTT CO_2 emissions. The data are coming from 10 different sources, and are expressed as relative percentage changes to Jet-A1 (A [49], B [54], C [57], D [58], E [55], F [59], G [60], H [61], I [56], J [62]).

Table 1
Modeling results - developed Jet-model, with high accuracy (R-Square 0.993). All independent variables have p-values much lower than 1%, which confirms their unique and important impact on FC.

Variable	Coefficient	Std. Error	T-value	p-value
Viscosity	0,0039	0,0007	5,3819	> 0,0001
Density	−0,9030	0,0323	−27,9778	> 0,0001
LHVmass	−0,6101	0,0977	−6,2449	> 0,0001
R-Square	**0,993**			

$$\alpha_{JET} = 0,0039 \cdot \gamma - 0,9030 \cdot \zeta - 0,6101 \cdot \eta \tag{8}$$

where, independent variables represent percentage changes relative to the standard Jet-A1; γ - viscosity, ζ - density and η - LHVmass.

The high accuracy of the model could be noticed in Fig. 7 that represents graphically the performance of the developed Jet-model in the prediction of fuel consumption changes for the data (SAF) used in the model development stage.

The average error of prediction for the whole population was only 0,21%, and it could be noticed that model predicts very well the results. The next step was an external validation of the model, against that data that the model has never seen, meaning the data that were excluded from the training matrix. Additionally, for the external validation, only experimental jet engine tests with SAF were taken into analysis. Based on SAF fuel properties reported in each source (summarized in Table 5 located in Appendix C), fuel consumption was calculated using the developed Jet-model. Subsequently, the results from Jet-model were compared to the values of FCvol for every SAF tested in jet engines and reported in each source. The outcomes are presented in Fig. 8.

The external validation proved a good accuracy of the Jet-model with an average absolute error of 0,68%. The biggest error of 3,63% occurs for SPK in jet engine TRS-18-046-1 that was tested in source I [56]. Nevertheless, the same engine was used in a different source H [61] powered by the same fuel (SPK), and the model predicted almost precisely the correct value with a negligible error of 0,37%.

3.2. Jet-model simulations for five commercial sustainable aviation fuels

The developed Jet-model was used for simulation of the end-use performance for five ASTM D7566 certified fuels (FT-SPK, HEFA, FT-SPK/A, SIP, ATJ-SPK). SAF fuel properties reported by A. Zschocke et al. [69] were taken for estimation of the performance. Fig. 12 in Appendix D, represents the viscosity, density, LHVmass, LHVvol, carbon, and hydrogen content of considered SAF in blends with fossil Jet-A1 within the whole blending spectrum (from 0% to 100%). The most viscous fuel is SIP with values oscillating around 14 mm^2/s, whereas viscosity values of FT-SPK, HEFA, FT-SPK/A and ATJ-SPK are very similar and close to 4 mm^2/s. The highest density of 805,2 kg/m^3 has FT-SPK/A due to the content of aromatic compounds, in contrast to remaining SAF that are mixtures of paraffinic and isoparaffinic molecules. The lowest values of density oscillating around 757 kg/m^3 have ATJ-SPK and HEFA, those values are lower than in the case of SIP and FT-SPK, and the reason could be associated with lower hydrocarbon chains length of the paraffinic and isoparaffinic mixtures. Despite the lowest density, the trend is

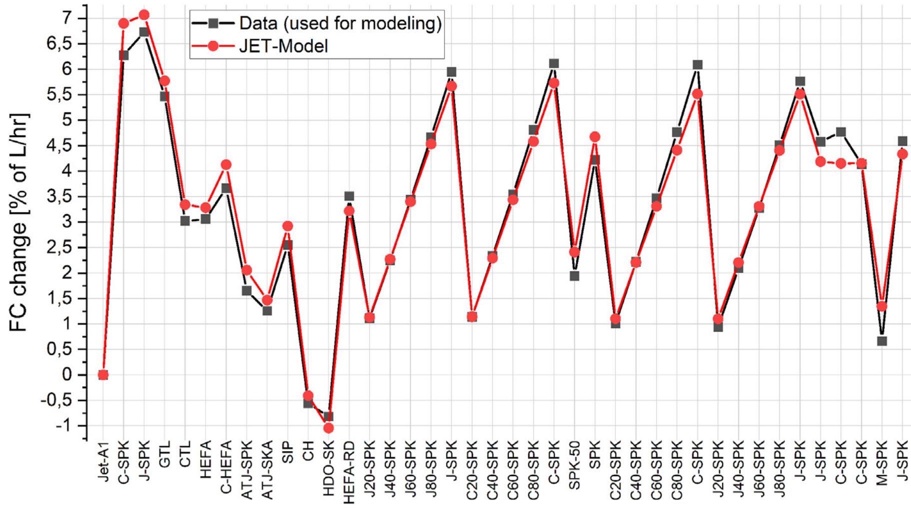

Fig. 7. Internal validation - representation of the Jet-model prediction outcomes for the internal data that was used in the model development stage.

