[Journal of Cleaner Production 167 (2017) 1068](http://dx.doi.org/10.1016/j.jclepro.2017.03.183)e[1083](http://dx.doi.org/10.1016/j.jclepro.2017.03.183)

Contents lists available at [ScienceDirect](http://www.sciencedirect.com/science/journal/09596526)

Journal of Cleaner Production

journal homepage: [www.elsevier.com/locate/jclepro](http://www.elsevier.com/locate/jclepro)

Benchmarking aircraft metabolism based on a Sustainable Airline Index



S¸ an Kılkıs¸ [a](#_bookmark0), S¸ iir Kılkıs¸ [b](#_bookmark1), [\*](#_bookmark2)

a *Delft University of Technology, Netherlands*

b *The Scientiﬁc and Technological Research Council of Turkey, Turkey*

a r t i c l e i n f o

*Article history:*

Received 5 March 2016 Received in revised form 19 February 2017

Accepted 27 March 2017

Available online 30 March 2017 Handling Editor: R.L. Lozano

*Keywords:* Airlines Aviation

Aircraft metabolism Composite index Sustainability

CO2 emissions

a b s t r a c t

Airlines are mobile, micro-communities that exhibit varying levels of performance. This paper develops and applies a composite indicator to address a gap in the literature for benchmarking airlines based on aspects of sustainable aviation. First, the concept of aircraft metabolism is developed to relate ﬂows of energy, carbon dioxide emissions, water, and waste with operational outputs, such as the transport of revenue loads. The Sustainable Airline Index is then constructed based on 4 dimensions and 20 indicators to benchmark aircraft metabolism. The dimensions are 1) airline services and quality, 2) fuel con- sumption and efﬁciency, 3) carbon dioxide emissions and intensity, and 4) sustainable aviation measures. The index is applied to a sample of 16 airlines based on data from corporate sustainability reporting and annual reports. The results are compared based on six schemes that involve equal or unequal weights with linear or geometric aggregation. Unequal weights are determined based on exploratory factor analysis. The net change in rank among all schemes is 2.3 positions. Monte Carlo experiments are also conducted to rank airlines based on simulated mean values in which the top 4 airlines in the sample are *A9*, *A11*, *A3* and *A15*. Airlines that decouple revenue loads from similar increases in resource usage have higher rankings in the composite indicator based on well-rounded performances in aircraft metabolism. The results are applicable to support the carbon neutral growth strategy of the sector and to consider multiple dimensions towards more sustainable practices on the airside of aviation.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Aircraft are mobile, micro-communities for the traveling human population in an increasingly interconnected world. As complex systems, aircraft undertake a multitude of services while ensuring the provision of energy for propulsion and ﬂight control systems as well as water and food for cabin crew and passengers. Optimized procedures during climb, cruise, and descent, as well as the landing and take-off (LTO) cycle, are a key aspect of competitive airline operations. Globally, the aviation sector emitted 781 million tonnes of CO2 in 2015 of which 80% were from long-haul ﬂights over 1500 km ([ATAG, 2016](#_bookmark63)). Overall, the aviation sector accounted for about 12% of human-induced CO2 emissions from transport sources ([ATAG, 2016](#_bookmark63)).

Most recently, the ﬁrst global scheme for market-based mea-

sures in the aviation sector was adopted, the pilot phase of which

\* Corresponding author.

*E-mail address:* [s.kilkis-2@student.tudelft.nl](mailto:s.kilkis-2@student.tudelft.nl) (S¸ . Kılkıs¸ ).

will initiate in 2021 ([ICAO, 2016a](#_bookmark90)). Already, 87% of the sector has indicated voluntary participation ([ICAO, 2016b](#_bookmark91)). In addition, avia- tion will continue to be included in the EU Emissions Trading Scheme (ETS) beyond 2016 ([EC, 2016a; EC, 2016b](#_bookmark73)). The Interna- tional Air Transport Association (IATA) has also set three targets for more sustainable aviation in airlines based on a Carbon Neutral Growth (CNG) Strategy ([IATA, 2013a](#_bookmark83)). The ﬁrst two targets consist of improving fuel efﬁciency by an average of 1.5% per year up to the year 2020 and capping aviation CO2 emissions from 2020 onwards ([IATA, 2013b](#_bookmark84)). The third target aims to reduce CO2 emissions by 50% relative to 2005 levels by 2050 ([IATA, 2013b](#_bookmark84)). Such medium and long-term targets are important since aviation is expected to receive 4.1% average annual demand growth in the next 20 years ([IATA, 2014a](#_bookmark86)).

In this way, measures that enable the transport of greater rev-

enue loads with less resource spending are an increasing priority for the aviation sector in an aspect of relative decoupling ([UNEP,](#_bookmark138) [2011](#_bookmark138)). A mix of technological and operational solutions will be instrumental in advancing this process. The IATA Technology Roadmap evaluated a total of 23 technology sets that contained

<http://dx.doi.org/10.1016/j.jclepro.2017.03.183>

0959-6526/© 2017 Elsevier Ltd. All rights reserved.

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1069

Nomenclature

* 1. Weighting scheme based on equal weights

*ASK* Available Seat Kilometers (in millions)

*ATK* Available Tonne Kilometers (in millions)

* 1. Weighting scheme with unequal indicator weights
  2. Weighting scheme with unequal indicator and dimension weights

*Ct* Total CO2 emissions (tonnes of CO2)

*CI* CO2 intensity (kg of CO2 per unit output)

* 1. Linearly aggregated dimension value

*D1* Airline services and quality dimension

*D2* Fuel consumption and efﬁciency dimension

*D3* CO2 emissions and intensity dimension *D4* Sustainable aviation measures dimension *E* Fuel efﬁciency (liters per unit output) EFA Exploratory factor analysis

EW Equal weighting in relation to scheme A

*F* Fuel consumption (liters)

*I* Normalized value of an indicator

*i* Value of data entry for an indicator

*LF* Load factor, as in passenger (*p*) and cargo (*c*)

*max* Maximum value in the data set

*min* Minimum value in the data set

*Q* Quartile based on simulated mean SAI values

*Qa* Combined quality score of the airline

*RPK* Revenue Passenger Kilometers (in millions) *RFTK* Revenue Freight Tonne Kilometers (in millions) *Sc* Star Category of Skytrax

*TKP* Tonne Kilometer Performed (in millions)

*w* Average passenger and baggage weight (tonne)

*Wa* World Airlines Award ranking

*X* Expenses

*y* Year

*Greek symbols*

a Dimension weights, dimensionless

D*C* Improvement in CO2 intensity D*E* Improvement in fuel efﬁciency l Eigenvalue

PQ

Geometric aggregation Linear aggregation

*Subscripts*

*c* Cargo

*p* Passenger

*RTK* Fuel spending or CO2 emissions speciﬁc to RTK

*t* Total fuel spending or CO2 emissions *TKP* Fuel spending or CO2 emissions per TKP *x* Dimension number

*y* Indicator number

*Acronyms*

ASPIRE Asia and Paciﬁc Initiative to Reduce Emissions ATAG Air Transport Action Group

CNG Carbon Neutral Growth

CSR Corporate Social Responsibility ETS Emissions Trading Scheme

HC Halocarbons

IATA International Air Transport Association ICAO International Civil Aviation Organization LTO Landing and Take-Off Cycle

SAFUG Sustainable Aviation Fuel Users Group SAI Sustainable Airlines Index

SESAR Single European Sky Air Trafﬁc Management Research SOPs Standard operating procedures

SRA Sustainability Ranking of Airports

various solutions for airframe and engine technologies, alternative fuels, and air trafﬁc managemnt. For example, wingtip devices, such as winglets and sharklets that are available at the most mature technology readiness level, provided a 3%e6% fuel savings ([IATA,](#_bookmark85) [2013c](#_bookmark85)). Hybrid or blended wing-body conﬁgurations and second generation engine core concepts that have a time horizon after 2025 are expected to provide up to 25% and 30% fuel savings, respectively ([IATA, 2013c](#_bookmark85)). Clearly, the future of aviation will be determined by a portfolio of innovative solutions.

* 1. *Literature review*

Related studies have focused on the drivers of efﬁciency in air- lines, comparisons with other transport modes, aviation biofuels, policy schemes, public views towards aviation, and aspects of corporate social responsibility (CSR) as indicated in the subsequent literature review (see Sections [1.1.1 to 1.1.6](#_bookmark3)). In contrast, this research work develops and applies a benchmarking tool based on a composite indicator to compare airlines based on aspects of sustainable aviation (Section [1.2](#_bookmark4)). Such an approach has not been undertaken in the literature.

* + 1. *Drivers of efﬁcient operations in airlines*

Several studies analysed cases in which airlines strived for more efﬁcient operations to attain competitive advantage. For example, [Saranga and Nagpal (2016)](#_bookmark126) evaluated the drivers of technical and cost efﬁciency in 13 low-cost carriers in India. [Lynes and Andrachuk](#_bookmark105)

[(2008)](#_bookmark105) analysed motives to implement new technologies for cleaner operation and lower production costs in aircraft to raise airline image. [Delbari et al. (2016)](#_bookmark70) proposed a framework in which the competitiveness of full-service airlines may be evaluated across 12 key indicators, including connectivity. [Cui and Li (2015)](#_bookmark68) found that ﬁnancial crises had a positive effect on the fuel efﬁciency of 11

airlines during the years 2008 and 2012. [Jani´](#_bookmark93)c [(2007)](#_bookmark93) found an 18%

decrease in average fuel spending per volume of output during the decade up to 2000 in the US airline industry. A higher bypass ratio in engines that enabled lower speciﬁc fuel consumption per unit of net thrust was put forth as one of the main drivers. [Jani´](#_bookmark94)c [(2014)](#_bookmark94)

further analysed scenarios for supersonic civilian transport.

At the same time, processes of decision-making for enabling more efﬁcient airline operations involve certain trade-offs. In this respect, [Rosskopf et al. (2014)](#_bookmark119) compared ﬂeet plans for European airlines that were optimized for either economic or environmental goals. Pareto-optimal plans indicated that airlines could deviate by about 3% from the economic optimum to achieve a 6% improve- ment in satisfying the environmental goal. Such decisions actively shape the dynamics of the sector. For example, [Arjomandi and](#_bookmark59) [Seufert (2014)](#_bookmark59) found that the most technically efﬁcient airlines were from China and North Asia while the best environmental performers tended to be from Europe. Low-cost carriers were also found to exhibit an environmental orientation more so than full- service carriers based on the results of bootstrapped data envel- opment analysis models.

In addition, operational choices, including the frequency of

1070 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

ﬂight departures, have a direct impact on operating costs, load factors, and fuel consumption. [Zou et al. (2014)](#_bookmark146) analysed the fuel efﬁciency and cost savings of 15 mainline airlines and regional subsidiaries in the US. An average airline in the sample was at least 9% less efﬁcient than the most efﬁcient carrier. [Scotti and Volta](#_bookmark128) [(2015)](#_bookmark128) analysed the CO2 intensity of 18 European airlines in the decade between 2000 and 2010. The average improvement was found to be 6% based on changes in productivity, efﬁciency, and technical aspects. In addition to airlines, [Reis and Silva (2016)](#_bookmark118) evaluated the combination carrier strategy of 10 air cargo com- panies based on loads and cost structure.

In the aspect of network structures, [Ryerson and Kim (2014)](#_bookmark120)

evaluated the merged networks of two pairs of airlines in North America. Route and hub consolidation was found to enable fuel savings of 25e28%. [Steven and Merklein (2013)](#_bookmark135) assessed the role of strategic alliances in reducing the carbon intensity of airlines. The coordination of ﬂight schedules was indicated to enable better load factors while common investments were limited, including those to lower the average age of aircraft. In contrast, new aircraft have an impact on material and primary energy usage. [Huang et al. (2016)](#_bookmark82) estimated the beneﬁts of supplying lightweight alloys and steel for aircraft based on additive manufacturing for the fuselage, en- gine, Nacelle, and other systems.

* + 1. *Comparison with other transport modes*

Airlines are the preferred mode of transport for non-urban passenger activity ([IEA, 2016](#_bookmark92)). While long-haul travel has limited options, short-haul travel can have alternatives. [Filimonau et al.](#_bookmark76) [(2014)](#_bookmark76) compared the greenhouse gas (GHG) emissions of trans- port modes between two European cities 1000 km apart. A ﬂight with intermediate change had the highest footprint since more GHG emissions were produced in the LTO cycle per passenger- kilometer than any other stage of ﬂight. Options for train and coach had the lowest footprint while those for car and direct ﬂight had similar levels of GHG emissions. In addition, [Pereira et al.](#_bookmark115) [(2017)](#_bookmark115) compared the carbon intensity factors of transport modes between two Brazilian cities about 350 km apart. An inter-city bus that was driven by a biofuel blend was found to be more carbon benign ([Pereira et al., 2017](#_bookmark115)). The beneﬁts of biofuel-driven ﬂights over jet kerosene usage were limited due to shorter distances.

* + 1. *Analyses on alternative fuels in aviation*

Aviation biofuels are among the portfolio of solutions for reducing the carbon impact of air ﬂight as a radical technology ([IATA, 2013c](#_bookmark85)). In the current context, [Cremonez et al. (2015)](#_bookmark67) ana- lysed the prospects for aviation biofuels in Brazil. The high demand

for the use of biodiesel in the vehicle ﬂeet was found to compro- mise the use of biofuels for the aviation sector. [K](#_bookmark98)o€[hler et al. (2014)](#_bookmark98) compared the lead markets for second-generation aviation biofuels

in Germany, Brazil, and the US. [Hari et al. (2015)](#_bookmark80) analysed the drivers and challenges in the production of sustainable aviation fuels with lower lifecycle GHG emissions and an affordable price. [Winchester et al. (2015)](#_bookmark143) conducted analyses based on the costs of advanced fermentation from perennial grasses.

* + 1. *Emission mitigation policy schemes*

Policy tools have a role in promoting higher efﬁciency gains and overcoming market barriers. [Xu et al. (2016)](#_bookmark145) analysed strategies for selecting optimal aircraft types under different policy schemes and found that a cap and trade mechanism increased the demand for lower carbon air transport. [Dray et al. (2014)](#_bookmark72) analysed the demand and emissions response from the use of a carbon tax in the aviation sector and found that the sector can reduce its lifecycle CO2 emis- sions by up to 34% by 2050. [Cui et al. (2016)](#_bookmark69) analysed future sce- narios for 18 global airlines under a scheme of emission limits using

data for the number of employees, aviation kerosene, revenue, GHG emissions, and capital stock. [Preston et al. (2012)](#_bookmark116) estimated that the inclusion of the aviation sector in EU ETS would encompass 35% of global aviation CO2 emissions. [Miyoshi (2014)](#_bookmark109) proposed that a transparent distribution of revenue may dampen equity issues for African airlines.

