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Abstract: One of the most viable options to decarbonise the aviation industry is to operate existing engines and aircrafts through alternative jet fuels (AJFs). The key advantages of these fuels are that they work with existing engine technology, allowing a seamless transition between conventional petroleum jet fuels and more sustainable feedstocks. Lifecycle Assessment models have introduced datasets which attempt to estimate the emissions of AJFs' process pathways from various feedstocks. To assist with inherent uncertainty in decision making and policy formation in AJFs, a more relativistic uncertainty in the performance of different technology solutions must be assessed to provide an impartial picture of technologies. Here, we propose an integrated multi-criteria decision analysis-based framework to improve performance uncertainty of competing AJF pathways. While existing studies tend to measure effectiveness via cost-benefit analysis or carbon reduction, our proposed framework will provide an in-depth understanding of competing technologies under four dimensions: *financial (e.g., capital cost, running cost, feedstock prices; and revenues), environmental (e.g., CO_2 emissions savings), technical (e.g., technology maturity; transferability) and social (e.g., social acceptance; wealth and job creation).* Compared to standard approaches, our framework can handle data in different forms of uncertainty. Furthermore, we also discuss how different AJFs might be produced more effectively and stress practical points on the need for government and stakeholder integration on the large-scale production of AJFs. By focusing on motives, attitudes and decision making of experts, end-users and stakeholders – rather than merely the pure techno-economic or environmental aspects of AJFs'– this paper makes a new contribution to the field.

Keywords*:* Alternative Jet Fuels; Multi-criteria Analysis; Dempster-Shafer Theory; Uncertainty Modelling

1 INTRODUCTION

Alternative jet fuels (AJFs) offer a promising viable solution to a looming global problem. From a socio-economic standpoint, the popularity of air transport has increased, partially due to the introduction of cheaper fares per km of travel, reduced manufacturing costs and new routes resulting in anthropogenic emissions rising beyond 3% (Nicklass et al, 2017). The production process of petroleum jet fuel (Jet A-1) is emissions intensive, approximating to around 88.1 grams of CO_2 equivalency per Megajoule

gCO_2e/MJ (Han et al, 2017). It is therefore vital that new solutions are sought in order to reduce the impact of the production process throughout the AJF's lifecycle.

AJF's are a type of "drop-in" fuel designed to work with existing aeroplane engine technologies and feature many components with each feedstock being produced via requirement specific production processes. Such processes differ in terms of environmental and economic parameters and have been the focus of many studies in the form of lifecycle assessment (LCA) and techno-economic analyses. Due to the widely available feedstocks that can be converted to AJF's, priority based uncertainty exists in terms of their sustainability performance due in part to numerous stakeholders perceiving certain dimensions of AJF process pathways differently.

In this study, we use an integrated multi-criteria decision analysis (MCDA)-based framework to assess the relative performance of different AJFs and reducing their performance uncertainty. Our methodology explicitly takes different stakeholders' perspectives into account. Moreover, it allows us to evaluate the effectiveness of decision support management strategies under multiple criteria and with data in different forms. For example, some criteria are measured on monetary scale (e.g., additional investment cost, additional running costs), while a discrete scale can be used for those factors that are difficult to quantify in monetary values (e.g., technical transferability, stakeholders' attitudes). In addition, we allow for uncertainty for our 19 criteria. Our proposed approach is a generic framework and as such could be applied to assess to any AJFs.

By focusing on a motives, attitudes and decision making of end-users, stakeholders and experts – rather than merely the pure technical or financial aspects of AJFs – the paper makes a new contribution to the field. We also discuss how AJFs could be exploited in real applications and we conclude by making some practical points on the need for government and policy makers to take the lead on the large-scale implementation of AJFs.

2 UNCERTAINTY ANALYSIS IN ALTERNATIVE JET FUEL SUSTAINABILITY

Determining the full scope of sustainability for AJF's require a multi-faceted exploration of environmental, financial, technical and social factors and the most influential criteria that can affect such performance. The production process of AJF's are pre-meditated by the feedstock that is being used to produce the fuel. This creates many different pathways all with separate technological performance efficiencies. The by-product of choice of feedstock leads to high degrees of uncertainty when attempting to assess the sustainable performance of AJF's.