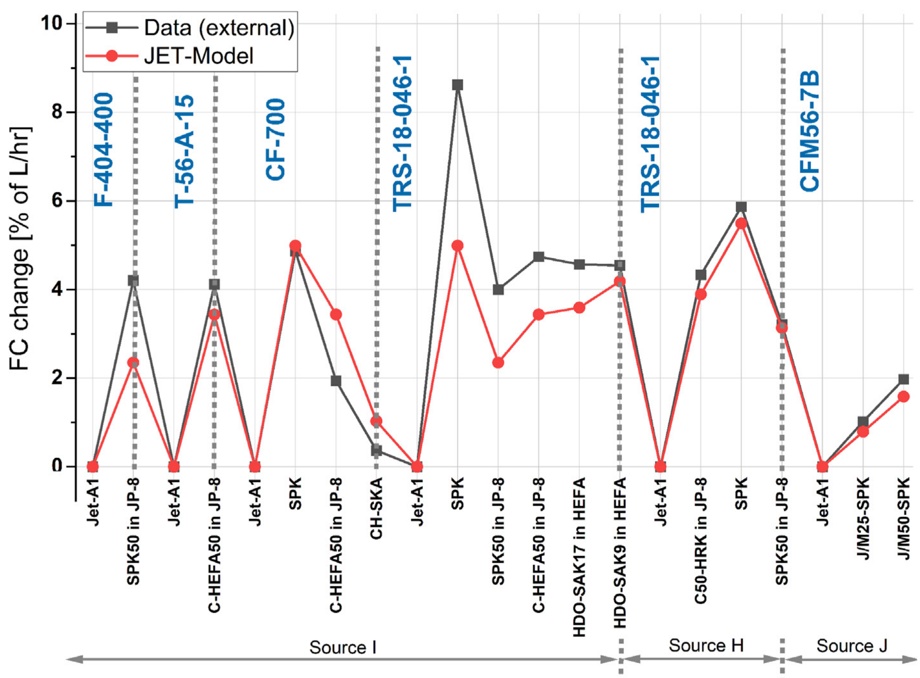

Fig. 8. External validation - representation of the Jet-model prediction outcomes for the external data (experimental jet engine runs only). This data was excluded from the model development stage.

reversed for mass-based calorific content highest for ATJ-SPK and lowest for FT-SPK/A. SAF have no oxygen in their molecules, therefore, high carbon content would mean directly low hydrogen content. From the five tested SAF, FT-SPK/A has the highest carbon content 86.1%, which is almost identical to that of standard Jet-A1, (subsequently, ATJ-SPK and SIP: 85,1%, HEFA: 84,8%, and FT-SPK: 84,6%).

Based on absolute values of SAF properties, relative to Jet-A1% changes for viscosity, density and LHVmass were calculated for the whole concentration spectrum, which subsequently served as an input to Jet-model for FCvol calculation. Fig. 9 shows results of Jet-model simulation where FCvol, FCmass, EC, and CO_2 emissions for all SAF are presented.

In comparison to Jet-A1, the volumetric fuel consumption is lower only for blends with FT-SPK/A. This interesting result could be associated with the high density of that SAF, which leads FT-SPK/A to the highest values of LHVvol. For the fleet operator, FT-SPK/A could be the best choice in terms of fuel economy, especially when the cost of fuel is on a volume basis. Otherwise, on a mass-basis, it is not as beneficial as FCmass values are higher than for Jet-A1. The FCmass of blends consisting of HEFA, ATJ-SPK, and FT-SPK are lower compared to neat Jet-A1, which was also observed by R.M.P. Gaspar and J.M.M. Sousa [54]. When looking at the composition of FT-SPK/A, it is the most similar to fossil Jet-A1, which also contains aromatic compounds. Therefore, among all SAF, FT-SPK/A would be the most compatible with the current fleet of aircrafts. A disadvantage of FT-SPK/A is a higher TTT CO_2 emission compared to Jet-A1, however, that could be compensated