* + 1. *Public views towards sustainable aviation*

Public views on selecting more sustainable aviation options can transform the sector from the bottom-up. In this respect, [Higham](#_bookmark81) [et al. (2016)](#_bookmark81) conducted interviews to determine public views to- wards the use of voluntary, regulatory, and market options for altering current practices in air travel, including through a carbon tax. [Hagmann et al. (2015)](#_bookmark77) analysed the elasticity of ﬂight choice to the perceived eco-friendliness of airlines. The authors found that passengers place priority on direct ﬂight availability, safety, and the presence of a green ﬂeet more so than other factors, such as seat space and frequent ﬂyer programs. In contrast, [Mayer et al. (2015)](#_bookmark108) found no statistically signiﬁcant correlation between the perceived passenger image of airlines and actual data on carbon efﬁciency, load factors, and aircraft type, including those for low- cost carriers.

* + 1. *Aspects of corporate social responsibility in airlines*

From the view of airline managers, [Kuo et al. (2016)](#_bookmark100) found that approaches towards CSR were driven mainly by economic and ethical motives to attain increased reputation and to promote sustainability. [Seo et al. (2015)](#_bookmark129) compared the relation between service quality and CSR based on 15 airlines that spanned low-cost and full-service carriers in North America. For another sample based on 8 Chinese airlines, [Wang et al. (2015)](#_bookmark142) found that the most important CSR measures were those for operational aspects, including on-time performance, safety, and ﬂight frequency.

At the same time, there is an apparent need to use operational and technological metrics across economic, social, environmental, and institutional aspects to assess sustainability in air transport

systems ([Jani´](#_bookmark93)c, [2007](#_bookmark93)). In other sectors, [Morioka and Carvalho](#_bookmark110)

[(2016)](#_bookmark110) evaluated the possibility of developing a performance sys- tem to better integrate sustainability into corporate measuring systems. However, those for the aviation sector, notably through the approach of a composite indicator as a metric to benchmark sustainable airline performance, have not been undertaken.

* 1. *Aims of the research work*

Composite indicators are useful to measure multi-dimensional concepts that cannot be captured by a single indicator ([Nardo](#_bookmark111) [et al., 2005](#_bookmark111)). For this reason, composite indicators are well-suited to assess aspects of sustainable aviation. On the landside of the aviation sector, the Sustainability Ranking of Airports (SRA) Index was previously developed by the authors to benchmark airports ([K](#_bookmark102)ı[lk](#_bookmark102)ıs¸ [and K](#_bookmark102)ı[lk](#_bookmark102)ıs¸, [2016](#_bookmark102)). In contrast, there remains a gap for developing and applying composite indicators to compare the performance of airlines in aspects related to sustainable aviation on the airside. Among other indices in the transport sector, [Mariano](#_bookmark107) [et al. (2017)](#_bookmark107) developed a composite index to compare countries based on the performance and CO2 emissions of ground transport vehicles. [Azevedo et al. (2013)](#_bookmark65) developed an index to evaluate the supply chain of the automotive sector based on the level of green practices and resilience. The indicators in the index were weighted based on expert designated importance levels using the Delphi technique. Other studies developed multi-criteria tools for sectors beyond transport, including those to assess the sustainability of cities ([K](#_bookmark101)ı[lk](#_bookmark101)ıs¸, [2016](#_bookmark101)), electricity corporations ([Maas et al., 2016](#_bookmark106)), or environmental initiatives in stock exchange practices ([Orsato et al.,](#_bookmark114)

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1071

[2015](#_bookmark114)).

Hence, the present research work contributes to the literature with a composite indicator that is dedicated to assessing aspects of sustainability on the airside of the aviation sector with a focus on airlines. The composite indicator has the potential to contribute to tracking progress towards the IATA targets and benchmarking airline performance based on sustainable aviation measures. Sec- tion [2](#_bookmark5) provides the details of the method that is followed by an application to an airline sample, the results of the research work, and the conclusions in Sections [3](#_bookmark28)e[5](#_bookmark28), respectively.

1. Method

The method of the research work involves the construction and application of a composite indicator, namely the Sustainable Air- lines Index (SAI). SAI is designed to benchmark airlines with a comparative approach based on aspects that relate to energy, water, and environmental management in aircraft ﬂeets. The system boundary is deﬁned through the concept of aircraft metabolism that is introduced to provide the main framework for the composite indicator (Sections [2.1 and 2.2](#_bookmark6)). The method continues with the determination of the sample, data collection per airline, as well as the processing and normalization of data. The sensitivity of the results to changes in weighting and aggregation schemes is ana- lysed in this process (Section [2.6](#_bookmark10)). The rationale for the inclusion of indicators in the SAI is given in Section [2.7](#_bookmark17).

* 1. *Conceptualization of aircraft metabolism*

Aircraft are semi-open systems that have a managed set of in- teractions with the surrounding environment based on ﬂows in and out of the system boundary. [Fig. 1](#_bookmark7) puts forth an aircraft metabolism

model for this research work that is analogous to the concept of urban metabolism for cities ([Tillie et al., 2014; Fern](#_bookmark136)a´[ndez, 2016](#_bookmark136)). Urban metabolism relates to the processes that occur in cities to provide growth, energy, and waste reduction ([Kennedy et al., 2007](#_bookmark96)).

Here, the scope involves mobile, micro-communities of air-bound

aircraft all over the world belonging to a speciﬁc airline. In the aspect of energy, aircraft use jet fuel when in-ﬂight or taxing and electricity from power units at the airport. Potable water is supplied for the airborne journey while water usage also takes place for engine washing and maintenance on the ground. Material usage is required for operations, such as ﬂight checks, catered food, bever- ages, and other items for passengers and ﬂight safety. These inputs enable ﬂight and passenger services from boarding to deplaning and involve various outputs. Onboard recycling reduces the amount of general waste that is sent to the landﬁll after landing.

As further indicated within [Fig. 1](#_bookmark7), ﬂight services include me- chanical and hydraulic systems for propulsion and control surfaces for lift and stability. Avionics and instrumentation include elec- tronics that provide communication, navigation, monitoring, and weather radar. The environmental control system provides adia- batic heating for the crew and passengers, cabin pressurization, and oxygen and humidity control according to standards on air quality ([ASHRAE, 2009](#_bookmark60)). In addition, various interactions exist in aspects that characterize an energy-water nexus ([Varbanov, 2014](#_bookmark141)). For example, the amount of potable water that is supplied onboard has an impact on the center of gravity and weight of the aircraft. This, in turn, has an impact on fuel spending and the CO2, NOx, SO2, and halocarbons (HC) emissions that are released from the exhaust nozzle to the atmosphere. As a result, the concept of aircraft metabolism spans a complex network of considerations for revenue loads, transport distance, service quality, and aspects of energy, water, and environment systems.

* 1. *Sustainable airline index construction*

The conceptualization of aircraft metabolism implies the pos- sibility of using various metrics to benchmark the sustainability of aviation with less impact on the environment while preserving the quality of aviation services. In this framework, indicators for the SAI must pertain to the complexity of expressing aircraft metabolism in a way that may be comparable across airlines and may be based on the use of data that can be obtained and/or calculated from CSR and

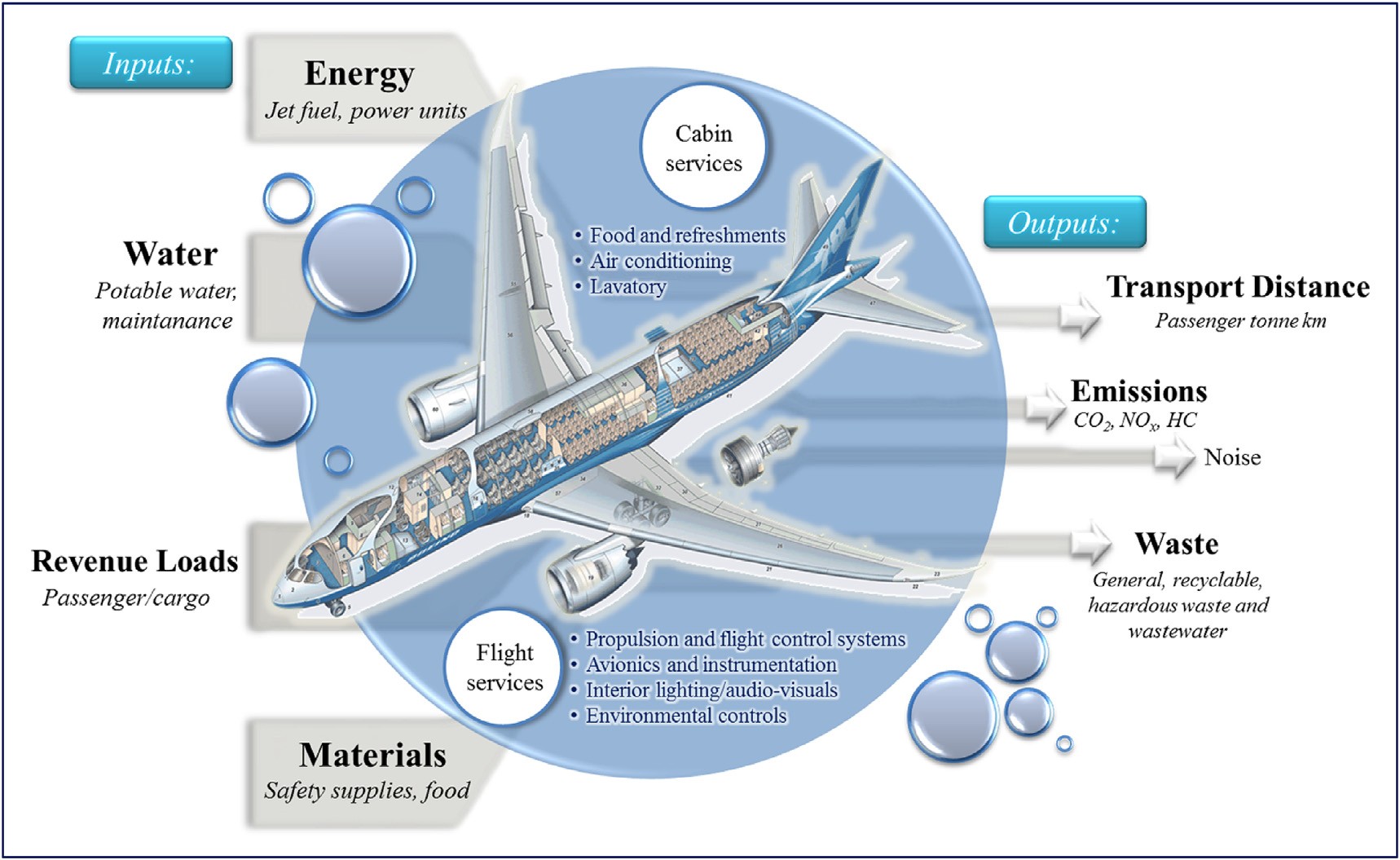


Fig. 1. Conceptualization of the aircraft metabolism model.

1072 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

annual reports. Hence, the inclusion of any indicator is based on multiple considerations of relevance, accessibility, comparability, and coherence ([OECD-JRC, 2008](#_bookmark113)). [Table 1](#_bookmark11) provides a total of 20 indicators in 4 dimensions that are proposed in this research work to construct the SAI as a composite indicator. [Table 1](#_bookmark11) further summarizes the direction of change that is implied in each indi- cator, i.e. whether higher or lower values are desirable for nearing the objectives of more sustainable aviation.

* 1. *Determination of the sample*

The determination of the airline sample is based on a two- phased approach as a variant of multistage cluster sampling. The ﬁrst criterion is used to determine those airlines that take place in the top 10 largest airlines in the world based on ﬂeet size, the number of countries served, and/or air trafﬁc ([IATA, 2015](#_bookmark88)). Top airlines from the regions of Asia-Paciﬁc and Europe are also added to this initial sample. Next, the largest public companies in the airline sector based on revenue ([Forbes, 2015](#_bookmark78)) and the airlines that take place in the world rankings based on airline quality are eval- uated ([Skytrax, 2014](#_bookmark132)). Airlines that satisfy at least two of the se- lection criteria qualify as sample candidates to which a fourth criterion is applied. In this respect, as a prerequisite, airlines must provide sufﬁciently detailed CSR and/or annual reports that contain a robust coverage of data for the indicators of the SAI. In total, 38 airlines were considered for the sample (see supplementary material) of which 42% were eliminated mainly due to the last criterion, including low-cost carriers. [Table 2](#_bookmark14) provides the 16 air- lines in the sample along with the main sources for the data collection. All airlines in the sample are full-service network car- riers. [Table 2](#_bookmark14) further marks the distribution of the sample based on the airline alliance to which the airlines may belong.

* 1. *Data processing and factor analysis*

According to the method, data entries are collected per airline *Aj* from *A1* to *A16* for the 20 main indicators in the SAI to construct an initial data matrix. Data is further subjugated to tests of normality based on the use of higher-order moments to assess the need for any data processing. In addition, the Pearson correlation matrix between the indicators is subjugated to exploratory factor analysis

(EFA). EFA provides a means to extract the presence of principal factors that can provide insight on the underlying (unobserved) structure of an index ([Hair et al., 2010](#_bookmark79)). The selection of the factors that are to be retained as principal factors are based on multiple criteria for eigenvalue threshold, variance, cumulative variance, and the scree plot ([Loewen et al., 2015](#_bookmark103)).

* 1. *Data normalization*

The min-max method is chosen for the step of normalization that provides a rescaling of values with an identical range between 0 and 1 ([OECD-JRC, 2008](#_bookmark113)). In contrast, an alternative based on *z*- scores uses a scaling factor based on the standard deviation from mean values. The methods differ by the extent to which exceptional performance in limited indicators is rewarded ([OECD-JRC, 2008](#_bookmark113)).