2.1 Environmental

Environmental factors range from emissions that are generated through the jet fuel lifecycle i.e. from well-to-wake (including engine combustion during flights) to damage impact categories which impact the surrounding environment. In some cases, savings of CO_2 is possible through the optimisation of certain process pathways. Emissions across the jet fuel lifecycle are calculated in g/MJ. The reasons for using energy values are twofold. The first is due to uncertainty arising from the catalytic conversion selectivity of syngas into the jet fuel product where highly variable product compositions are possible, featuring long alkane carbon chains (jet fuel composition is derived between C_8-C_{16}) of the converted product. Other products from AJF production are also produced which if purged to the atmosphere may increase the carbon footprint or can be sold externally and utilised by an external source (i.e. producer gas).

2.2 Financial

Economic uncertainty can be defined as the conditional volatility of a disturbance that is unforecastable from the perspective of economic agents. Large price swings can have significant negative impact on AJF's. Financial aspects include the jet fuel industry, and its costs from an economic context are sensitive to changes in energy prices. Forecasting oil prices, jet fuel prices and CO_2 prices can therefore be challenging. Airline companies face a significant amount of uncertainty related to the timing and content of government policy changes, these uncertainties will affect the decision making processes for many stakeholders.

2.3 Technical

Technical elements may include production requirements which enforce what equipment is being used during the production of AJF's. It's at this point where the maturity of the technology also comes into question. Technology maturity is related to a set of technological readiness levels. Any process pathway that has a low readiness level may hinder the ability to upscale the fuel production process to an industrial scale due to the uncertainty that exists in the testing and efficiency of the technology. Reliability will also carry weight, as it will determine the standard level of service, affecting production, downtime and cost.

2.4 Social

Social criteria include all potential impacts on different stakeholders including the airlines, up-stream suppliers, passengers, potential refinery workers and governmental bodies. In terms of uncertainty, it is also apparent that job creation and wealth will fluctuate between pathways due to different types of technology being used and the specialist job types and skillsets that must be acquired. One key point that must be stressed is that stakeholder interest will differ between different types of processes, for example, airline companies may take environmental savings and engine efficiency as a key priority next to cost. While customers may focus on the efficiency of travel i.e. duration as well as be interested in the emissions saved, knowing that their flight is low carbon.

3 METHODOLOGY

In seeking to assess the relative performance of different AJF, we use an MCDA-based framework methodology. This involves a three-stage process; namely, prioritization of stakeholder criteria; data fusion of stakeholder opinions and their personal targets; and formulation of recommendations. These stages are described in details hereafter.

3.1 Multi-Criteria Decision Analysis: Analytical Hierarchy Process

Several methods could be used to generate weights for each criterion (e.g., Direct Rating method, Max100, Min100, Point Allocation method, Simos' cards method, and the Analytic Hierarchy Process (AHP)). For our application, we opted for a Point Allocation method, in which criteria are rated relative to each other by distributing 100 points between them to reflect their relative importance. Such choice is motivated by its simplicity from a user's perspective. We have obtained two sets of weights: 1) one with preferences on financial dimensions to reflect commercially motivated stakeholders' preferences; 2) the other with preferences on social and environmental dimensions to reflect socially and environmentally motivated stakeholders. In our analysis, we used an equal weighting scheme as a benchmark to check how sensitive or robust rankings of strategies are to decision makers' preferences. Table 1 illustrates the selected criteria for the performance evaluation of AJF.

3.2 Dempster-Shafer Theory

Dempster-Shafer theory (DST) is used to consolidate the rankings and opinions from stakeholders that have an investment into AJF into an aggregated and parameterised performance value. Basic probability assignments and mass functions are used to determine the criteria in Table 1. Criteria prioritisation was carried out by four groups of stakeholders that have some connection with the AJF process pathways. The stakeholders involved include 1. Airline companies; 2. Passengers; 3. Suppliers and 4. Government. The prioritization of criteria is performed by several stakeholders with each stakeholder representing a single data source as part of a mathematical body of evidence. The stakeholders use their own grading system and were able to subjectively rate performance using this method. Table 2 illustrates a performance ranking in order to assign belief vectors to the basic probability values from various sources with uncertain data.