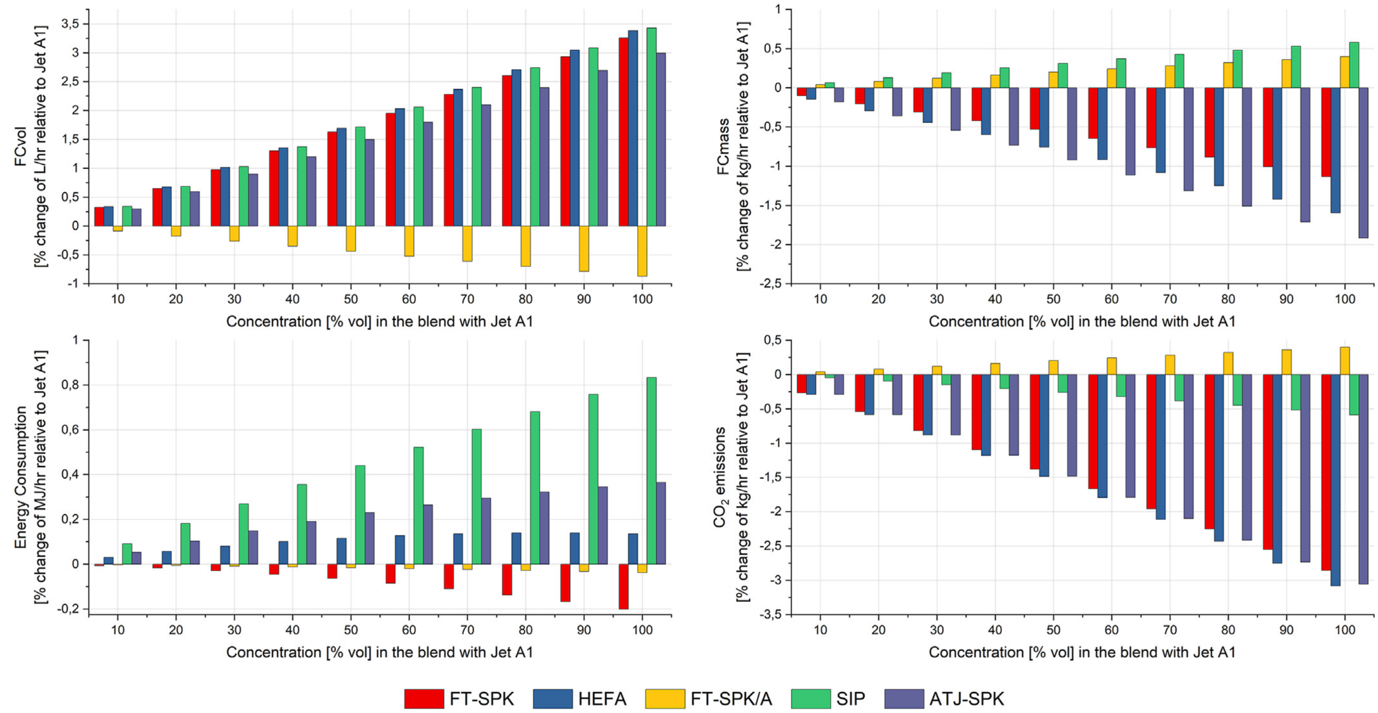

Fig. 9. End-use performance of five ASTM D7566 certified SAF (FT-SPK, HEFA, FT-SPK/A, SIP, ATJ-SPK), predicted by the Jet-model. The results indicate that FT-SPK/A provides the highest reductions of FCvol, while ATJ-SPK the lowest values of FCmass. The lowest energy consumption is observed for FT-SPK blends, while the best reductions of TTT CO_2 emissions are for HEFA, ATJ-SPK and FT-SPK, respectively.

effectively with a low well-to-tank part for FT-SPK/A. When it comes to energy consumption, FT-SPK/A blends have almost identical values as fossil Jet-A1. FT-SPK, HEFA, SIP, and ATJ/SPK have relatively similar values of FCvol. Among SAF, SIP has the highest FCmass and energy consumption. This fact, together with higher viscosity and potential incompatibilities with materials of seals and gaskets could be the reason for the maximum of 10% blending wall for SIP. When it comes to TTT CO_2 emissions, SIP blends have lower values than Jet-A1, but higher than ATJ-SPK, HEFA, and FT-SPK.

Fuel blends such as ATJ-SPK and HEFA offer the highest reductions in TTT CO_2 emissions (around 3% lower than Jet-A1). This is also associated with the lowest FCmass of those blends, which is in line with observations of B. Gawron and T. Białecki [33]. HEFA and ATJ-SPK blends have moderate EC compared to other SAF, but slightly higher than Jet-A1. FT-SPK has the lowest EC, which reaches levels below the Jet-A1. Nevertheless, those reductions of EC are not so substantial, as the pure blend of FT-SPK has only 0,2% lower EC than Jet-A1. In contrast, neat SIP fuel causes a difference in EC of 1%. The pure FT-SPK has 2,83% lower TTT CO_2 emissions than standard Jet-A1.

4. Scalability, applicability and limitations

Developed Jet-model offers wide possibilities for instant, cost-free, and accurate analysis of end-use performance for aviation fuels over the fleet of aircrafts in cruising conditions. A strong benefit of the Jet-model is that independent variables are represented by fuel properties, which together are a universal language between various single chemical compounds, groups of molecules, refinery streams, and ready fuel products. Therefore, the Jet-model could be applied for analysis from laboratory scale to industrial across the whole spectrum of Technology Readiness Levels (TRL). The Jet-model could be applied to:

1. Fuel consumption calculations for SAF applied in jet engines of aircrafts.
2. Optimization of fuel's volume, mass, or energy consumption in jet engines and support in the selection of the best options based on user's criteria.
3. Reduction of the costs and time for experimental tests including expensive flight cycles, by performing preliminary analysis with Jet-model, and selecting the best fuel candidates for subsequent experimental campaigns.
4. Estimation of the TTT part of carbon dioxide emissions, that combined with the WTT part, constitute the whole Well-To-Thrust assessment of the environmental impact.

The scalability and limitation related aspects of the present work could be considered in model development and its application. The modeling approach could be effectively scaled to the larger quantity of observations provided that fuel tests are performed at aircraft cruising conditions. Nevertheless, the limitation is the high cost of such tests when thinking of an empirical path. The alternative to experiments are thermodynamic simulation data. The variety of fuel properties taken into the modeling procedure could also be greater. However, it is important to consider that data are coming from various sources, therefore all of them must report the same set of fuel properties. Otherwise, the lack of data points in the modeling matrix will adversely affect the quality of the final model.

The limitation in the model application is that the Jet-model is dedicated to the analysis of liquid drop-in fuels, the model was not studied for gaseous fuels such as hydrogen or ammonia. Additionally, the Jet-model was developed based on the data from the existing fleet of aircraft jet engines, it was not tested for other aircraft powertrains (fuel cells, or hybrids).

When it comes to practical application, the Jet-model can be used to estimate the fuel consumption changes of the aircraft powered by SAF instead of standard Jet-A1 at the given route. This information could assist in the optimal refueling of the aircraft, reducing its weight and thus decreasing the FC, GHG emissions, and flight costs.