In the normalized values of the data entries based on the min- max method, a value of 1 represents the most favourable value in the data set from the aspect of sustainable aviation. According to the desired direction of change, Equation [(1)](#_bookmark8) is used for indicators in which the most favourable value is the maximum value. Equation

[(2)](#_bookmark9) is used when the opposite is true such that minimum values denote better airline performance. Here, variable *ix.y* is the data entry for the *y*th indicator in a given dimension *x*. The variables *minx.y* and *max x.y* are the minimum and maximum values in the data set for the same indicator, respectively. The resulting values *Ix.y* are the normalized values for particular entries in the data matrix. *Ix*:*y* ¼ *ix*:*y* — min*x*:*y* , max*x*:*y* — min*x*:*y* fdimensionlessg (1)

*Ix*:*y* ¼ *ix*:*y* — max*x*:*y* , min*x*:*y* — max*x*:*y* fdimensionlessg

(2)

* 1. *Weighting and aggregation schemes*

Equation [(3)](#_bookmark16) formulates the linearly aggregated value of the SAI for an airline *Aj* when the normalized values for each of the ﬁve indicators in dimensions *x* ¼ 1 to *x* ¼ 4 are summed, namely those for indicators *I1.1* to *I4.5*. Here, a*x.y* are the weights for each indicator that may be taken equal for each dimension. At the same time,

Table 1

Indicators in the SAI index.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Dimension (*D*) | Indicator (*ix.y*) | Unit | [/Y[a](#_bookmark12) | Source |
| Airline Services and Quality (D1)  Fuel Consumption and Efﬁciency (*D2*) | * 1. Revenue Passenger Kilometers (RPK)   2. Revenue Tonne Kilometers (RTK)   3. Passenger Load Factor (LFp)   4. Airlines Award and Star Score (Qa)   5. Change in Operating Revenue   6. Total Fuel Consumption   7. Speciﬁc Fuel Spending per 100 RPK | Million km Million km Dimensionless Dimensionless Dimensionless 1000 L  liters | [  [  [ Y [ Y Y | CSR [b](#_bookmark13) CSR [b](#_bookmark13) CSR [b](#_bookmark13)  Equation [(6)](#_bookmark19) CSR [b](#_bookmark13)  CSR [b](#_bookmark13)  Equation [(7)](#_bookmark23) |
|  | 2.3. Fuel Spending per 100 TKP | liters | Y | Equation [(8)](#_bookmark24) |
|  | 2.4. Share of Fuel Cost in Operating Expenses | Dimensionless | Y | Equation [(9)](#_bookmark27) |
| CO2 Emissions and Intensity (*D3*)  Sustainable Aviation Measures (*D4*) | 2.5. Fuel Efﬁciency Improvement   * 1. CO2 Emissions (Scope 1)   2. Speciﬁc CO2 Intensity per 100 RPK   3. CO2 Intensity per 100 TKP   4. Previous CO2 Emissions (Scope 1)   5. CO2 Intensity Improvement   6. Fuel/CO2 Saving Operational Measures   7. Fuel/CO2 Saving Technology Measures   8. Average Age of Aircraft Fleet | Dimensionless Metric tonnes kg CO2  kg CO2  Metric tonnes Dimensionless Dimensionless Dimensionless  Dimensionless | [ Y Y Y Y [  [  [ Y | Equation [(10)](#_bookmark20) CSR [b](#_bookmark13)  Equation [(12)](#_bookmark22)  Equation [(13)](#_bookmark25) CSR [b](#_bookmark13)  Equation [(14)](#_bookmark26) [Table A5](#_bookmark50) [Table A6](#_bookmark50)  CSR [b](#_bookmark13) |
|  | * 1. Scope of Environmental Reporting   2. Total Employed Airline Personnel | Dimensionless  Dimensionless | [  [ | [Table A7](#_bookmark50)  CSR [b](#_bookmark13) |

a Indicates the desirable direction of change, i.e. higher ([) or lower (Y) values.

b References for CSR and/or Annual Reports are as provided in [Table 2](#_bookmark14).

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1073

Table 2

International airlines in the sample.

Airline Aj International Airline Data Source(s) Airline Alliance [a](#_bookmark15)

I II III

*A1* ● Air Canada ([Air Canada, 2014a; Air Canada, 2014b](#_bookmark55)) ✓

*A2* ● Air China ([Air China Limited, 2014a; Air China Limited, 2014b;](#_bookmark56) ✓

[China Civil Aviation, 2009](#_bookmark56))

*A3* ● Air France ([Air France](#_bookmark57) e [KLM, 2014a; Air France](#_bookmark57) e [KLM, 2014b](#_bookmark57)) ✓

*A4* ● All Nippon Airways ([All Nippon Airways, 2013; All Nippon Airways, 2012](#_bookmark58)) ✓

*A5* ● British Airways ([British Airways Plc, 2014a; British Airways Plc, 2014b;](#_bookmark66) ✓

[Sustainable Aviation, 2014](#_bookmark66))

*A6* ● Delta Air Lines ([Delta Air Lines Inc, 2014a; Delta Air Lines Inc, 2014b](#_bookmark71)) ✓

*A7* ● Emirates ([Emirates Group, 2014](#_bookmark74))

*A8* ● Japan Airlines ([Japan Airlines, 2014](#_bookmark95)) ✓

*A9* ● KLM Royal Dutch Airlines ([KLM Royal Dutch Airlines, 2014](#_bookmark97)) ✓

*A10* ● Korean Airlines ([Korean Air, 2014](#_bookmark99)) ✓

*A11* ● Lufthansa Group ([Lufthansa Group, 2014](#_bookmark104)) ✓

*A12* ● Qantas Airways ([Qantas Airways Limited, 2014a; Qantas Airways Limited, 2014b;](#_bookmark117) ✓

[Qantas Airways Limited, 2013](#_bookmark117))

*A13* ● SAS Scandinavian Airlines ([SAS Group, 2014](#_bookmark127)) ✓ *A14* ● Singapore Airlines ([Singapore Airlines, 2014a; Singapore Airlines, 2014b](#_bookmark131)) ✓ *A15* ● Turkish Airlines ([Turkish Airlines, 2014a; Turkish Airlines, 2014b](#_bookmark137)) ✓ *A16* ● United Airlines ([United Airlines Inc, 2014a; United Airlines Inc, 2014b](#_bookmark139)) ✓

a Indicates members of Star Alliance (I), SkyTeam (II), and Oneworld (III).

numerous studies examined the sensitivity of indices to changes in equal versus unequal weighting schemes and aggregation rule. For example, [Saisana et al. (2005a), Saisana and Saltelli (2008, 2010)](#_bookmark123), and [Athanasoglou et al. (2014)](#_bookmark64) analysed the variation of country ranks in the Environmental Performance Index, including through the analysis of weight-aggregation pairs. Among other studies, [Saisana et al. (2005b)](#_bookmark124) analysed the variation of country ranks in the Technology Achievement Index. Aspects of uncertainty and sensi- tivity need to be analysed to represent the nature of composite indicators in addressing issues of complexity ([Saisana et al., 2005b](#_bookmark124)) and to better provide advice for policy-makers ([Saisana et al., 2011](#_bookmark125)).

based on sets of randomly generated values. In the iterations of the Monte Carlo experiment, indicator weights are allowed to vary randomly between 0 and 1 and subjugated to the unity sum property. The mean values of the simulated SAI values are then compared with the results of the six weighting and aggregation schemes.

* 1. *Rationale for the SAI indicators*

As indicated in [Table 1](#_bookmark11), the SAI is based on quantitative in- dicators in the ﬁrst three dimensions. These are the dimensions of airline services and quality (*D1*), fuel consumption and efﬁciency

4 5 (*D2*), and CO2 emissions and intensity (*D3*). The fourth dimension on

X X

*SAI Aj* ¼ a*x*:*y* × *Ix*:*y AJ* fdimensionlessg (3)

*x*¼1 *y*¼1

In this respect, the normalized values of the indicators are subjugated to three weighting schemes A to C to determine the sensitivity of the airline rankings in the SAI. Scheme A represents equal weighting (EW) so that indicator weights are a 0.2 with a sum of 1.0 per dimension. In Equation [(3)](#_bookmark16), these weights allow the highest possible value of SAI to be 4.0.

¼

In scheme A, EW implies the use of equal trade-offs between indicators and dimensions ([OECD-JRC, 2008; Munda and Nardo,](#_bookmark113) [2005](#_bookmark113)). In contrast, differentiated weights may be justiﬁed by us- ing the results of EFA ([OECD-JRC, 2008](#_bookmark113)). In scheme B, indicator weights are determined based on the squared sum of the factor pattern coefﬁcients scaled to unity as described by [Nicoletti et al.](#_bookmark112) [(2000)](#_bookmark112). The dimension weights are kept equal as in the previous scheme. In scheme C, both indicator and dimension weights are allowed to vary based on the results of the EFA. In addition, schemes A to C are subjugated to linear and geometric aggregation for a total of six schemes. The latter uses the *n*th root of the product of values rather than the sum where *n* is the total number of in- dicators. In this way, geometric aggregation can favour more consistent performance across the indicators ([OECD-JRC, 2008](#_bookmark113)). The presence of lower values in any indicator(s) can directly penalize the index results.

Further aspects of uncertainty and sensitivity are addressed

based on the use of a Monte Carlo framework ([Nardo et al., 2005;](#_bookmark111) [OECD-JRC, 2008](#_bookmark111)). In the context of the SAI, Equation [(3)](#_bookmark16) is calcu- lated 10,000 times using indicator weights that are determined

sustainable aviation measures (*D4*) supplements the other di- mensions with a mixture of both quantitative and qualitative in- dicators. The sub-sections below provide the rationale for the inclusion of speciﬁc indicators. All indicators are harmonized across different airlines and reporting schemes.

* + 1. *Airline services and quality (D1)*

Airlines are corporate entities that are organized to transport passengers and/or cargo to speciﬁed destinations safely in a time conscience manner. Available seat kilometers (*ASK*) and available freight tonne kilometers (*AFTK*) are frequently reported to repre- sent the capacity of the airline ﬂeet to transport passengers and cargo. In contrast, the utilization of the available seat conﬁguration, cargo area, and transport distance is given by revenue passenger kilometers (*RPK*) and revenue freight tonne kilometers (*RFTK*). Equations [(4) and (5)](#_bookmark18) express the latter metrics based on *ASK* or *AFTK* and the passenger (*LFp*) or cargo (*LFc*) load factors, respec- tively. In addition, *LFp* represents a useful and accessible metric of operational efﬁciency. These three indicators are included in the SAI to represent the magnitude and efﬁciency of revenue loads.

*RPK* ¼ *ASK* × *LFp* fmillion passenger kilometersg (4)

*RFTK* ¼ *ATK* × *LFc* fmillion tonne kilometersg (5)

In the aspect of airline service quality, passenger surveys can address satisfaction with onboard comfort, including cabin tem- peratures, and concerns such as destination coverage ([Skytrax,](#_bookmark133) [2015a, 2016](#_bookmark133)). Equation [(6)](#_bookmark19) provides a combined quality score *Qa*

1074 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

based on two recognized benchmarks, namely, the World Airlines Award, *Wa* ([Skytrax, 2014](#_bookmark132)) and 5-star airline category, *Sc* ([Skytrax,](#_bookmark134) [2015b](#_bookmark134)).

*Qa* ¼ *Wa*×ð6 — *Sc*Þ fdimensionlessg (6)

In addition, increase in airline service quality and the number

local currency. On an improvement basis, Equation [(11)](#_bookmark21) puts forth the means of determining the improvement in fuel efﬁciency for airlines, D*E* for a year *y*.

# *Xs* ¼ *Xf* .*Xt* × 100 fdimensionlessg (10)

and frequency of destinations through global expansion and/or alliances can impact operating revenue with certain trade-offs. Changes in operating revenue, which include revenue from sales of ﬂight tickets and cargo, are used to compare airlines on an economic basis. Overall, *D1* benchmarks airlines on the basis of

ð*y*—1Þ

D*E* ¼ *E*

ð*y*—1Þ

— *Ey* .*E*

# fdimensionlessg (11)

revenue loads, operational efﬁciency, service quality, and economic performance.

* + 1. *Fuel consumption and efﬁciency (D2)*

On an annual basis, the fuel consumption of the aircraft ﬂeet of a given airline indicates the input of jet kerosene to transport reve- nue loads across the total distance ﬂown. Airlines may report fuel efﬁciency, *E* based on different but interrelated ratios of fuel con- sumption to available capacity or revenue loads. Reporting based on *ASK* and *AFTK* do not take into account load factors. Others are not sensitive to the fuel split for transporting passengers versus

* + 1. *CO2 emissions and intensity (D3)*

The indicators in *D3* benchmark airlines based on the ﬂow of CO2 emissions from aircraft to the atmosphere. The magnitude of CO2 emissions is based on the direct combustion of jet kerosene by the aircraft (Scope 1). Indirect CO2 emissions due to the usage of elec- tricity on the ground (Scope 2) and those from subsidiary services (Scope 3), such as food catering, are not included. However, a switch to less CO2 intensive sources, especially while taxiing at the airport, can have an impact on reducing the Scope 1 emissions of aircraft. In Equation [(12)](#_bookmark22), the CO2 emissions at Scope 1 that is made speciﬁc to *RPK* is divided by *RPK* to obtain the CO2 intensity, *CIRPK*.

cargo in the freight compartment of aircraft (see supplementary material). In contrast, passenger speciﬁc fuel usage is deﬁned as

the ratio of total passenger equivalent weight to total revenue

*CIRPK*

¼ *C*

*RPK*

2

× 103 . *RPK* × 106

weight multiplied by the total amount of fuel usage ([IATA, 2014b](#_bookmark87)).

# × 10

ftonnes of CO2 per 100 RPKg (12)

Equation [(7)](#_bookmark23) is used to obtain fuel efﬁciency *ERPK* per 100 *RPK* based on fuel usage that is made speciﬁc to *RPK*, namely *FRPK*.

In addition, a metric based on the use of *TKP* can provide a uniform means of comparing CO2 intensity across airlines with

# *ERPK* ¼ *FRPK* × 103 . *RPK* × 106 × 102 fthousand liters per 100 RPKg (7)

Technical issues are not the only factors that determine fuel efﬁciency. Operational measures can also improve efﬁciency, including those that seek to optimize the utilization of the seat capacity and/or integrate ﬂexibility to better balance seasonal variances in passenger loads with those in cargo loads. Equation [(8)](#_bookmark24) formulates fuel efﬁciency to capture another comparison such that the total fuel consumption *Ft* is divided by the total tonne-kilometer performed (*TKP*) ([ATAG, 2013](#_bookmark62)).

*ETKP* ¼ *Ft* × 103 . *TKP* × 106

# × 10 fthousand liters per 100 TKPg (8)

2

differing passenger and cargo proﬁles. Equation [(13)](#_bookmark25) formulates the means of calculating another version of CO2 intensity based on a ratio with *TKP*, namely *CITKP*.