Table 1: Framework Sustainability Criteria

Criteria	Descriptions
Environmental Dimension	
Global Warming Potential	*Lifecycle emissions for AJF's are calculated through grams of CO_2 equivalency per mega joule i.e. gCO2e/MJ.*
Savings of CO_2	*Accumulated savings of CO_2 compared to conventional petroleum jet fuel technologies.*
Energy requirements	*Energy requirements for the AJF processes.*
Financial Dimension	
Investment costs	*The investment required to provide a business as usual scenario such as the standard production rate of AJF. This can include but is not limited to technology, specialist services, construction of physical and transport structures to support production of AJFs*.
Operation and maintenance costs	*Operation and maintenance costs typically comprise ongoing expenses related to the continuous activity of the AJF refineries. This includes electricity requirements and regular maintenance of essential processes and equipment.*
Savings	*Total savings from the use of AJF's compared with traditional petroleum-based jet fuels.*
Payback Period (PP)	*PP indicates the duration required before the select AJFs process becomes profitable.*
Net Present Value (NPV)	*NPV indicates the current value of a project in terms of the different between present cash inflow and present cash outflow.*
Technical Dimension	
Production	*Production rate of jet fuel based upon required resources.*
Technological Maturity	*Technological maturity of the process pathway based upon technological readiness level (1-9). Calculated via weakest link theory i.e. the technology within the process with the lowest Technological readiness level.*
Process Reliability	*The reliability of the process to behave consistently and produce expected outputs.*
Process Efficiency	*The overall general efficiency of the process pathway.*
Technical Transferability	*Refers to the extent to which a particular business case could be technically transferred for use in a different environment. Decision makers were invited to identify the technical hurdles transferability might face and potential technical opportunities.*
Organisational Transferability	*The potential of a process pathway to be transferred to a different organisation. Stakeholders identified the barriers transferability might face.*
Legislative Transferability	*The extent a particular business case could be legally transferred for use in a different environment. Decision makers were invited to identify legal hurdles transferability might face (e.g., regulation of feedstock such as biomass, CO_2 credit exchange).*
Social Dimension	
Stakeholders' Interest	*Generated opinions related to interventions by local stakeholders (e.g., airline companies and local authorities) regarding the AJF business cases. This criterion is measured on a qualitative 9-point ordinal scale.*
Wealth	*Wealth refers to the extent to which the implementation of an AJF business case would generate wealth. This criterion is also measured on a qualitative 9-point ordinal scale.*
Job Creation	*Job creation refers to the extent to which the implementation of an AJF business case would generate jobs.*

Table 2: Performance Sustainability Scale

Grade	*Global Performance Ranking*
No Target (NT)	0.1
Very Low (VL)	0.3
Low (L)	0.5
Medium (M)	0.7
High (H)	0.9
Very High (VH)	1.0

Peer experts provide the Basic Probability Assignments (BPA) either directly or from a pair-wise questionnaire. Contrasting sources are then aggregated using DST. A distance-to-target (DTT) method (Weiss et al., 2007) is used to normalise the probability values based upon expected future targets that are set by the road network operator. These targets can also be aligned by local, regional and international government bodies and institutions.

Whilst DTT was originally derived as a LCA method to evaluate and prioritise the different environmental impact categories, for this paper DTT has been expanded to include environmental issues (such as emission levels, energy consumption), social perspectives (such as wealth and job creation), technical perspectives (technological maturity, process efficiency) and economic issues (investment, operational costs etc.). The method is modified to give an aggregated score while the AHP enables prioritisation. The reduction targets can be achieved by marginal improvements in technology. This allows the LCA method to be in full synergy with AHP and DST as opposed to acting as just an input value to the information fusion process. Using a version of the DTT method proposed by Weiss (2007), the difference between the apparent status of a criterion per year and a future target value is calculated as:

$$DTT_{(i)} = ASB_{(i)} - FST_{(i)} \quad (1)$$

With $DTT_{(i)}$ being the distance-to-target value dependent on the context of the particular criteria, $ASB_{(i)}$ the apparent level of environmental, social and economic burden represents the definition of sustainability in the model and $FST_{(i)}$ the future 'sustainability target'. In this context, sustainability takes a value which considers all facets of evidence in the form of a sustainability index (representing the prioritised set of criteria).

In order to determine the performance ranking $PR_{(i)}$ of a specific criterion, the future sustainability target (comprising the environmental and socio-economic criteria below) is divided by the performance burden related to the specific criterion, which gives a value representing a distance to target weight.

$$PR_{(i)} = \frac{FST_{(i)}}{ASB_{(i)}} \quad (2)$$

The distance to target weights for the particular case study used in this research are provided in the case study results within Section 5. Using the individual performance rankings in Table 2 we have $G_k \in \{NT, VL, L, M, H, VH$ and the BPA for each information source, the overall performance weights (*r_i*) for a criterion *i* would then be calculated as follows:

$$r_i = \sum_{k=1}^{p} r\,(G_k) \times BPA\,(G_k) \times DTT_i \quad (3)$$

Where (G_k) represents the global performance ranking $G_k \in \{NT, VL, L, M, H, VH\}$ represents the individual performance ranking of a sustainability grade G_k, BPA represents the basic probability assignment or mass function related to each sustainability grade G_k and *P* represent the number of grades applicable. *P* = *6* for $G_k \in \{NT, VL, L, M, H, VH\}$. DTT_i is the distance to target weight for a criterion *i* which is calculated after the BPA's have been converted by the global performance ranking.