5. Conclusions

This work developed a state-of-the-art mathematical model that effectively and accurately predicts the impact of the most significant aviation fuel properties on jet-engine performance. Based on the literature review and thorough investigation of the possible approaches, fuel consumption change in relation to Jet-A1 over the aircraft cruising conditions was selected as a suitable approach for the representation of the end-use performance. The results show that:

1. When looking into changes of single fuel properties versus changes of FCvol: increasing values of density, LHVvol, and carbon content decreased fuel consumption in jet engines, while the growth of LHVmass, hydrogen content, and viscosity increased FCvol.
2. In the majority of cases, the volumetric fuel consumption of SAF and their blends with Jet-A1 are higher compared to fossil Jet-A1, while mass-based FC, and TTT carbon dioxide emissions are lower.
3. Developed Jet-model represents the impact of viscosity (γ), density (ζ), and LHVmass (η) on FC (α_{JET}) in jet-engines over the aircraft cruising conditions:

$$\alpha_{JET} = 0,0039 \cdot \gamma - 0,9030 \cdot \zeta - 0,6101 \cdot \eta$$

Model parameters are expressed in percentage changes relative to the standard Jet-A1. All three independent variables are highly significant and bring a unique and important input into the performance (p-values below 1%). The very high accuracy of the Jet-model is represented by an R-Square of 0,993 which translates into the average absolute error of only 0,21% when comparing Jet-model predictions versus internal data used for modeling.

4. The external validation confirmed the high accuracy of the Jet-model against the data that the model has never seen. The average absolute error was 0,68% against the experimental-only data from three independent sources.
5. Developed Jet-model was successfully applied for simulation of the end-use performance for five ASTM D7566 certified SAF. The results for FT-SPK, HEFA, FT-SPK/A, SIP, ATJ-SPK from 0%(Jet-A1) to 100% (pure SAF) concentration show rather small differences in FCvol ($-0,85\% \leq FCvol \leq 3,72\%$), FCmass ($-2,09\% \leq FCmass \leq 0,87\%$), EC ($-0,18\% \leq EC \leq 1,12\%$), and carbon dioxide emissions ($-3,22\% \leq CO_2 \leq 0,42\%$).
6. Among SAF, FT-SPK/A has the highest carbon content (lowest hydrogen content), the highest LHVvol, and very high density. Fuel properties of FT-SPK/A are the most similar to fossil Jet-A1 mainly due to the aromatic content. In consequence, the end-use performance of that SAF is also very similar to standard kerosene. The purely paraffinic kerosene version, FT-SPK, has the lowest carbon content (highest hydrogen content), intermediate LHVmass, the lowest LHVvol, and low density compared to other SAF. Therefore, aromatic content in SAF plays a very important role, it affects fuel properties and jet-engine performance.
7. Due to the exceptionally high viscosity of SIP, energy consumption and FCmass of that fuel is the highest among other SAF. This is a sign of inefficient energy conversion, caused by the challenges related to flow, which in practice settled the blending wall of 10% for SIP with Jet-A1.
8. HEFA and ATJ-SPK provide the most efficient way of CO_2 reductions from the TTT perspective in contrast to other SAF. On the one hand, due to low density, they increase volumetric FC. On the other hand, HEFA and ATJ-SPK have respectively the lowest FCmass.

As presented in the present work, SAF have the potential to outperform regular Jet-A1, not only from the environmental perspective but also when looking into fuel and energy consumption. The Jet-model has a significant real-life application in SAF development and testing.

Credit author statement

Yuri Kroyan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Michal Wojcieszyk: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. Ossi Kaario: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision. Martti Larmi: Conceptualization, Methodology, Resources, Writing – original draft, Supervision, Project administration, Funding acquisition.

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.

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Abbreviations

ASTM	American Society for Testing and Materials
ATJ-SPK	Alcohol-To-Jet Synthetic Parafnic Kerosene
BADA	Base of aircraft data
C-HEFA	Hydroprocessed Esters and Fatty Acids made from camelina
C-HRK	Hydro-processed renewable jet fuel made from camelina
C-SPK	Synthetic paraffinic kerosene made from camelina
CAPEX	Capital expenditures
CH-SK	Catalytic hydro-thermolysis based synthetic kerosene
CH-SKA	Synthetic Aromatic Kerosene made by catalytic hydro-thermolysis
CHJ	Catalytic Hydrothermolysis Jet fuel
CNN	Constructive Neural Network
CO_2	Carbon dioxide
EC	Energy Consumption
EU	European Union
FAME	Fatty Acid Methyl Esters
FC	Fuel consumption
FCmass	Mass-based fuel consumption
FCvol	Volume-based fuel consumption
FT-SPK	Fischer-Tropsch Synthesized Isoparafnic Kerosene