*CITKP* ¼ *Ct* × 103 . *TKP* × 106

# × 10 ftonnes of CO2 per 100 TKPg (13)

2

The CO2 emissions of the previous year are important to compare the magnitude of CO2 emissions regardless of annual changes in passenger and cargo loads. Moreover, Equation [(14)](#_bookmark26) provides the method of determining the annual percentage improvement in CO2 intensity based on the reporting scheme as adopted by the airline over the intensity of the previous year (*y* e

In Equation [(8)](#_bookmark24), *TKP* represents the total revenue load carried on each ﬂight stage of the total distance ([ATAG, 2013](#_bookmark62)). Accordingly, Equation [(9)](#_bookmark27) relates the sum of *RPK* and *RFTK* to *TKP* when an average passenger weight *wp* is used to convert the units to a common basis. Here, *wp* is taken to be 0.15 tonne based on a rec- ommended passenger equivalent freight mass ([IATA, 2014b;](#_bookmark87)

*CI* —

*1*).

D*CI* ¼

ð*y*—1Þ

*CIy* .*CI*

ð*y*—1Þ f

# dimensionlessg

(14)

[Chandra et al., 2014](#_bookmark87)).

*TKP* ¼ *wp* × *RPK* þ *RFTK* fmillion tonne kilometersg (9)

Other indicators in *D2* of the SAI include the share of the total cost of fuel consumption in total operating expenses, *Xs* that pro- vides an energy economy perspective. Equation [(10)](#_bookmark20) gives the ratio of the total fuel expenses, *Xf* to total operating expenses, *Xt*. The ratio eliminates any differences in monetary units due to the use of

* + 1. *Sustainable aviation measures (D4)*

The indicators in *D4* provide an evaluation of sustainable avia- tion measures that are undertaken by airlines to improve aspects of aircraft metabolism. First, measures to conserve fuel and reduce CO2 emissions are evaluated based on two categories. Operational measures include systems for payload management, optimized ﬂight management, and ground operations and maintenance. Technology based measures include fuel efﬁcient aircraft technol- ogy, the use of composite materials, and the eco-design of more

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1075

lightweight onboard items. It further includes aerodynamic retroﬁt measures and alternative fuel mixtures. Both technology and operational measures are expected to contribute the most in real- izing a carbon wedge for 2020 ([IATA, 2013b](#_bookmark84)).

Another indicator in *D4* accounts for the average age of the airline ﬂeet. The renewal of the airline ﬂeet can be a sustainable aviation measure given a proper recycling of materials. Here, a relatively younger ﬂeet can represent beneﬁts in improved envi- ronmental performance based on the emission factors of aircraft models ([ICAO, 2011](#_bookmark89)). In the aspect of other ﬂows, such as NOx emissions, waste, and water, there is not a uniﬁed boundary in the reporting schemes of airlines. Hence, a qualitative survey is un- dertaken on the scope of environmental reporting based on water management, NOx emissions, HC, and hazardous and non- hazardous waste generation.

The last indicator in *D4* accounts for the number of employed

personnel, including the pilot and crew attendants. On a socio- economic basis, this indicator represents the number of jobs that the airline provides to sustain its operations. Airline personnel also have a vital role in realizing sustainable aviation measures to decouple increases in air trafﬁc from environmental pressure. These range from energy saving ﬂight procedures to onboard waste recycling.

1. Application of the SAI index

The application of SAI to the 16 airlines in the sample involved an extensive process of data collection. The data sources for most of the indicators are based on the CSR reports of the respective airlines (see [Table 1](#_bookmark11)). Data on operational aspects, including economic and ﬂeet related data, are collected from the annual reports of the air- lines for the same reporting year. In some cases, airlines reported in different units so that conversion factors for jet fuel ([United](#_bookmark140) [Nations, 2016](#_bookmark140)) were used to obtain common units. In these ways, the process of data collection resulted in a harmonized data set based on the indicators of the SAI. Data collection for dimensions *D1* to *D4* as an implementation of this stage of the method is sum- marized in the sections below. The data sets of the original compilation for airlines are given in [Tables A1](#_bookmark50)e[A6 of the Appendix](#_bookmark50).

* 1. *Results of data collection for D1*

The data inputs to the 5 indicators in *D1* are used to compare aspects of airline services and quality in the 16 airlines ([Table A1](#_bookmark50)). The average airline in the sample transported passengers a distance of 131,937 million passenger kilometres and cargo a distance of 4539 million tonne kilometres to gain operating revenue. The passenger load factor in the average airline was about 80%, which means that 20% of the available seats were not ﬁlled with passen- gers on an annual basis. The average combined quality score was 68 based on Equation [(6)](#_bookmark19), which corresponds to a rank of 34 consid- ering the average star category of 4 out of a maximum of 5. The change in operating revenue for the average airline in the sample was 4.2%. An average airline increased its revenue based on the sales of ﬂight tickets and the transport of cargo over the previous year.

* 1. *Results of data collection for D2*

The data inputs for *D2* enabled a comparison of airlines based on fuel usage and efﬁciency using Equations [(7)](#_bookmark23)e[(11)](#_bookmark23) ([Table A2](#_bookmark50)). The average airline in the sample consumed 6,347,599 thousand liters of jet fuel in the process of transporting passengers and cargo to designated destinations. The average airline spent 3.92 L of jet fuel to transport one passenger and 26.13 L to transport one tonne of

load per distances of 100 km. In order to perform these revenue loads, the average airline spent 31.5% of its operating expenses to purchase jet fuel. In this context, airlines have an interest to improve fuel efﬁciency according to which an average airline was able to improve metrics of fuel efﬁciency by 0.9% over the previous reporting year.

* 1. *Results of data collection for D3*

The data inputs into *D3* provide the basis to compare the airline sample based on CO2 emissions and intensity using Equations [(12)](#_bookmark22)e[(14)](#_bookmark22) ([Table A3](#_bookmark50)). Accordingly, the average airline in the sample emitted 15,760,321 metric tonnes of CO2 emissions from the direct combustion of jet fuel (Scope 1). Per distances of 100 km, the average airline emitted 9.8 kg of CO2 into the atmosphere to transport one passenger and 65.5 kg of CO2 to transport one tonne of load. In the previous reporting year, the average airline emitted 14,935,834 metric tonnes of CO2 due to lower volume of air trafﬁc in transporting passengers and cargo. In contrast, there is a need to decouple increases in passenger and cargo air trafﬁc from increases in CO2 emissions. The average airline reported an improvement of 1.1% less CO2 intensity over the previous year.

* 1. *Results of data collection for D4*

The sustainable aviation measures of the different airlines are compared based on the data inputs for *D4* ([Table A4](#_bookmark50)). Based on [Table A4](#_bookmark50), the average airline received a score of 11.3 and 10.6 for the scoring of operational and technology oriented measures to save fuel and CO2 emissions (see Section [3.4.1](#_bookmark29)). The aircraft ﬂeet had an average age of 10 years. The scope of environmental reporting received an average score of 1.6 (see Section [3.4.2](#_bookmark30)). On the aspect of employment, the average airline has a workforce of 45,002 em- ployees, including ﬂight crew, engineers, and ground handling personnel who make operational and sustainable aviation mea- sures possible.

* + 1. *Fuel and CO2 saving measures*

Within the SAI, more sustainable airlines have a balanced mix of both operational and technology oriented measures to reduce jet fuel usage and CO2 emissions. The results of the scores for the 20 measures under these two categories are given in [Tables A5 and A6](#_bookmark50) [of the Appendix](#_bookmark50). Measures that are reported to have more than a 10% contribution in the total annual fuel and/or CO2 savings are distinguished by binary scoring. Some airlines also collaborate in projects for route optimization, including demonstration ﬂights under the Asia and Paciﬁc Initiative to Reduce Emissions (ASPIRE) ([ASPIRE, 2015](#_bookmark61)) and the initiative for Single European Sky Air Trafﬁc Management Research (SESAR) ([SESAR, 2016](#_bookmark130)). Increasingly, energy and CO2 emission saving measures are integrated into standard operating procedures (SOPs) ([FAA, 2003](#_bookmark75)). Airlines that are engaged in the Sustainable Aviation Fuel Users Group ([SAFUG, 2014](#_bookmark121)) also undertake periodic ﬂights with jet kerosene and biofuel mixtures and/or plan a biofuels facility near the home airport.

* + 1. *Environmental reporting of airlines*

Other than CO2 emissions, the average airline reports mostly on NOx emissions at low altitude (<3000 ft) while water consumption is reported mostly for ofﬁce buildings at the home airport and maintenance centers. Only a few airlines report on the total water consumption, including potable water uploaded to the aircraft, and water recycling. Similarly, some airlines report on the waste for the airline ﬂeet while others report on the waste that is generated at the main airport hub. The average score that is included in [Table A4](#_bookmark50) is based on the scoring of sub-categories for the available options

1076 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

on the reporting of pollutant emissions, water, and waste (see [Table A7](#_bookmark50)).

* 1. *Evaluation of the need for data processing*

Tests of normality based on higher-order moments indicate that the data does not require further data processing based on trans- formation. In particular, for all indicators, values of skewness and kurtosis were below statistical thresholds based on absolute values of 2 and 3.5 ([Saisana, 2012](#_bookmark122)), respectively. Values of skewness ranged from —1.1 to 1.2 with an average of —0.1 and kurtosis ranged from —1.4 to 0.8 with an average of —0.2. In contrast, three values in *i*1.4, *i*1.5, and *i*4.5 for airlines *A2*, *A15*, and *A11* had values over 2 times the standard deviation. These outliers were substituted with the next highest or lowest value according to the direction of the in- dicator based on the winsorization method ([Saisana, 2012](#_bookmark122)). Any positive or negative correlations between the indicators in the data set were allowed up to an absolute value of *r* < 0.92 ([Saisana, 2012](#_bookmark122)).

1. Results and discussion

The data that is collected for the SAI provides insight on the relative positioning of the airlines in the sample. According to the method, these values are subjugated to EFA (Section [4.1](#_bookmark31)) and normalization (Section [4.2](#_bookmark32)). The normalized values are used to identify best practices based on the performance of the airlines per dimension. The overall value of the SAI is compared based on the analysis of alternative schemes for weighting and aggregation (Section [4.3](#_bookmark43)), including the simulated mean values of the 10,000 Monte Carlo experiments. The analyses are discussed within the perspective of aircraft metabolism for sustainable aviation (Section [4.4](#_bookmark49)).

* 1. *Results of the factor analysis*

[Table 3](#_bookmark33) provides the sub-structure of the SAI based on the application of EFA with principal factor analysis as the extraction method ([Xlstat, 2015](#_bookmark144)). Accordingly, eigenvalues l are at most 2.336 while the principal factors may explain about 50% and at most 80% of the cumulative variance after varimax rotation. In addition, the factor patterns are interpreted based on the indicators for which the squared cosine is the largest. In this respect, the value-addition of the indicators in representing various aspects of sustainable airlines are grouped into sub-domains as indicated in [Table 3](#_bookmark33). For

example, the ﬁrst sub-domain in *D3* is based on indicators that measure various aspects of CO2 intensity, namely per 100 RPK (*i*3.2), per 100 TKP (*i*3.3), and annual improvement (*i*3.5). The second sub- domain is based on aspects of CO2 emissions, namely the total magnitude of annual CO2 emissions regardless of changes in either passenger and/or cargo loads (*i*3.1 and *i*3.4), which further comply with the aims of *D3*.

* 1. *Data normalization and dimension results*

The data entries in [Tables A1](#_bookmark50)e[A4](#_bookmark50) are normalized based on Equation [(1) or (2)](#_bookmark8) according to the desired direction of change in the indicators. The normalized values are then subjugated to the respective weighting schemes at the indicator level, including EFA derived weights as given in [Table 3](#_bookmark33). Accordingly, [Table 4](#_bookmark40) provides the results for the airlines in the sample per each dimension of the SAI index. Here, the top 4 airlines in each dimension are also marked. Among these airlines, three of the marked airlines in di- mensions *D1* to *D3* and two airlines in *D4* are the same under the indicator level weighting schemes for both EW and EFA with linear aggregation. Best practices may be identiﬁed from these results as discussed herein.

* + 1. *Best practices of airlines in D1*

The top 2 airlines in *D1* are *A11* and *A7* in both schemes with the third airline as *A15* in EW and *A6* in EFA. These airlines combine high levels of performance in more than one indicator, including those in revenue loads. For example, the average *RPK* of these airlines are 201,970 million passenger-km, the average *RFTK* is 5053 million tonne-km, and the average *LFp* is 81.2, all of which are above the sample average. A combined airline quality score and change in operating revenue is also above average, which depends on greater passenger satisfaction and operational efﬁciency among the inter- relation of other factors. As a whole, these airlines outperform other airlines in *D1* of the SAI on the basis of both airline services and quality.

* + 1. *Best practices of airlines in D2*

The top performing airlines in *D2* are found to be *A1* and *A9* in both schemes with the third airline as *A3* in EW and *A12* in EFA. These airlines have higher fuel efﬁciency for undertaking longer transport loads with less fuel input. In particular, speciﬁc fuel spending per 100 RPK is 3.63 L and fuel spending per 100 TKP is

24.19 L, both of which are less than the sample averages. The

Table 3

Results of the exploratory factor analysis.[a](#_bookmark34)

*Dx* Sub-domain Signiﬁcant

Selection Criteria Values for Principal Factors [c](#_bookmark36) EFA Derived Weights [e](#_bookmark38)

Indicators [b](#_bookmark35)   [f](#_bookmark39)

Eigenvalue l Variance (%) [d](#_bookmark37)

Cum. Variance (%) [d](#_bookmark37)

Indicators Factors Dimension

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *D1* | Revenue loads | *i*1.1, *i*1.2, *i*1.3 | 1.875 | 37.506 | 37.506 | 0.24, 0.23, 0.16 | 0.63 | 0.24 |
|  | Service performance | *i*1.4, *i*1.5 | 1.142 | 22.844 | 60.350 | 0.24, 0.13 | 0.37 |  |
| *D2* | Fuel spending | *i*2.1, *i*2.2, *i*2.3 | 2.139 | 42.789 | 42.789 | 0.10, 0.34, 0.32 | 0.76 | 0.23 |
|  | Fuel economy | *i*2.4, *i*2.5 | 0.748 | 13.559 | 56.348 | 0.12, 0.12 | 0.24 |  |
| *D3* | CO2 intensity | *i*3.2, *i*3.3, *i*3.5 | 2.336 | 46.719 | 46.719 | 0.19, 0.31, 0.10 | 0.60 | 0.32 |
|  | CO2 emissions | *i*3.1, *i*3.4 | 1.643 | 32.866 | 79.585 | 0.30, 0.10 | 0.40 |  |
| *D4* | Aviation measures | *i*4.1, *i*4.2, *i*4.3, *i*4.4 | 1.477 | 30.535 | 30.535 | 0.10, 0.07, | 0.60 | 0.20 |
|  |  |  |  |  |  | 0.28, 0.15 |  |  |
|  | Employment | *i*4.5 | 0.988 | 19.758 | 50.293 | 0.40 | 0.40 |  |

a Extracted using Ref. ([Xlstat, 2015](#_bookmark144)) with principal factor analysis as the extraction method at the dimension level to increase cases to variable ratio.

b Indicates the indicators for which the squared cosine values are the largest in the factor patterns after the application of varimax rotation.

c Selected based on multiple criteria, including Kaiser and/or Jolliffe criteria ([Loewen et al., 2015](#_bookmark103)), individual variance, cumulative variance, and scree plot.

d Indicates the percentage of variance after the application of varimax rotation with Kaiser normalization and rotation converged in 50 rotations.

e Indicator weights are given in the order of the indicators in the third column and obtained based on the square of sums of the principal factor coefﬁcients scaled to unity.

f For comparability with equal weighting schemes, dimension weights may be multiplied by 4 so that the values are 0.98, 0.93, 1.29 and 0.80, respectively.