Overall performance rankings are used to assess the level of emissions and socio-economic aspects of the AJF pathway using an Alternative jet fuel sustainability index. The overall performance rankings for the criteria $C_1, C_2, ..., C_N$ are denoted by r_1, r_2, r_3,... r_N . An AJF sustainability index value is then given by combining:

$$ITSI = \mathrm{r}_1 \times w_1 + \mathrm{r}_2 \times w_2 + \ldots + \mathrm{r}_\mathrm{n} \times w_n \tag{4}$$

where $w_1, w_2 \ldots, w_2$ represent the weights of criteria C_1, C_2,...,C_n obtained using AHP. The key performance for a scheme is assessed by the summed performance ranking of the index, which sorts the criteria from highest performing areas of the AJF process to areas which perhaps require more focus.

The criterias individual values are compared with a Distance-to-target (DTT) method which allows for pre-defined future targets to be compared with the marginal values of the criteria (Weiss et al., 2007). These targets can be determined by local, regional and international government bodies and institutions. Whilst DTT was originally an LCA method to evaluate and prioritize the different environmental impact categories, in this paper it is enhanced to take into account a range of sustainability dimensions and modified to give an aggregated score, whilst AHP handles prioritization. The reduction targets can be achieved by improvements in technology. Using a modified version of the Distance-to-target method used by Lin (Lin et al., 2005), the weighting and percentile of the initial performance state is calculated via

$$DTT_{(initial)} = ASB_{(initial)} - FST_{(initial)} \tag{5}$$

or if the target should be of a higher value, (1) is inverted. With $DTT_{(tbase)}$ being the distance-to-target value dependent on the context of the criteria in focus, $ASB_{(tbase)}$ the apparent level of sustainability burden and $FST_{(tbase)}$ the future sustainability target. We refer to sustainability in this context as a subjective value which takes into account all facets of evidence in the form of a sustainability index (representing the group of criteria). The following equations are used to calculate the performance of criterion with negative (2) or positive (3) distance to target values.

$$PR_{(tyear)} = \frac{DTT_{(tyear)}}{ASB_{(tyear)}} X\ 100 \tag{6}$$

4 PRELIMINARY RESULTS

In this performance evaluation exercise for uncertainty reduction, we considered six AJFs assessed against 19 criterial parameters including investment cost, additional running cost, flexibility, CO_2 emissions, technical transferability, organizational transferability, legislative transferability, stakeholders' interest, and job and wealth creation.

The results of the AJF performance assessment are in tables 3 and 4. Table 3 reports the fusion of all stakeholder opinions and AJF process pathways into a solitary overall performance summary for one AJF process pathway – Wood pellet biomass via gasification and Fischer-Tropsch catalytic conversion (Figure 1). There are six processes that are involved in the production of this AJF. The first process is the recovery of wood pellets which is carbon neutral as the pellets belong to a waste stream. The pellets are then transported by barge to the bio refinery and gasification then begins. A rich CO Syngas is produced during gasification before Fischer-Tropsch transforms the syngas into jet fuel.