FT-SPK/A Synthetic Parafnic Kerosene with Aromatics via Fisher-Tropsch
GHG Greenhouse Gases
HDO Hydrodeoxygenation
HDO-SKA Hydro-deoxygenated Synthetic Aromatic Kerosene
HEFA Hydroprocessed Esters and Fatty Acids
HEFA-RD Hydroprocessed Esters and Fatty Acids based renewable diesel
HH-SPK Hydroprocessed Hydrocarbons - Synthesized Isoparafnic Kerosene
HTL Hydro-thermal liquefaction
ICAO International Civil Aviation Organization
IEA International Energy Agency
J-SPK Synthetic paraffinic kerosene made from jatropha
LCA Life Cycle Assessment
LHV Lower heating value
LHV_{mass} Lower heating value mass-based
LHV_{vol} Lower heating value volume-based
LTO Landing and Take-Off Cycle
M-SPK Synthetic paraffinic kerosene made from microalgae
MSW Municipal Solid Waste
NASA The National Aeronautics and Space Administration
PET polyethylene terephthalate
PTL Power to liquid
RPM Rotations per minute
SAC Sulfonated Activated Carbon
SAF Sustainable Aviation Fuels
SIP Renewable Synthesized Iso-Parafnic Kerosene
SKA Synthetic Aromatic Kerosene
SSA Steady-State Analysis
TSFC Thrust-Specific Fuel Consumption
TTT Tank-to-Thrust
UCO Used Cooking Oil
UN United Nations
USD United States Dollar
WTT Well-to-Tank

Appendices

A. Data sources

Table 2
Information about the test conditions and methods applied in selected data sources.

Source	Test conditions	Test method	Details
A(49)	LTO: Take-off (100% Power), Climb (85% Power), Approach (30% Power), Idle (7% Power)	Simulation	HERMES software - 0D thermodynamic simulations [64,70]
B(54)	Take-off (100% Power), Top of climb (91% Power), Cruise (82% Power), Low Power (60% Power), Idle (10% Power).	Simulation	Thermodynamic modeling of a typical two spool turbofan in a 0-D approach and Gasturb software [66]
C(57)	Cruise consditions (altitude 10588 m, Flight Mach Number 0,84)	Simulation	PYTHIA software - 0D thermodynamic simulations, Cranfield University [63]
D(58)	Cruise consditions (cruise power + air mass flow 1.3 kg/s)	Experiment	RR-Allison T63-A-700 turboshaft gas turbine, model 250-C18 B
E(55)	Cruise consditions (altitude 10668 m, Flight Mach Number 0,8)	Simulation	PYTHIA software - 0D thermodynamic simulations, Cranfield University [63]
F(59)	LTO: Take-off (100% Power), Climb (85% Power), Approach (30% Power), Idle (7% Power)	Simulation	Gasturb software - gas turbine performance simulations [66]
G(60)	LTO: Take-off (100% Power), Climb (85% Power), Approach (30% Power), Idle (7% Power)	Simulation	Turbomatch software - 0D gas turbine performance simulations, Cranfield University [65]
H(61)	Ground-level tests of Jet engine (TRS-18) in altitude chamber (altitude from 1481 m(7C) to 11268 m (−31C), air flow up to 3 kg/s). Cruise conditions.	Experiment	Jet Engine: TRS-18-046-1
I(56)	Cruise condition as at both flight and ground-level (altitude chamger, air flow up to 4,5 kg/s)	Experiment	4 Jet engines: F-404-400, T-56-A15, CF-700, TRS-18-046-1
J(62)	LTO, climb, cruising conditions (Mach Number 0,78), accelerations and decelerations	Experiment	Jet engine: CFM56-7B, Continental airline flight test

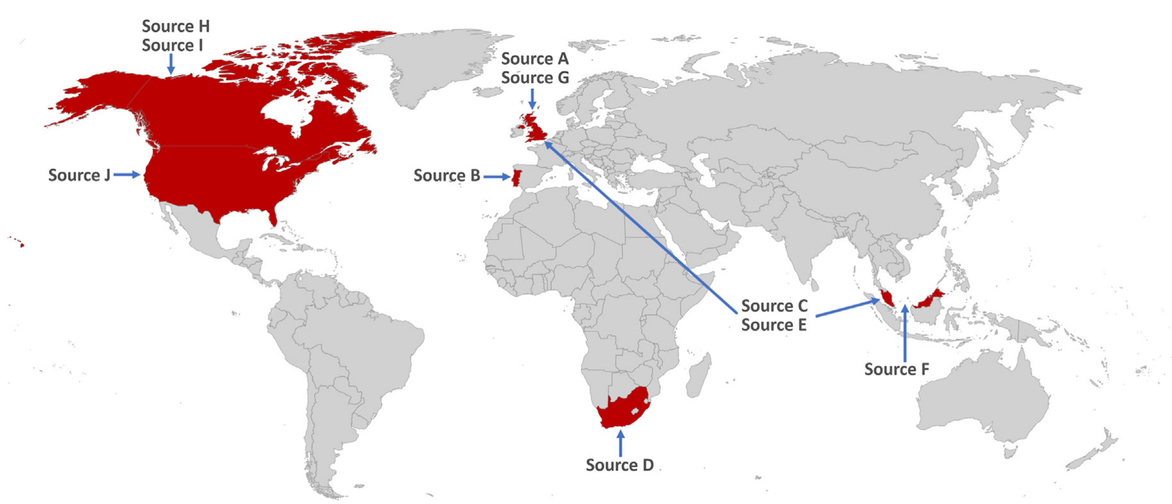

Fig. 10. Map of the sources.

B. Limitations of the steady state analysis

Table 3
Matrix of fuel properties and TSFC based on SSA data, all variables are represented as percentage changes relative to the standard Jet-A1 tested in each source.