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1077

Table 4

Dimension results under weighting schemes with linear aggregation.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Aj* | *D1* |  |  | *D2* |  |  | *D3* |  |  | *D4* |  |  |
|  | EW [a](#_bookmark41) | EFA [b](#_bookmark42) |  | EW [a](#_bookmark41) | EFA [b](#_bookmark42) |  | EW [a](#_bookmark41) | EFA [b](#_bookmark42) |  | EW [a](#_bookmark41) | EFA [b](#_bookmark42) |
| *A1* | 0.45 | 0.45 |  | 0.75 (1) | 0.85 (1) |  | 0.81 (1) | 0.86 (1) |  | 0.38 | 0.31 |  |
| *A2* | 0.31 | 0.31 |  | 0.52 | 0.66 |  | 0.55 | 0.60 |  | 0.47 | 0.60 (4) |  |
| *A3* | 0.51 | 0.52 |  | 0.68 (3) | 0.72 (4) |  | 0.55 | 0.56 |  | 0.74 (1) | 0.64 (2) |  |
| *A4* | 0.48 | 0.46 |  | 0.51 | 0.42 |  | 0.62 (4) | 0.55 |  | 0.66 (4) | 0.54 |  |
| *A5* | 0.55 | 0.56 |  | 0.25 | 0.21 |  | 0.26 | 0.26 |  | 0.42 | 0.39 |  |
| *A6* | 0.58 (4) | 0.58 (3) |  | 0.23 | 0.31 |  | 0.32 | 0.39 |  | 0.64 | 0.62 (3) |  |
| *A7* | 0.66 (2) | 0.63 (2) |  | 0.20 | 0.17 |  | 0.24 | 0.23 |  | 0.40 | 0.56 |  |
| *A8* | 0.29 | 0.30 |  | 0.34 | 0.19 |  | 0.34 | 0.35 |  | 0.57 | 0.51 |  |
| *A9* | 0.50 | 0.51 |  | 0.72 (2) | 0.75 (2) |  | 0.61 | 0.62 (4) |  | 0.68 (3) | 0.52 |  |
| *A10* | 0.50 | 0.52 |  | 0.46 | 0.51 |  | 0.49 | 0.52 |  | 0.61 | 0.49 |  |
| *A11* | 0.67 (1) | 0.73 (1) |  | 0.68 (4) | 0.64 |  | 0.43 | 0.37 |  | 0.71 (2) | 0.72 (1) |  |
| *A12* | 0.40 | 0.42 |  | 0.64 | 0.73 (3) |  | 0.54 | 0.61 |  | 0.43 | 0.45 |  |
| *A13* | 0.07 | 0.05 |  | 0.59 | 0.54 |  | 0.72 (2) | 0.68 (2) |  | 0.46 | 0.34 |  |
| *A14* | 0.52 | 0.56 (4) |  | 0.39 | 0.45 |  | 0.51 | 0.53 |  | 0.48 | 0.45 |  |
| *A15* | 0.58 (3) | 0.55 |  | 0.62 | 0.67 |  | 0.68 (3) | 0.66 (3) |  | 0.52 | 0.44 |  |
| *A16* | 0.54 | 0.53 |  | 0.47 | 0.58 |  | 0.21 | 0.24 |  | 0.51 | 0.59 |  |
| *AV* | 0.48 | 0.48 |  | 0.50 | 0.53 |  | 0.49 | 0.50 |  | 0.54 | 0.51 |  |

a The dimension results correspond to weighting scheme A.

b The results correspond to weighting scheme B and C (prior to the application of dimension weights).

airlines further optimize the share of fuel costs in total operating expenses and showcase an improvement in fuel efﬁciency from the previous year. For example, airlines *A1*, *A9*, and *A3* have an average improvement in fuel efﬁciency above the IATA target at 1.8%.

* + 1. *Best practices of airlines in D3*

The monitoring of trends under *D3* may aid airlines in assessing the level of progress towards the second and third IATA targets, including the capping of aviation CO2 emissions from 2020 on- wards. The top airlines in *D3* are *A1*, *A13*, and *A15* in both schemes, respectively. These airlines are able to handle more revenue loads than an average airline in the sample with lower CO2 emissions per transport distance. For example, the top 3 airlines in *D3* have average Scope 1 CO2 emissions of 7,699,618 metric tonnes, speciﬁc CO2 intensity at 9.18 kg per 100 RPK, and CO2 intensity of 61.18 kg per 100 TKP. An average improvement in CO2 intensity at 1.93% enable less CO2 to be emitted per revenue load and transport dis- tance despite increases in CO2 emissions over the previous year at 6,578,314 metric tonnes.

* + 1. *Best practices of airlines in D4*

The top 3 airlines in *D4* are *A3* and *A11* in both schemes and *A9* in EW and *A6* in EFA. These airlines implement a mix of operational and technological measures, including the optimization of routes and LTO cycles as well as engine upgrades. The measures that are indicated to have the most signiﬁcant impact on fuel and CO2 emission savings involve aspects of managing aircraft weight and center of gravity, the eco-design of onboard items, and aviation biofuels. In addition, the airlines apply comprehensive environ- mental management schemes that range across various pollutants (e.g. NOx, SOx, HC/CFC-11), water usage, water recycling, water pollutants, such as glycol, and stringent waste management. The age of the airline ﬂeet is equal to the sample average at 10 years for *A3* and *A9* while the average employed airline personnel for the top airlines is 70,568, most of which are above the average values.

* 1. *Sensitivity of SAI results to alternative schemes*

[Table 5](#_bookmark44) compares the results of the SAI values when the six alternative weighting and aggregation schemes are applied to the normalized values of the indicators. The average value of SAI in the ﬁrst three schemes is 2.02 while those of the last three schemes are 1.80, 2.01, and 1.79, respectively. [Table 5](#_bookmark44) also provides the net

changes in rank positions (D) across all weighting and aggregation schemes. Accordingly, the average change in rank is found to be 2.3 positions. Among the airlines, *A14* retains the rank position of 9 in all six schemes. In contrast, airlines that are most susceptible to changes under the alternative schemes are *A1* and *A4* that have either exceptional and/or relatively lower levels of performance in indicators *i1.1*, *i3.2*, *i3.3*, *i4.1*, and *i4.5*, as well as four indicators in *D2*.

[Table 5](#_bookmark44) further indicates the schemes in which airlines obtain their top and lowest rank positions. For example, *A9* and *A11* that had obtained top 4 ranks in the most number of dimensions in [Table 4](#_bookmark40) also obtain rank options in the top 4 of the sample in various schemes based on overall SAI values. At the same time, airline *A11* is outperformed by *A3* in the given schemes with geometric aggre- gation while the reverse is true in schemes A and B with linear aggregation. In contrast, airlines that do not obtain top 4 ranks in any of the dimensions in [Table 4](#_bookmark40), such as *A5*, *A8* and *A16*, directly receive relatively lower rank options in [Table 5](#_bookmark44).

In some cases, the top and lowest rank options repeat across multiple schemes as indicated in the markings in [Table 5](#_bookmark44). In the case of 10 airlines, the top or lowest ranks that are obtained in geometrically aggregated schemes correspond to those in at least one linearly aggregated scheme, i.e. *A2*, *A4*, *A7*, *A8*, *A10*, *A11*, *A12*, *A13*, *A14*, and *A15*. Here, changes in rank are largely due to trade-offs between indicators in which airlines may have lower or higher performance. Values of geometrically aggregated ( ) SAI values also exhibit changes under the different schemes as indicated in [Table 5](#_bookmark44) while rank positions retain relatively stable outcomes. These results may be attributed to limited trade-off possibilities and less compensability between indicators that minimize the volatility of rank positions to changes in different schemes.

Q

The results of the 10,000 Monte Carlo experiments are further

used to analyse the presence of airlines in a particular rank position relative to other airlines in the sample. [Fig. 2](#_bookmark48) provides the results of these experiments for the 16 airlines in the sample when ordered according to the simulated mean values of the SAI. The plus signs ( ) in the box plot of [Fig. 2](#_bookmark48) represent these values as SAI (*Aj*) bar while the boxes represent the interquartile range with a 95% con- ﬁdence interval for the values of a given airline, *Aj*. The rank posi- tions of the airlines based on simulated mean values are precisely at or within the top and lowest rankings in the six weighting and aggregation schemes in [Table 5](#_bookmark44) so that the ranks are within expectations.

þ

In addition, the shadings in the chart area of [Fig. 2](#_bookmark48) indicate the

1078 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

Table 5

Comparison of SAI results and rank positions under six schemes.

Aj Weighting and Aggregation Schemes Rank Position Evaluations [c](#_bookmark47)

A B C

P Q P Q P Q P Q P Q

SAI [a](#_bookmark45) SAI [b](#_bookmark46) SAI [a](#_bookmark45) SAI [b](#_bookmark46) SAI [a](#_bookmark45) SAI [b](#_bookmark46) Top Rank Lowest Rank D Rank A1 2.39 2.54 2.49 2.25 2.60 2.25 1 (B, C) ✓ 5 (A) ✓ 4

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A2 | 1.86 | 1.73 | 2.17 | 1.53 | 2.17 | 1.53 | 7 (B, C) | * 10 (AeC) | ✓ ✓ | 3 |
| A3 | 2.48 | 2.74 | 2.44 | 2.43 | 2.41 | 2.43 | 1 (AeC) | * 3 (A,B) | ✓ | 2 |
| A4 | 2.26 | 2.27 | 1.97 | 2.01 | 1.98 | 2.01 | 6 (AeC) | ✓ ✓ 10 (B, C) | ✓ | 4 |
| A5 | 1.49 | 1.60 | 1.42 | 1.42 | 1.39 | 1.41 | 13 (AeC) | * 16 (A) | ✓ | 3 |
| A6 | 1.77 | 1.56 | 1.90 | 1.38 | 1.85 | 1.38 | 11 (C) | * 14 (AeC) | ✓ | 3 |
| A7 | 1.50 | 1.48 | 1.60 | 1.31 | 1.53 | 1.31 | 14 (B, C) | * 15 (AeC) | ✓ ✓ | 1 |
| A8 | 1.54 | 1.29 | 1.34 | 1.15 | 1.33 | 1.15 | 14 (A) | * 16 (AeC) | ✓ ✓ | 2 |
| A9 | 2.50 | 2.69 | 2.39 | 2.39 | 2.40 | 2.39 | 1 (A) | * 4 (B) | ✓ | 3 |
| A10 | 2.07 | 2.22 | 2.03 | 1.97 | 2.03 | 1.97 | 7 (AeC) | ✓ ✓ 8 (B, C) | ✓ | 1 |
| A11 | 2.49 | 2.41 | 2.46 | 2.14 | 2.36 | 2.13 | 2 (A, B) | * 5 (AeC) | ✓ ✓ | 3 |
| A12 | 2.02 | 2.02 | 2.21 | 1.79 | 2.24 | 1.79 | 6 (B, C) | * 8 (AeC) | ✓ ✓ | 2 |
| A13 | 1.84 | 1.70 | 1.61 | 1.51 | 1.70 | 1.50 | 11 (AeC) | ✓ ✓ 13 (B, C) | ✓ | 2 |
| A14 | 1.90 | 2.01 | 2.00 | 1.78 | 2.02 | 1.78 | 9 (AeC) | ✓ ✓ 9 (AeC) | ✓ ✓ | 0 |
| A15 | 2.40 | 2.49 | 2.32 | 2.21 | 2.37 | 2.20 | 4 (AeC) | ✓ ✓ 5 (B) | ✓ | 1 |
| A16 | 1.73 | 1.64 | 1.94 | 1.46 | 1.83 | 1.45 | 11 (B) | * 13 (A) | ✓ | 2 |
| AV | 2.02 | 2.02 | 2.02 | 1.80 | 2.01 | 1.79 | 8 (A, B) | ✓ ✓ 10 (C) | ✓ | 2.3 |

a The maximum possible value of a linearly aggregated SAI value is 4 with an average value of about 2.0.

b Geometrically aggregated SAI schemes are multiplied by *n* that scales the values to a similar average over 4. Any zero values are eliminated.

c The checkmarks indicate the related aggregation for the top or lowest rank in at least one of the weighting schemes (in parenthesis).