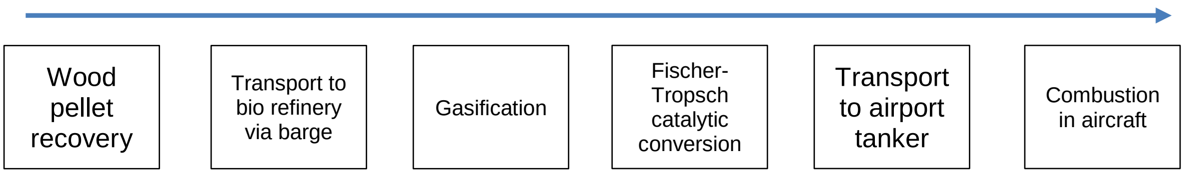

Figure 1: Wood pellet biomass via gasification and Fischer-Tropsch

Table 3: BPA values following data fusion

Performance Criteria	**Sustainability Grade BPA**					
	NT	***VL***	***L***	***M***	***H***	***VH***
Global Warming Potential (C_1)	0	0.02521	0.13445	0.80672	0.03361	0
Savings of CO_2 (C_2)	0	0.01092	0.52459	0.45901	0.00546	0
Energy requirements (C_3)	0	0.62791	0.37209	0	0	0
Investment costs (C_4)	0	0	0.07692	0.92307	0	0
Operation and maintenance costs (C_5)	0	0	0.66666	0.05556	0.27778	0
Savings (C_6)	0	0	0	0.71428	0.28571	0
Payback Period (C_7)	0	0	0.5	0.5	0	0
Net Present Value (C_8)	0	0	0	0	0.48076	0.51925
Flexibility (C_9)	0	0	0	0.85714	0.14285	0
Production (C_{10})	0	0	0	0	0. 05263	0.94736
Technological Maturity (C_{11})	0	0	0	0	0.71428	0.28571
Process Reliability (C_{12})	0	0	0	0.5	0.5	0
Process Efficiency (C_{13})	0	0	0.07692	0.92307	0	0
Technical Transferability (C_{14})	0	0.01092	0.52459	0.45901	0.00546	0
Organisational Transferability (C_{15})	0	0	0.02521	0.13445	0.80672	0.03361
Legislative Transferability (C_{16})	0	0	0	0	0.85714	0.14285
Stakeholders' Interest (C_{17})	0	0	0.62791	0.37209	0	0
Wealth (C_{19})	0	0	0	0	0.05263	0.94736
Job Creation (C_{20})	0	0	0.66666	0.05556	0.27778	0

Table 4 illustrates the overall AJF sustainability index which suggests where prioritization of overall process pathways should be placed. In other words, global warming potential, CO_2 savings, stakeholder interest, process reliability and technical transferability need to be focused upon in order to allow for the implementation of AJFs to be a success.

5 CONCLUSIONS

In this paper, we proposed an integrated multi-criteria decision analysis (MCDA)-based framework to compare and evaluate a range of competing AJFs. As such, the work adds to the body of knowledge on the potential benefits and applicability, and the continued barriers to the wider production of AJFs. We have also used a wide range of criteria, and different forms of data and relations, to assess and compare the business cases and to reflect the multiple interests and priorities of a wide range of stakeholder. This is in contrast to conventional cost benefit analysis which typically focuses on the economic benefits at the expense of other factors like the environment, technological and legal transferability and legislative barriers.

In general, we have introduced a method capable of handling uncertainty in the prioritisation from four different stakeholders' opinions to determine the overall performance of AJFs to date. The method is flexible, allowing performance criteria to be ranked based upon future targets, stakeholder perceptions and the processes of sustainable feedstocks.

Table 4: Alternative Jet Fuel Sustainability Index calculations

Performance Criteria	Final AJFi Index Results				
	Apparent Performance Grade	***DTT weighting***	***AHP***	***AJFi Performance Value***	***Priority***
Technical Transferability (C_{14})	Low	X 0.4	X 0.100	0.0209836	1
Process Reliability (C_{12})	Medium/High	X 0.5	X 0.100	0.025	2
Stakeholders' Interest (C_{17})	Low	X 0.5	X 0.100	0.0313955	3
Savings of CO_2 (C_2)	Low	X 0.6	X 0.100	0.0314754	4
Global Warming Potential (C_1)	Medium	X 0.5	X 0.100	0.040336	5
Technological Maturity (C_{11})	High	X 0.6	X 0.100	0.0428568	6
Operation and maintenance costs (C_5)	Low	X 0.71	X 0.100	0.04733286	7
Payback Period (C_7)	Low/Medium	X 0.5	X 0.100	0.05	8
Energy requirements (C_3)	Very low	X 0.8	X 0.100	0.0502328	9
Net Present Value (C_8)	Very High	X 1.0	X 0.100	0.051925	10
Investment costs (C_4)	Medium	X 0.6	X 0.100	0.0553842	11
Savings (C_6)	Medium	X 0.8	X 0.100	0.0571424	12
Organisational Transferability (C_{15})	High	X 0.8	X 0.100	0.0645376	13
Job Creation (C19)	Low	X 1.0	X 0.100	0.066666	14
Legislative Transferability (C_{16})	High	X 0.8	X 0.100	0.0685712	15
Process Efficiency (C_{13})	Medium	X 0.75	X 0.100	0.06923025	16
Flexibility (C_9)	Medium	X 1.0	X 0.100	0.085714	17
Production (C_{10})	Very High	X 1.0	X 0.100	0.094736	18
Wealth (C_{18})	Very High	X 1.0	X 0.100	0.094736	19
OVERALL PERFORMANCE	Medium		X 0.100	0.556993	

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