Source	Fuel	Viscosity	Density	LHVmass	LHVvol	TSFC
		% change of cP	% change of kg/m3	% change of MJ/kg	% change of MJ/L	% change of mg/N*s
X(51)	**Jet-A1**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
	B100	−21,05	−0,02	−23,57	−23,59	17,08
	B75	−15,79	−0,02	−17,68	−17,69	15,84
	B50	−10,53	−0,01	−11,78	−11,79	9,01
	B25	−5,26	−0,01	−5,89	−5,90	−11,49
Y(52)	**Jet A**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
	B50 SME	58,50	4,53	−5,53	−1,25	−6,38
	B100 SME	117,00	9,06	−11,06	−3,00	−9,42
	B50 CME	59,25	4,78	−5,05	−0,51	−9,49
	B100 CME	118,50	9,55	−10,10	−1,51	−15,36
	B50 RME	124,50	4,71	5,17	10,13	5,79
	B100 RME	249,00	9,43	−10,34	−1,88	8,85
	B50 HOG	249,50	7,94	−9,13	−1,92	−4,80
Z(53)	**Jet A1**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
	B100	98,00	8,64	−15,82	−8,55	−10,27
	HJ	6,67	−5,93	1,02	−4,97	−32,29
	JP8	−13,33	−3,95	0,23	−3,73	−19,20

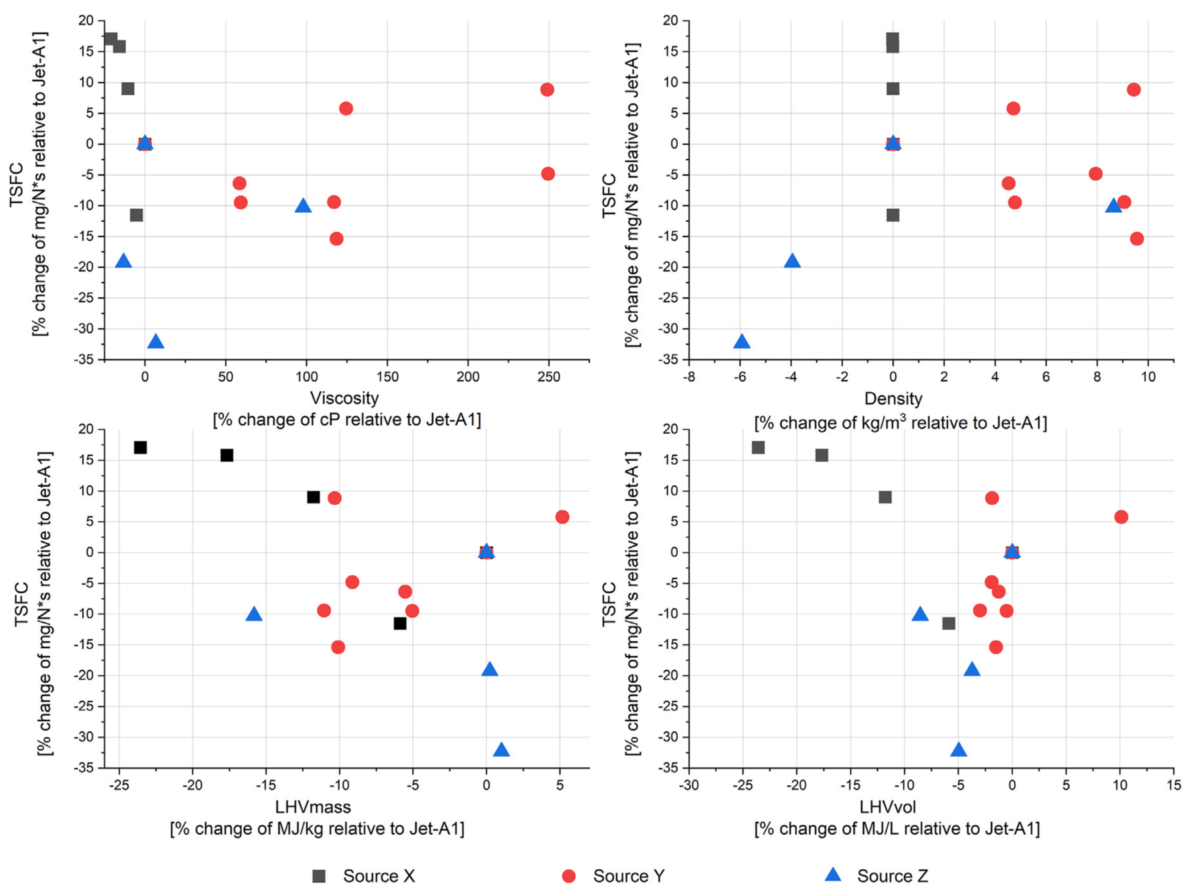

Fig. 11. The impact of aviation fuel properties (density, viscosity, LHVmass, and LHVvol) on jet engine performance represented by the thrust-specific fuel consumption (TSFC). Based on the three independent data sources X(51), Y(52) and Z(53), no clear trends could be detected.

C. Modeling and validation matrix

Table 4
Matrix used for the development of the model.