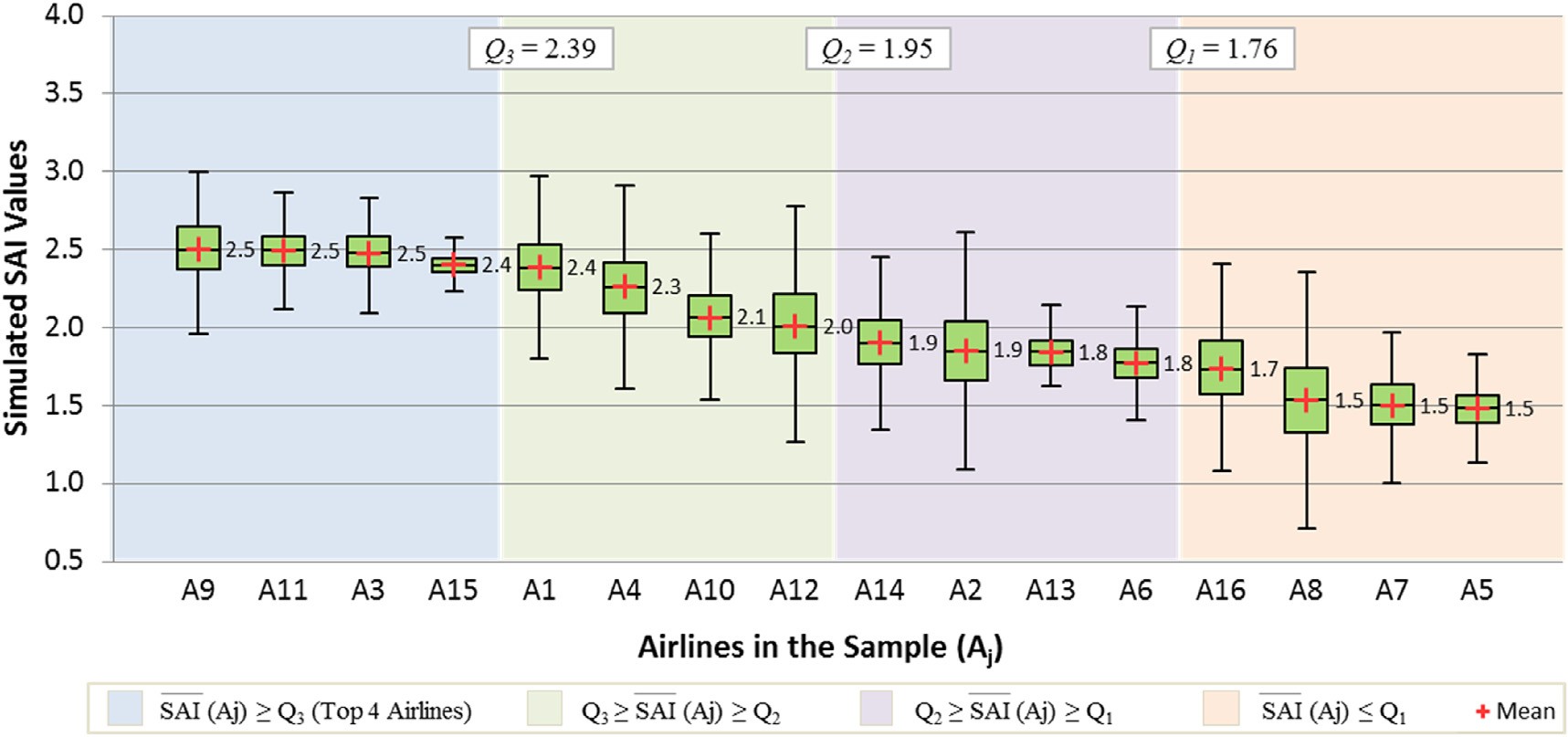


Fig. 2. Results of the Monte Carlo Experiments for the Airlines in the Sample. a Based on 10,000 iterations with random weights that are subjugated to the unity sum property.

airlines that are above certain quartile values, namely, simulated mean SAI values of 2.39 (*Q3*), 1.95 (*Q2*), and 1.76 (*Q1*). Accordingly, the top 25% of the SAI values belong to airlines *A9* (rank 1), *A11* (rank 2), *A3* (rank 3), and *A15* (rank 4). The mean SAI values of these air- lines are 2.50, 2.49, 2.48, and 2.40, respectively. Any changes in rank when compared to [Table 5](#_bookmark44) take place among airlines that are in the same quartiles. One of the limited exceptions is *A1* (rank 5) based on a simulated mean SAI value of 2.38 that remains slightly below the threshold of *Q3* while the airline may rank better in other simula- tions, including in schemes B and C with linear aggregation.

The rankings in [Fig. 2](#_bookmark48) proceed with *A4* (rank 6), *A10* (rank 7), and *A12* (rank 8) that have the next best outcomes. For example, *A4* had favourable performance in dimensions *D3* and *D4* according to [Table 4](#_bookmark40). In total, 8 airlines are within the blue and green shaded areas in [Fig. 2](#_bookmark48) based on simulated mean SAI values above *Q2*. In these ways, the results in [Fig. 2](#_bookmark48) can be used to also identify airlines that perform either above or below certain quartiles. Airlines in the latter context may be attributed with a greater need to make

improvements in multiple indicators of the SAI. At the same time, all airlines may use the results of the SAI to make further progress in transitioning towards more sustainable practices on the airside of aviation.

* 1. *Perspectives on improving aircraft metabolism*

The use of the SAI index as a benchmarking metric puts forth the need to attain more optimized levels of performance across mul- tiple indicators based on a comprehensive set of sustainable avia- tion measures. The top airlines based on the SAI have relatively high levels of performance across multiple aspects, including those in resource ﬂows and environmental reporting. Consistently well- rounded levels of performance are prioritized in the SAI since these domains explain underlying factors of the composite indi- cator. The IATA targets also require airlines to ﬁnd solutions to satisfy revenue loads with lower impacts on fuel usage and CO2 emissions.

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1079

In contrast, the 8 airlines that are below *Q2* have more mixed levels of performances. For example, some have relatively high revenue loads but inconsistent performances in the other in- dicators (e.g. *A6* and *A16*). Others have relatively lower fuel efﬁ- ciency due to lower load factors and/or an intentional choice to have less dense seat conﬁgurations in long-haul ﬂights for pas- senger comfort (e.g. *A8*). Others involve high performance in pas- senger satisfaction and change in operating revenue but lower performance in fuel efﬁciency and CO2 intensity (e.g. *A7*). The SAI can be used to guide airlines towards obtaining better perfor- mances in multiple aspects simultaneously without compromises in aviation services and resource efﬁciency.

1. Conclusion

The ability to decouple operational success from environmental impact in the aviation sector requires greater efﬁciency in aircraft metabolism so that airline ﬂeets can transport more revenue loads with less resource spending and emissions. This paper developed and applied a composite indicator to benchmark aspects of meta- bolism in the aircraft ﬂeet of airlines. The composite indicator, namely the SAI, addressed a gap in the literature for comparing the performance of airlines in an integrative approach that involves revenue loads, energy, CO2 emissions, and measures for sustainable aviation. The six weighting and aggregation schemes provided relatively stable outcomes with a net change of 2.3 rank positions. The Monte Carlo experiments were further used to put forth rankings based on simulated mean SAI values. The top performing airlines among a sample of 16 airlines are found to be *A9*, *A11*, *A3*, and *A15*.

The best practices of the top airlines in the sample can provide

guidance for more sustainable practices in the airline industry to- wards carbon neutral growth. In particular, decision-makers can use the results of the SAI to plan for a balanced approach to improve aircraft metabolism. Better performing airlines can also diffuse best practices to other airlines in related alliances. Increases in demand

growth in the sector can be increasingly managed with less resource usage based on a synergistic approach that spans energy, water, and environment systems. The nexus of resource ﬂows in airlines is further impacted by the weight of aircraft. For this reason, operational measures must be coupled with innovative technology while improving engine performance, enhancing aerodynamic ef- ﬁciency, optimizing ﬂight paths, and reducing airborne weight. The index has applicability to other airlines according to data availability.

In the future, the use of the SAI as a benchmarking tool can encourage airlines to strive for higher values by exceeding above average performances in multiple dimensions. The mobile, micro- communities of airlines can be one of the living laboratories to streamline resource ﬂows, including the use of water and materials. Aircraft can also have spill-over effects to improve the metabolism of stationary communities on the ground. After all, human in- habitants are all like crew members onboard a single planet called Spaceship Earth.

Acknowledgements

This paper is based on a manuscript that was presented at the 10th SDEWES Conference in Dubrovnik, Croatia between September 27 and October 2, 2015. The authors gratefully acknowledge the Evaluation Committee for providing further motivation for the research work based on a Best Poster Award and the anonymous reviewers for their valuable suggestions.

Appendix A. Supplementary data

Supplementary data related to this article can be found at [http://](http://dx.doi.org/10.1016/j.jclepro.2017.03.183) [dx.doi.org/10.1016/j.jclepro.2017.03.183](http://dx.doi.org/10.1016/j.jclepro.2017.03.183).

Appendix

Table A1

Data Inputs to Indicators in *D1*.[a](#_bookmark51)

0.38

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| International | Airline services and quality (*D1*) |  | | | | |
| Airline *Aj* | Revenue Passenger | Revenue Tonne | Passenger Load | World Airlines Award | Change in Operating |  |
|  | Kilometers e RPK (million passenger km) | Kilometers e RTFK (million tonne km) | Factor e *LFp* (%) | and Star Score e *Qa* | Revenue (%) |  |
| *A1* | 91,391 | 3499 | 82.80 | 48 | 1.94 |  |
| *A2 A3* | 141,968  127,815 | 5015  5294 | 80.81  83.80 | 255  50 | —1.30 |  |
| *A4*  *A5* | 58,413  131,333 | 2463  4646 | 75.30  81.30 | 6  34 | 10.53  5.49 |  |
| *A6* | 313,803 | 6289 | 83.80 | 147 | 3.01 |  |
| *A7* | 188,606 | 2155 | 79.70 | 8 | 13.2 |  |
| *A8* | 59,136 | 1879 | 71.00 | 46 | 5.69 |  |
| *A9* | 89,039 | 5890 | 85.80 | 64 | 0.38 |  |
| *A10 A11 A12 A13* | 68,834  213,475  110,905  33,451 | 8289  9395  2321  622 | 78.00  82.23  79.27  75.00 | 52  20  30  156 | 3.87  —0.36  —0.56 |  |
| *A14*  *A15 A16* | 93,766  91,997  297,053 | 6764  2371  5731 | 78.96  79.00  83.80 | 3  10  159 | 0.97  19.33  3.03 |  |
| *Average* | 131,937 | 4539 | 80.04 | 68 | 4.17 |  |

1.13

a Data is converted from revenue passenger miles and/or summed for domestic and international ﬂights, e.g. *A4*.

1080 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

Table A2

Data Inputs to Indicators in *D2*.[a](#_bookmark52)

International Fuel Consumption and Efﬁciency (*D2*)

1.0

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Airline *Aj* | Total Fuel  Consumption (1000 L) | Speciﬁc Fuel  Spending per 100 RPK (liters) | Fuel Spending per 100 TKP (liters) | Fuel Cost in  Operating Expenses (%) | Improvement in Fuel Efﬁciency (%) |  |
| *A1* | 3,992,617 | 3.48 | 23.20 | 29.84 | 1.5 |  |
| *A2* | 6,294,046 | 3.63 | 23.92 | 35.85 | 0.1 |  |
| *A3* | 6,071,605 | 3.72 | 24.82 | 26.40 | 1.9 |  |
| *A4* | 3,131,491 | 4.18 | 27.90 | 22.21 | 0.3 |  |
| *A5* | 6,998,115 | 4.31 | 28.74 | 34.87 | 0.2 |  |
| *A6 A7 A8* | 14,477,609  8,796,563  3,213,796 | 4.07  4.33  4.48 | 27.13  28.89  29.90 | 33.35  39.15  24.80 | —0.9  —1.1 |  |
| *A9*  *A10 A11* | 4,737,037  4,843,336  10,820,709 | 3.69  3.90  3.92 | 24.61  26.02  26.13 | 26.40  36.54  22.49 | 1.9  1.0  3.8 |  |
| *A12 A13* | 4,571,605  1,495,062 | 3.62  3.98 | 24.12  26.51 | 27.32  35.56 | —1.8 |  |
| *A14*  *A15* | 5,454,892  4,025,152 | 3.93  3.73 | 26.19  24.89 | 39.04  37.17 | 0.6  0.9 |  |
| *A16* | 12,637,942 | 3.77 | 25.13 | 33.34 | 1.6 |  |
| *Average* | 6,347,599 | 3.92 | 26.13 | 31.52 | 0.9 |  |

2.7

a Data is converted to common units as needed, e.g. from coal equivalents (*A2*), tonnes, or gallons (*A14* and *A16*).

Table A3

Data Inputs to Indicators in *D3*.

0.8

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| International | CO2 Emissions and Intensity (*D3*) |  | | | | |
| Airline *Aj* | Scope 1 CO2 Emissions (metric tonnes) | Speciﬁc CO2 Intensity per 100 RPK (kg) | CO2 Intensity per 100 TKP (kg) | Previous Scope 1 CO2 Emissions (metric tonnes) | Improvement in CO2 Intensity (%) |  |
| *A1* | 9,013,680 | 7.86 | 52.38 | 9,123,918 | 1.5 |  |
| *A2* | 15,750,390 | 9.09 | 59.86 | 9,875,271 | 0.1 |  |
| *A3* | 15,491,000 | 9.50 | 63.32 | 15,997,000 | 1.9 |  |
| *A4* | 7,990,000 | 10.68 | 71.18 | 7,990,000 | 3.6 |  |
| *A5* | 18,087,654 | 11.14 | 74.29 | 17,634,509 | 0.5 |  |
| *A6 A7 A8* | 31,159,188  22,444,429  8,200,000 | 8.76  11.06  11.44 | 58.40  73.72  76.28 | 30,359,915  19,358,116  7,870,000 | —0.9  —1.1 |  |
| *A9*  *A10 A11* | 12,085,000  12,361,107  27,609,039 | 9.42  9.96  9.84 | 62.79  66.41  66.66 | 12,213,000  12,624,981  27,968,627 | 1.9  1.0  3.8 |  |
| *A12 A13* | 11,520,444  3,815,000 | 9.12  10.15 | 60.77  67.65 | 12,422,703  3,752,000 | —1.7 |  |
| *A14*  *A15* | 13,517,430  10,270,174 | 9.73  9.53 | 64.90  63.51 | 13,292,760  6,859,024 | 1.1  0.9 |  |
| *A16* | 32,850,593 | 9.80 | 65.32 | 31,631,516 | 0.5 |  |
| *Average* | 15,760,321 | 9.82 | 65.47 | 14,935,834 | 1.1 |  |

3.4

Table A4

Data Inputs to Indicators in *D4*.[a](#_bookmark53)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| International | Sustainable Aviation Measures | (*D4*) |  | | | |
| Airline *Aj* | Fuel/CO2 Saving Operational Measures | Fuel/CO2 Saving Technology Measures | Average Age of Aircraft Fleet (Years) | Scope of Environmental Reporting | Total Employed Airline Personnel |  |
| *A1* | 11 | 10 | 12.6 | 1.7 | 26,826 |  |
| *A2* | 11 | 9 | 6.3 | 1.0 | 59,328 |  |
| *A3* | 12 | 12 | 10.0 | 1.7 | 53,423 |  |
| *A4* | 12 | 11 | 9.9 | 2.0 | 32,731 |  |
| *A5* | 10 | 11 | 12.8 | 2.0 | 38,592 |  |
| *A6* | 12 | 10 | 16.9 | 2.3 | 80,000 |  |
| *A7* | 10 | 9 | 6.4 | 1.7 | 52,516 |  |
| *A8* | 12 | 10 | 8.5 | 1.3 | 33,285 |  |
| *A9* | 12 | 12 | 10.0 | 1.7 | 30,635 |  |
| *A10* | 11 | 11 | 9.3 | 2.7 | 20,433 |  |
| *A11* | 12 | 12 | 11.2 | 1.3 | 118,214 |  |
| *A12* | 11 | 9 | 7.7 | 1.3 | 30,845 |  |
| *A13* | 11 | 11 | 10.9 | 1.7 | 14,127 |  |
| *A14* | 11 | 10 | 6.7 | 1.3 | 23,189 |  |
| *A15* | 11 | 11 | 6.7 | 1.3 | 18,882 |  |
| *A16* | 11 | 11 | 13.5 | 0.7 | 87,000 |  |
| *Average* | 11.3 | 10.6 | 10.0 | 1.6 | 45,002 |  |

a The data inputs to the sub-indicators in the scoring of three indicators are provided in [Tables A5-A7](#_bookmark50).

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1081

Table A5

Fuel and CO2 saving operational measures.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Operational Measures | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 |
| Optimization of seating conﬁguration  Optimization of over-fuel amounts | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 |
| (<100 kg per aircraft)  Calibration of potable water carried | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| on board aircraft |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Management system for aircraft weight/center of gravity  Optimization of in-ﬂight cruising | 1  1 | 2  1 | 2  1 | 1  1 | 1  1 | 1  2 | 1  1 | 2  1 | 2  1 | 2  1 | 2  1 | 1  1 | 1  1 | 1  1 | 1  1 | 1  1 |
| speed and altitude  Promoting route optimization | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| (SESAR/ASPIRE extra)  Reduction of APU usage (>1e5 min | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| per ﬂight) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Electronic propulsion for taxiing/ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| towing on the ground  Thrust reversers at idle after | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| landing/single engine taxi  Engine compressor washing for | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| peak engine performance |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Table A6

Fuel and CO2 saving technology measures.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Technology Measures | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 |
| Engine replacement/upgrade to | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| increase fuel efﬁciency  New generation ﬂeet renewal to | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| increase fuel efﬁciency |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Hybrid, light-weight on-board | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| composite material carts |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Eco-design of on-board items (trays, | 1 |  | 2 | 1 | 1 | 1 |  | 1 | 2 | 1 | 1 |  | 1 |  | 1 |  |
| travel amenities) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Lightweight Unit Load Device (ULD) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| containers |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Retroﬁtting of existing aircraft with | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| winglets/sharklets |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Aviation biofuels in ﬂights and/or | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| biofuels fuels facility |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Replacement of paper-ﬁlled pilot ﬂight | 1 |  | 1 | 1 | 1 | 1 |  | 1 | 1 | 1 | 1 |  | 1 | 1 | 1 | 1 |
| bags with iPads |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Usage of ground (apron) ﬂeet with | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| alternative fuels |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Route optimization RNAV (ICAO target | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 100% by 2016) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

Table A7

Assessment of environmental reporting.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Measure | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 |
| Pollutant Emissions Score (1e3)[a](#_bookmark54) | 1 | 0 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 2 | 1 | 1 | 1 | 0 | 1 |

* CO2 (Scope 3 operations)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ✓ | ✓ | |  | ✓ | ✓ | ✓ |  | ✓ | ✓ |  | ✓ |  | ✓ |  | |
|  |  | | ✓ |  | ✓ |  | ✓ |  |  | ✓ |  |  |  |
|  |  | |  |  |  |  |  |  | ✓ | ✓ |  | ✓ |  |
|  | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |  |  |  |  | ✓ | |
|  | ✓ | |  |  | ✓ |  |  | ✓ | ✓ |  |  |  |  |  | |
|  | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |  | ✓ |  |  |  |  | |
| 1 | 1 | 1 | 1 | 2  ✓ | 1 | 1 | 1 | 1 | 3  ✓ | 1 | 2 | 2  ✓ | 1 | 1 | 0 |

* Other emissions (CO, PM)
* NOx (total ﬂight operations)
* NOx (low altitude < 3000 ft)
* SOx (low altitude < 3000 ft)
* HC/CFC-11 (LTO cycle) [a](#_bookmark54)

Water Reporting Score (1e3)

* Total water withdrawal

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| * Ground operations * Water recycling * Water pollutants (e.g. glycol) ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓  ✓  ✓ | ✓ | ✓  ✓ | ✓ | ✓ | ✓ |  |
| Waste Reporting Score (1e3)[a](#_bookmark54) 3 | 2 | 1 | 3 | 2 | 3 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 3 | 1 |
| * Non-hazardous waste ✓ |  | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |  | ✓ | ✓ | ✓ | ✓ |  |
| * Hazardous/toxic waste ✓ |  |  | ✓ | ✓ | ✓ |  |  |  |  |  |  | ✓ | ✓ | ✓ |  |
| * Waste management/recycling ✓ | ✓ |  | ✓ | ✓ | ✓ |  | ✓ |  | ✓ | ✓ | ✓ |  | ✓ | ✓ | ✓ |
| * Jettisons and spills (Class I, II) ✓ |  | ✓ | ✓ |  | ✓ | ✓ |  | ✓ |  |  |  | ✓ |  |  |  |
| * Wastewater treatment | ✓ |  | ✓ |  |  |  |  |  | ✓ |  |  |  |  | ✓ |  |
| * Disposal of retired aircraft | ✓ |  |  |  |  | ✓ |  |  |  |  |  |  |  |  |  |

a Near average marks receive a score of 2 with scores of 1 and 3 given for below and above average performances, respectively.

1082 *S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083*

References

[Air Canada, 2014. Citizens of the World: Corporate Sustainability Report 2013,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref1) [Dorval](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref1).

[Air Canada, 2014. Air Canada 2013 Annual Report, Dorval](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref2).

[Air China Limited, 2014. Corporate Social Responsibility Report 2013, Beijing](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref3). [Air China Limited, 2014. Air China 2013 Annual Report, Beijing](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref4).

[Air France](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref5) e [KLM, 2014. Corporate Social Responsibility Report 2013, Tremblay-en-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref5) [France](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref5).

[Air France](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref6) e [KLM, 2014. Annual Report 2013, Tremblay-en-France](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref6). [All Nippon Airways, 2012. ANA 2012-2013 Corporate Plan, Tokyo](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref7).

[All Nippon Airways, 2013. Flight Path to New Horizons: Annual Report 2012, Tokyo](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref8).

[Arjomandi, A., Seufert, J., 2014. An evaluation of the world's major airlines' technical](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref9) [and environmental performance. Econ. Model 41, 133](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref9)e[144](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref9).

[ASHRAE, 2009. Air Quality within Commercial Aircraft. ASHRAE Standard 161-2007,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref10) [Atlanta](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref10).

ASPIRE, 2015. Asia and Paciﬁc Initiative to Reduce Emissions. [http://www.aspire-](http://www.aspire-green.com/) [green.com/](http://www.aspire-green.com/).

ATAG, 2013. Reducing Emissions from Aviation through Carbon Neutral Growth from 2020. Air Transport Action Group. [http://atag.org](http://atag.org/).

[ATAG, 2016. Aviation Beneﬁts Beyond Borders. Air Transport Action Group, Geneva](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref13). [Athanasoglou, S., Weziak-Bialowolska, D., Saisana, M., 2014. Environmental Per-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref14) [formance Index 2014 JRC Analysis and Recommendations. European Commis-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref14)

[sion Publication EUR 26623 EN, Ispra](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref14).

[Azevedo, S., Govindan, K., Carvalho, H., Cruz-Machado, V., 2013. Ecosilient Index to](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref15) [assess the greenness and resilience of the upstream automotive supply chain.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref15)

[J. Clean. Prod. 56, 131](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref15)e[146](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref15).

[British Airways Plc, 2014. Annual Report and Accounts Year Ended 31 December](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref16) [2013, Harmondsworth](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref16).

[British Airways Plc, 2014. Responsible Flying for Everyone: Sustainability Report](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref17) [2013, Harmondsworth](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref17).

[Chandra, S., Chitgopeker, C., Crawford, B., Dwyer, J., Gao, Y., 2014. Establishing a](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref18) [benchmark of fuel efﬁciency for commercial airline operations. J. Aviat. Tech.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref18) [Eng. 4 (1), 32](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref18)e[39](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref18).

[China Civil Aviation, 2009. Performance-Based Navigation Implementation Road-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref19) [map. Beijing](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref19).

[Cremonez, P., Feroldi, M., Araújo, A., Borges, M., Meier, T., Feiden, A., Teleken, J.,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref20) [2015. Biofuels in Brazilian aviation: current scenario and prospects. Renew.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref20) [Sust. Energy Rev. 43, 1063](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref20)e[1072](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref20).

[Cui, Q., Li, Y., 2015. Evaluating energy efﬁciency for airlines: an application of VFB-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref21) [DEA. J. Air Transp. Manage 44](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref21)e[45, 34](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref21)e[41](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref21).

[Cui, Q., Wei, Y., Li, Y., 2016. Exploring the impacts of the EU ETS emission limits on](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref22) [airline performance via the Dynamic Environmental DEA approach. Appl. Energ](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref22) [183, 984](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref22)e[994](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref22).

[Delbari, S., Ng, S., Aziz, Y., Ho, J., 2016. An investigation of key competitiveness](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref23) [indicators and drivers of full service airlines using Delphi and AHP techniques.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref23)

[J. Air Transp. Manage 52, 23](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref23)e[34](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref23).

[Delta Air Lines Inc, 2014. Experience Makes for a Stronger Tailwind: 2013 Corporate](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref24) [Responsibility Report, Atlanta](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref24).

[Delta Air Lines Inc, 2014. Annual Report Pursuant to Section 13 for Fiscal Year 2013,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref25) [Atlanta](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref25).

[Dray, L., Evans, A., Reynolds, T., Sch](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref26)a€[fer, A., Vera-Morales, M., Bosbach, W., 2014.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref26)

[Airline](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref26) ﬂ[eet replacement funded by a carbon tax: an integrated assessment.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref26) [Transp. Pol. 34, 75](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref26)e[84](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref26).

EC, 2016a. Reducing Emissions from Aviation. [http://ec.europa.eu/clima/policies/](http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm) [transport/aviation/index\_en.htm](http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm).

EC, 2016b. Commission Welcomes Landmark International Agreement to Curb Aviation Emissions. [http://ec.europa.eu/clima/news/articles/news\_2016100701](http://ec.europa.eu/clima/news/articles/news_2016100701_en.htm)

[\_en.htm](http://ec.europa.eu/clima/news/articles/news_2016100701_en.htm).

[Emirates Group, 2014. Going Further: the Emirates Group Annual Report 2013-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref29) [2014, Dubai](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref29).

[FAA, 2003. Standard Operating Procedures for Flight Desk Crewmembers. Advisory](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref30) [Circular No. 120](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref30)e[71. U.S. Department of Transportation, Washington, D.C](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref30).

Ferna´ndez, J., 2016. Urban Metabolism. MIT Urban Metabolism Group. [http://www.](http://www.urbanmetabolism.org/)

[urbanmetabolism.org/](http://www.urbanmetabolism.org/).

[Filimonau, V., Dickinson, J., Robbins, D., 2014. The carbon impact of short-haul](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref32) [tourism: a case study of UK travel to southern France using life cycle analysis.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref32)

[J. Clean. Prod. 64, 628](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref32)e[638](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref32).

Forbes, 2015. World's Biggest Public Companies. [http://www.forbes.com/](http://www.forbes.com/global2000/) [global2000/](http://www.forbes.com/global2000/).

[Hagmann, C., Semeijn, J., Vellenga, D., 2015. Exploring the green image of airlines:](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref34) [passenger perceptions and airline choice. J. Air Transp. Manage 43, 37](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref34)e[45](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref34).

[Hair, J., Black, W., Babin, B., Anderson, R., 2010. Multivariate Data Analysis, seventh](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref35) [ed. Prentice Hall, Upper Saddle River](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref35).

[Hari, T., Yaakob, Z., Binitha, N., 2015. Aviation biofuel from renewable resources:](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref36) [routes, opportunities and challenges. Renew. Sust. Energy Rev. 42, 1234](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref36)e[1244](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref36).

[Higham, J., Cohen, S., Cavaliere, C., Reis, A., Finkler, W., 2016. Climate change, tourist](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref37) [air travel and radical emissions reduction. J. Clean. Prod. 111, 336](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref37)e[347](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref37).

[Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J.,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref38) [Masanet, E., 2016. Energy and emissions saving potential of additive](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref38) [manufacturing: the case of lightweight aircraft components. J. Clean. Prod. 135,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref38) [1559](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref38)e[1570](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref38).

[IATA, 2013a. Resolution on the implementation of the aviation CNG2020 strategy.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref39)

[In: 69th Annual General Meeting, Cape Town](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref39).

[IATA, 2013b. Historic Agreement on Carbon-neutral Growth. Press Release No: 34,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref40) [Cape Town](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref40).

[IATA, 2013c. IATA Technology Roadmap 2013, fourth ed. (Montreal)](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref41).

[IATA, 2014. New IATA Passenger Forecast Reveals Fast-growing Markets of the](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref42) [Future. Press Release No: 57, Geneva](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref42).

[IATA, 2014. Recommended Pract](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref43)ı[ce 1678: CO2](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref43) [Emissions Measurement Methodol-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref43) [ogy CSC(36), Los Angeles](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref43).

IATA, 2015. World Air Transport Statistics. [https://www.iata.org/publications/pages/](https://www.iata.org/publications/pages/wats.aspx) [wats.aspx](https://www.iata.org/publications/pages/wats.aspx).