Raw number	Source	Name of the fuel/blend	Viscosity at -20C % Change	Density 15C % Change	LHVvol % Change	LHVmass % Change	C % mass	H % mass	FC % Change
1	**A(49)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,04	13,96	**0,00**
2		**C-SPK**	−58,30	−9,39	−7,39	2,20	84,90	15,10	**6,28**
3		**J-SPK**	−54,21	−9,87	−7,47	2,67	84,50	15,50	**6,73**
4	**B(54)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,13	13,87	**0,00**
5		**GTL**	−33,67	−8,10	−5,98	2,31	84,40	15,60	**5,47**
6		**CTL**	−8,16	−4,99	−3,23	1,85	84,90	15,10	**3,02**
7		**HEFA**	40,31	−4,86	−2,88	2,08	84,80	15,20	**3,06**
8		**C-HEFA**	−15,82	−6,36	−3,97	2,55	84,60	15,40	**3,66**
9		**ATJ-SPK**	114,29	−3,49	−1,03	2,55	85,10	14,90	**1,65**
10		**ATJ-SKA**	−12,76	−2,00	−1,54	0,46	86,20	13,80	**1,26**
11		**SIP**	259,69	−3,49	−1,48	2,08	85,10	14,90	**2,55**
12		**CH**	−10,71	0,25	0,48	0,23	86,20	13,80	**−0,56**
13		**HDO-SK**	55,61	1,25	1,48	0,23	85,10	14,90	**−0,82**
14		**HEFA-RD**	276,96	−3,12	−2,00	1,16	85,30	14,70	**3,51**
15	**C(57)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
16		**J20-SPK**	2,45	−1,62	−1,07	0,56	85,82	14,18	**1,11**
17		**J40-SPK**	4,90	−3,24	−2,16	1,11	85,54	14,46	**2,25**
18		**J60-SPK**	7,35	−4,86	−3,27	1,67	85,24	14,76	**3,44**
19		**J80-SPK**	9,80	−6,48	−4,40	2,22	84,93	15,07	**4,67**
20		**J-SPK**	12,24	−8,10	−5,55	2,78	84,62	15,38	**5,95**
21		**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
22		**C20-SPK**	−0,61	−1,52	−1,16	0,37	85,88	14,12	**1,14**
23		**C40-SPK**	−1,22	−3,04	−2,32	0,74	85,65	14,35	**2,33**
24		**C60-SPK**	−1,84	−4,56	−3,50	1,11	85,41	14,59	**3,55**
25		**C80-SPK**	−2,45	−6,09	−4,69	1,48	85,17	14,83	**4,81**
26		**C-SPK**	−3,06	−7,61	−5,90	1,85	84,92	15,08	**6,11**
27	**D(58)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
28		**SPK-50**	−9,02	−2,86	−2,64	0,23	85,00	15,00	**1,94**
29		**SPK**	−17,56	−6,00	−4,96	1,11	84,60	15,40	**4,22**
30	**E(55)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
31		**C20-SPK**	−3,73	−1,49	−1,12	0,37	85,96	14,04	**1,01**
32		**C40-SPK**	−7,45	−2,98	−2,26	0,74	85,82	14,18	**2,22**
33		**C60-SPK**	−11,18	−4,46	−3,40	1,11	85,68	14,32	**3,47**
34		**C80-SPK**	−14,91	−5,95	−4,56	1,48	85,53	14,47	**4,76**
35		**C-SPK**	−18,63	−7,44	−5,73	1,85	85,37	14,63	**6,09**
36		**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
37		**J20-SPK**	−2,13	−1,54	−1,09	0,46	85,82	14,18	**0,95**
38		**J40-SPK**	−4,26	−3,08	−2,19	0,92	85,53	14,47	**2,10**
39		**J60-SPK**	−6,40	−4,63	−3,30	1,39	85,24	14,76	**3,28**
40		**J80-SPK**	−8,53	−6,17	−4,43	1,85	84,93	15,07	**4,51**
41		**J-SPK**	−10,66	−7,71	−5,58	2,31	84,62	15,38	**5,76**
42	**F(59)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,40	**0,00**
43		**J-SPK**	−54,21	−7,24	−3,99	3,50	85,40	15,50	**4,58**
44		**C-SPK**	−58,30	−6,75	−4,13	2,80	85,40	15,10	**4,77**
45	**G(60)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,04	13,40	**0,00**
46		**C-SPK**	−58,30	−6,34	−4,28	2,20	84,90	15,10	**4,14**
47		**M-SPK**	−51,13	−2,74	−1,27	1,51	84,80	15,20	**0,66**
48		**J-SPK**	−54,21	−6,84	−4,36	2,67	84,50	15,50	**4,59**

Table 5
Matrix used for the external validation of the model.

Raw number	Source	Name of the fuel/blend	Viscosity at -20C % Change	Density 15C % Change	LHVvol % Change	LHVmass % Change	C % mass	H % mass	FC % Change
1	**H(61)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
2		**C50-HRK in JP-8**	−4,26	−4,42	−4,29	0,14	85,30	14,70	**4,33**
3		**SPK**	−25,53	−7,43	−5,74	1,83	84,60	15,40	**5,87**
4		**SPK50 in JP-8**	−17,02	−4,18	−3,28	0,94	85,00	15,00	**3,21**
5	**I(56)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
6		**SPK50 in JP-8**	−17,02	−3,46	−2,34	1,16	85,00	15,00	**4,21**
7		**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**

Table 5 (*continued*)