[ICAO, 2011. Airport Air Quality Manual. Document No. 9889,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref45) ﬁ[rst ed. Quebec](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref45).

[ICAO, 2016a. Report of the executive committee on agenda item 22. In: 39th Session](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref46) [of the Assembly A39 -WP/530, Montreal](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref46).

ICAO, 2016b. Carbon Offsetting and Reduction Scheme for International Aviation. [http://www.icao.int/environmental-protection/Pages/market-based-measures.](http://www.icao.int/environmental-protection/Pages/market-based-measures.aspx) [aspx](http://www.icao.int/environmental-protection/Pages/market-based-measures.aspx).

[IEA, 2016. Energy Technology Perspectives 2016: towards Sustainable Urban Energy](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref48) [Systems. OECD-IEA, Paris](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref48).

[Jani´](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref49)c, [M., 2007. The Sustainability of Air Transportation: a Quantitative Analysis and](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref49)

[Assessment. Ashgate Publishing, Hampshire](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref49).

[Jani´](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref50)c, [M., 2014. Advanced Transport Systems: Analysis, Modeling, and Evaluation of](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref50) [Performances. Springer, London](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref50).

[Japan Airlines, 2014. JAL Report 2014, Tokyo](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref51).

[Kennedy, C.A., Cuddihy, J., Engel Yan, J., 2007. The changing metabolism of cities.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref52)

[J. Ind. Ecol. 11, 43](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref52)e[59](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref52).

[KLM Royal Dutch Airlines, 2014. Annual Report 2013, Amstelveen](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref53).

[K](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref54)o€[hler, J., Walz, R., Marscheder-Weidemann, F., Thedieck, B., 2014. Lead markets in](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref54) [2nd generation biofuels for aviation: a comparison of Germany, Brazil and the](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref54) [USA. Environ. Innov. Soc. Transitions 10, 59](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref54)e[76](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref54).

[Korean Air, 2014. Sustaining Excellence: 2014 Korean Air Sustainability Report,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref55) [Seoul](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref55).

[Kuo, T., Kremer, G., Phuong, N., Hsu, C., 2016. Motivations and barriers for corporate](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref56) [social responsibility reporting: evidence from the airline industry. J. Air Transp.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref56) [Manage 57, 184](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref56)e[195](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref56).

[K](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref57)ı[lk](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref57)ıs[¸,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref57) S¸ [., 2016. Sustainable development of energy, water and environment systems](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref57) [index for Southeast European cities. J. Clean. Prod. 130, 222](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref57)e[234](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref57).

[K](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58)ı[lk](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58)ıs¸, S¸ [., K](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58)ı[lk](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58)ıs¸, S¸ [., 2016. Benchmarking airports based on a sustainability ranking](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58) [index. J. Clean. Prod. 130, 248](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58)e[259](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref58).

[Loewen, S., Gonulal, T., 2015. Exploratory factor analysis and principal components](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref59) [analysis. In: Plonsky, L. (Ed.), Advancing Quantitative Methods in Second Lan-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref59) [guage Research. Routledge, New York](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref59).

[Lufthansa Group, 2014. Balance: Key Data on Sustainability within Lufthansa Group,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref60) [Cologne](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref60).

[Lynes, J., Andrachuk, M., 2008. Motivations for corporate social and environmental](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref61) [responsibility: a case study of Scandinavian Airlines. J. Int. Manage 14, 377](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref61)e[390](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref61). [Maas, K., Schaltegger, S., Crutzen, N., 2016. Advancing the integration of corporate](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref62) [sustainability measurement, management and reporting. J. Clean. Prod. 133,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref62)

[859](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref62)e[862](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref62).

[Mariano, E., Gobbo, J., Camioto, F., Rebelatto, D., 2017. CO](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref63)[2](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref63) [emissions and logistics](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref63) [performance: a composite index proposal. J. Clean. Prod. 163, 166](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref63)e[178 doi:](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref63) [10.1016/j.jclepro.2016.05.084](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref63).

[Mayer, R., Ryley, T., Gillingwater, D., 2015. Eco-positioning of airlines: perception](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref64) [versus actual performance. J. Air Transp. Manage 44](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref64)e[45, 82](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref64)e[89](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref64).

[Miyoshi, C., 2014. Assessing the equity impact of the European Union emission](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref65) [trading scheme on an African airline. Transp. Pol. 33, 56](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref65)e[64](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref65).

[Morioka, S., Carvalho, M., 2016. A systematic literature review towards a conceptual](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref66) [framework for integrating sustainability performance into business. J. Clean.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref66) [Prod. 136, 134](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref66)e[146](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref66).

[Munda, G., Nardo, M., 2005. Constructing Consistent Composite Indicators: the](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref67) [Issue of Weights. EUR 21834 EN, Ispra](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref67).

[Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., 2005. Tools for Composite Indicators](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref68) [Building. JRC Publication EUR 21682 EN, Ispra](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref68).

[Nicoletti, G., Scarpetta, S., Boylaud, O., 2000. Summary Indicators of Product Market](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref69) [Regulat](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref69)ı[on with an Extension to Employment Protection Legislation. Economics](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref69) [Department Working Papers No. 226. OECD, Paris, France](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref69).

[OECD-JRC, 2008. Handbook on Constructing Composite Indicators. Methodology](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref70) [and User Guide, Paris](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref70).

[Orsato, R., Garcia, A., Mendes-Da-Silva, W., Simonetti, R., Monzoni, M., 2015. Sus-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref71) [tainability indexes: why join in? A study of the ‘Corporate Sustainability Index](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref71) [(ISE)’ in Brazil. J. Clean. Prod. 96, 161](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref71)e[170](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref71).

[Pereira, R., Ribeiro, G., Filimonau, V., 2017. The carbon footprint appraisal of local](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref72) [visitor travel in Brazil: a case of the Rio de Janeiro-S~](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref72)a[o Paulo itinerary. J. Clean.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref72) [Prod. 141, 256](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref72)e[266](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref72).

[Preston, H., Lee, D., Hooper, P., 2012. The inclusion of the aviation sector within the](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref73) [European Union's emissions trading scheme: what are the prospects for a more](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref73) [sustainable aviation industry? Environ. Dev. 2, 48](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref73)e[56](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref73).

[Qantas Airways Limited, 2013. Feasibility Study of Australian Feedstock and Pro-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref74) [duction Capacity to Produce Sustainable Aviation Fuel, Public Report, Mascot](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref74).

[Qantas Airways Limited, 2014. Shaping Our Future: 2014 Longreach Review, Mascot](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref75). [Qantas Airways Limited, 2014. FY13 Results Group Performance, Mascot](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref76).

[Reis, V., Silva, J., 2016. Assessing the air cargo business models of combination](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref77) [airlines. J. Air Transp. Manage 57, 250](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref77)e[259](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref77).

[Rosskopf, M., Lehner, S., Gollnick, V., 2014. Economic](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref78)e[environmental trade-offs in](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref78) [long-term airline](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref78) ﬂ[eet planning. J. Air Transp. Manage 34, 109](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref78)e[115](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref78).

[Ryerson, M., Kim, H., 2014. The impact of airline mergers and hub reorganization on](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref79) [aviation fuel consumption. J. Clean. Prod. 85, 395](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref79)e[407](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref79).

*S¸. K*ı*lk*ı*s¸, S¸. K*ı*lk*ı*s¸ / Journal of Cleaner Production 167 (2017) 1068*e*1083* 1083

SAFUG, 2014. Sustainable Aviation Fuel Users Group. <http://www.safug.org/>. [Saisana, M., 2012. A Do-it-yourself Guide in Excel for Composite Indicator Devel-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref81)

[opment (European Commission JRC-COIN, Ispra)](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref81).

[Saisana, M., Saltelli, A., 2008. Sensitivity Analysis of the 2008 Environmental Per-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref82) [formance Index. Of](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref82)ﬁ[ce for Of](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref82)ﬁ[cial Publications of the European Communities,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref82) [Luxembourg](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref82).

[Saisana, M., Saltelli, A., 2010. Uncertainty and Sensitivity Analysis of the 2010](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref83) [Environmental Performance Index. Of](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref83)ﬁ[ce for Of](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref83)ﬁ[cial Publications of the Euro-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref83) [pean Communities, Luxembourg](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref83).

[Saisana, M., Nardo, M., Srebotnjak, T., 2005. Robustness Analysis of the 2005](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref84) [Environmental Sustainability Index. European Commission Publication EUR](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref84) [21807 EN, Ispra](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref84).

[Saisana, M., Saltelli, A., Tarantola, S., 2005. Uncertainty and sensitivity analysis](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref85) [techniques as tools for the quality assessment of composite indicators. J. R. Stat.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref85) [Soc. A 168 (2), 307](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref85)e[323](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref85).

[Saisana, M., D'Hombres, B., Saltelli, A., 2011. Rickety numbers: volatility of univer-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref86) [sity rankings and policy implications. Res. Policy 40, 165](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref86)e[177](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref86).

[Saranga, H., Nagpal, R., 2016. Drivers of operational ef](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref87)ﬁ[ciency and its impact on](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref87) [market performance in the Indian Airline industry. J. Air Transp. Manage 53,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref87) [165](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref87)e[176](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref87).

[SAS Group, 2014. Towards Long-term Sustainability: SAS Sustainability Report 2013,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref88) [Stockholm](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref88).

[Scotti, D., Volta, N., 2015. An empirical assessment of the CO](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref89)[2](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref89)[-sensitive productivity](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref89) [of European airlines from 2000 to 2010. Transp. Res. 37 (D), 137](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref89)e[149](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref89).

[Seo, K., Moon, J., Lee, S., 2015. Synergy of corporate social responsibility and service](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref90) [quality for airlines: the moderating role of carrier type. J. Air Transp. Manage 47,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref90) [126](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref90)e[134](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref90).

SESAR, 2016. Single European Sky Air Trafﬁc Management Research. [http://www.](http://www.sesarju.eu/) [sesarju.eu/](http://www.sesarju.eu/).

[Singapore Airlines, 2014. Sustainability Report 2012/13, Singapore](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref92).

[Singapore Airlines, 2014. Singapore Airlines Annual Report FY 2013/14, Singapore](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref93). Skytrax, 2014. The World's Top 100 Airlines in 2014. [http://www.](http://www.worldairlineawards.com/Awards/world_airline_rating_2014.html)

[worldairlineawards.com/Awards/world\_airline\_rating\_2014.html](http://www.worldairlineawards.com/Awards/world_airline_rating_2014.html).

Skytrax, 2015. World Airline and Airport Star Ranking. [http://www.airlinequality.](http://www.airlinequality.com/ratings/rating-background/) [com/ratings/rating-background/](http://www.airlinequality.com/ratings/rating-background/).

Skytrax, 2015. Certiﬁed 5-Star Airline Ratings. [http://www.airlinequality.com/](http://www.airlinequality.com/ratings/5-star-airline-ratings/) [ratings/5-star-airline-ratings/](http://www.airlinequality.com/ratings/5-star-airline-ratings/).

Skytrax, 2016. World Airline Awards Methodology. [http://www.worldairlineawards.](http://www.worldairlineawards.com/Awards/awards_methodology.html) [com/Awards/awards\_methodology.html](http://www.worldairlineawards.com/Awards/awards_methodology.html).

[Steven, M., Merklein, T., 2013. The in](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref98)ﬂ[uence of strategic airline alliances in pas-](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref98) [senger transportation on carbon intensity. J. Clean. Prod. 56, 112](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref98)e[120](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref98).

Sustainable Aviation, 2014. Sustainable Fuels UK Road-map. [http://www.](http://www.sustainableaviation.co.uk/) [sustainableaviation.co.uk](http://www.sustainableaviation.co.uk/).

[Tillie, N., Klijn, I., Frijters, E., Borsboom, J., Looije, M. (Eds.), 2014. Urban Metabolism](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref100)

e [Sustainable Development of Rotterdam. Mediacenter, Rotterdam](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref100).

[Turkish Airlines, 2014. Environmental and Social Responsibility Report, Istanbul](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref101). [Turkish Airlines, 2014. Annual Report 2013, Istanbul](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref102).

[UNEP, 2011. Decoupling Natural Resource Use and Environmental Impacts from](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref103) [Economic Growth (Working Group on Decoupling to the International Resource](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref103) [Panel, Paris)](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref103).

[United Airlines Inc, 2014. Environmental Sustainability at United, Chicago](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref104).

[United Airlines Inc, 2014. Annual Report Pursuant to Section 13 for Fiscal Year 2013,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref105) [Chicago](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref105).

United Nations, 2016. Energy Statistics Yearbook Conversion Factors. [http://unstats.](http://unstats.un.org/unsd/energy/yearbook/conversion.htm) [un.org/unsd/energy/yearbook/conversion.htm](http://unstats.un.org/unsd/energy/yearbook/conversion.htm).

[Varbanov, P., 2014. Energy and water interactions: implications for industry. Curr.](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref107)

[Opin. Chem. Eng. 5, 15](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref107)e[21](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref107).

[Wang, Q., Wu, C., Sun, Y., 2015. Evaluating corporate social responsibility of airlines](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref108) [using entropy weight and grey relation analysis. J. Air Transp. Manage 42,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref108) [55](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref108)e[62](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref108).

[Winchester, N., Malina, R., Staples, M., Barrett, S., 2015. The impact of advanced](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref109) [biofuels on aviation emissions and operations in the U.S. Energy Econ. 49,](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref109) [482](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref109)e[491](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref109).

Xlstat, 2015. A Complete Statistical Add-in for Microsoft Excel. [https://www.xlstat.](https://www.xlstat.com/en/) [com/en/](https://www.xlstat.com/en/).

[Xu, J., Qiu, R., Lv, C., 2016. Carbon emission allowance allocation with cap and trade](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref111) [mechanism in air passenger transport. J. Clean. Prod. 131, 308](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref111)e[320](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref111).

[Zou, B., Elke, M., Hansen, M., Kaﬂe, N., 2014. Evaluating air carrier fuel efﬁciency in](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref112) [the US airline industry. Transp. Res. 59 (A), 306](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref112)e[330](http://refhub.elsevier.com/S0959-6526(17)30644-3/sref112).