Raw number	Source	Name of the fuel/blend	Viscosity at -20C % Change	Density 15C % Change	LHVvol % Change	LHVmass % Change	C % mass	H % mass	FC % Change
8		**C-HEFA50 in JP-8**	−4,26	−3,67	−3,89	−0,23	85,30	14,70	**4,12**
9		**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
10		**SPK**	−25,53	−6,74	−5,22	1,62	84,60	15,40	**4,87**
11		**C-HEFA50 in JP-8**	−4,26	−3,67	−3,89	−0,23	85,30	14,70	**1,94**
12		**CH-SKA**	−14,89	−1,36	−1,13	0,23	86,10	13,90	**0,37**
13		**Jet-A1**	0,00	0,00	0,00	0,00	86,10	13,90	**0,00**
14		**SPK**	−25,53	−6,74	−5,22	1,62	84,60	15,40	**8,62**
15		**SPK50 in JP-8**	−17,02	−3,46	−2,34	1,16	85,00	15,00	**4,00**
16		**C-HEFA50 in JP-8**	−4,26	−3,67	−3,89	−0,23	85,30	14,70	**4,74**
17		**HDO-SAK17 in HEFA**	−19,15	−4,85	−3,74	1,16	85,54	14,46	**4,57**
18		**HDO-SAK9 in HEFA**	−10,64	−5,78	−4,25	1,62	85,16	14,84	**4,54**
19	**J(62)**	**Jet-A1**	0,00	0,00	0,00	0,00	86,60	13,40	**0,00**
20		**J/M25-SPK**	−26,14	−1,70	−0,67	1,05	86,18	13,83	**1,02**
21		**J/M50-SPK**	−52,29	−3,41	−1,37	2,10	85,75	14,25	**1,97**

D. Fuel properties of five commercial Sustainable Aviation Fuels

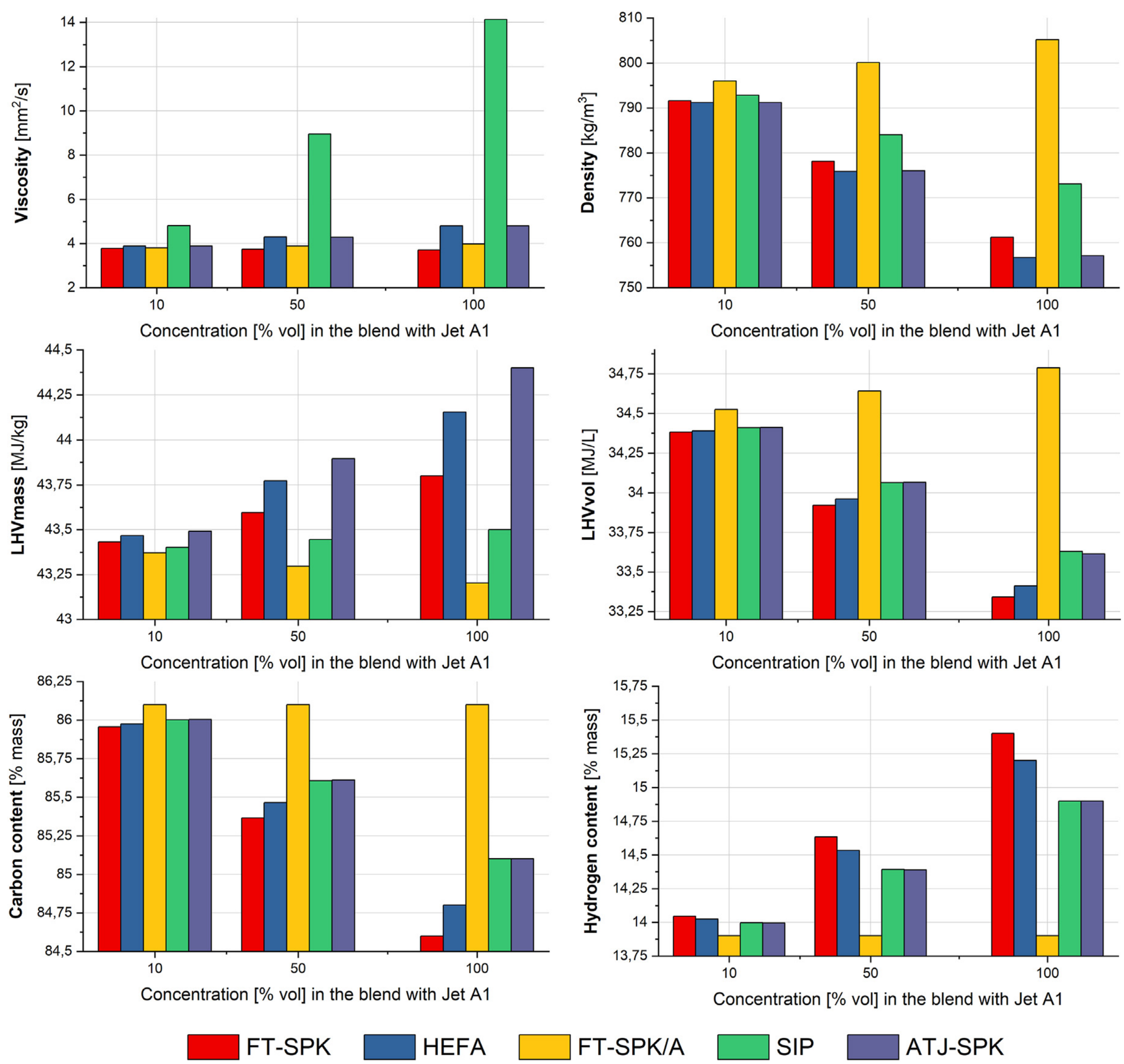

Fig. 12. Fuel properties of five ASTM D7566 certified SAF in blends with Jet A1.

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