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ORIGINAL PAPER

Fuel consumption optimization in air transport: a review, classification, critique, simple meta-analysis, and future research implications

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Abstract

Objective This paper presents a review, classification schemes, critique, a simple meta-analysis and future research implication of fuel consumption optimization (FCO) literature in the air transport sector. This review is based on 277 articles published in various publication outlets between 1973 and 2014.

Methodology A review of 277 articles related to the FCO in air transport was carried out. It provides an academic database of literature between the periods of 1973– 2014 covering 69 journals and proposes a classification scheme to classify the articles. Twelve hundred of articles were identified and reviewed for their direct relevance to the FCO in air transport. Two hundred seventy seven articles were subsequently selected, reviewed and classified. Each of the 277 selected articles was categorized on four FCO dimensions (Aircraft technology & design, aviation operations & infrastructure, socioeconomic & policy measures, and alternate fuels & fuel properties). The articles were further classified into six categories of FCO research methodologies (analytical - conceptual, mathematical, statistical, and empirical- experimental, statistical, and case studies) and optimization techniques (linear programming, mixed integer programming, dynamic programming, gradient based algorithms, simulation modeling, and nature based algorithms). In addition, a simple meta-analysis was also carried out to enhance understanding of the development and evolution of research in the FCO.

Findings and conclusions This has resulted in the identification of 277 articles from 69 journals by year of publication, journal, and topic area based on the two classification schemes related to FCO research, published between, 1973 to December- 2014. In addition, the study has identified the 4 dimensions and 98 decision variables affecting the fuel consumption. Also, this study has explained the six categories of FCO research methodologies (analytical - conceptual, mathematical, statistical, and empirical-experimental, statistical, and case studies) and optimization techniques (linear programming, mixed integer programming, dynamic programming, gradient based algorithms, simulation modeling, and nature based algorithms). The findings of this study indicate that the analytical-mathematical research methodologies represent the 47 % of FCO research. The results show that there is an increasing trend in research of the FCO. It is observed that the number of published articles between the period 1973 and 2000 is less (90 articles), so we can say that there are 187 articles which appeared in various journals and other publication sources in the area of FCO since 2000. Furthermore there is increased trend in research on FCO from 2000 onward. This is due to the fact that continuously new researchers are commencing their research activities in FCO research. This shows clearly that FCO research is a current research area among many research groups across the world. Lastly, the prices of jet fuel have significantly increased since the 2005. The aviation sector's fuel efficiency improvements have slowed down since the 1970s–1980s due to the slower pace of technological development in engine and aerodynamic designs and airframe materials.

We conclude that FCO models need to address the composite fuel consumption problem by extending models to include all the dimensions, i.e. aircraft technology & design, aviation operations & infrastructure, socioeconomic & policy

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measures, and alternative fuels & fuel properties. FCO models typically comprise all the four dimensions and this reality need to be taken into account in global FCO models. In addition, these models should have objectives or constraints to evaluate the aircraft sizes according to market structure, impact of various policy measures on fuel burn, and near term potential alternative fuel options in the global FCO problem. In the models reviewed, we evaluated that, only the few authors considered these factors. The literature identifies 98 decision variables affecting the fuel consumption related to various dimensions in air transport. So we can conclude that this analysis could represent the informational framework for FCO research in air transport.

Future scope Our analysis provides a roadmap to guide future research and facilitate knowledge accumulation and creation concerning the application of optimization techniques in fuel consumption of air transport. The addressed dimensions & decision variables could be of potential value to future researchers on the aviation fuel consumption optimization research and is also capable of further refinements. In future, for fuel consumption optimization the explored decision variables could be checked for their reliability and validity and a statistically significant model with minimum number of decision variable could be developed. Further, on the basis of this statistical significant model and with the best market requirement for transport aircraft, the researchers can frame the objective function for fuel consumption minimization problem & decide their dependent variables, independent variables, constant, and constraints. Furthermore, this study will also provide the base for fuel conservation, energy efficiency, and emission reduction in the aviation sector.

Keywords Air transport industry · Meta-analysis · Aircraft fuel efficiency · Fuel consumption optimization (FCO)

1 Introduction

Air Transport industry acts as a catalyst to the economic and social development of a nation. This industry encompasses all those activities which involve transportation of goods and people, by air. Air transport connects people, countries and cultures across the face of the globe. Additionally, it opens up a market to global players, thereby supporting trade and tourism significantly.

The Air transport industry has contributed significantly to the growth of commerce, communication, trade and tourism globally. In spite of a marked expansion, the air transport industry is faced with major issues like high fuel consumption, fuel prices, air traffic growth, competition, economic crisis, aviation emission, safety, design and operational challenges. In this study, fuel consumption has been considered, to be a major challenge for the air transport industry. Attributable to high oil prices and an escalation of competition, fuel consumption is rapidly becoming a critical aspect of the air transport industry. Widespread improvement in the global economy during the past year has also contributed to the demand of oil, thereby inflating its price. David L. Greene [1] pointed out that in the early 1970s, air transport doubled its energy efficiency and restrained the growth rate of fuel. In spite of this improvement, energy use by commercial air carriers grew at an annual rate of 2 % from 1970 to 1987. Mohammad Mazraati [2] concluded upon continuously increasing fuel consumption and air traffic. According to this study, world aviation oil demand was 1.18 MB/d in 1971, and reached 4.9 MB/d in 2006. The aviation sector accounts for about 5.8 % of total oil consumption worldwide. Aviation fuel consumption today corresponds to between 2 and 3 % of total fossil fuel use worldwide, more than 80 % of which is used by civil aviation [3]. Emma Nygren et al. [4] predicted that traffic will grow 5 % per year to 2026 and fuel demand 3 % per year. According to Schlumberger [5] the demand for jet fuel and aviation gasoline in the air transport sector is projected to reach 14 % of fuel demand in transportation in 2035, compared to 12 % in 2009.

Fuel consumption is one of major direct operating cost parameter in the air transport industry [6, 7]. Air transport fuel remains the most significant and variable component of operating costs and managing this aspect is an increasing challenge for the air transport sector. Airbus [8] predicted that in 2003, fuel represented about 28 % of total operating cost for a typical A320 family operator. But in the near future, it could be more than 45 % of all operating costs of an aircraft. The economy of a country largely depends on fuel prices. Increases in fuel consumption have an influence on the airlines in two ways; direct impact on the operating cost, and declines the demand for air travel and air cargo. According to Majka A. et al. [9] at one time fuel extraction cost and availability had little impact on the evolution of the air transport industry. Furthermore, aircraft fuel burn is proportional to CO_2 emission [10, 11]. Therefore, as the fuel consumption increases the aviation emission shall also increase and that is a big environmental concern today. Chang et al. [12] pointed that the higher fuel consumption of aircrafts is one of the major cause of inefficiency of airlines. Therefore, in such a highly competitive environment, in order to reduce the direct operating cost of an aircraft the FCO is essential. In this study, the FCO in air transport means finding a minimum value of fuel consumption function of several variables subject to a set of constraints and improving the energy efficiency of the aircraft system. The researchers, airlines, aircraft manufacturer and regulatory organizations are continuously trying to reduce the air transport fuel consumption along with the economic cost of flying an aircraft. Further, this reduction will also lead to the reduction of the greenhouse gas emission, caused by the air transport. But before implementing a customized model of the FCO in air transport it is essential to systematically organize, classify, and reviews the published literature and also to identify the factors causing the variation in fuel consumption.

The goal of this study was to examine the historical trends published in fuel consumption optimization (FCO) research studies in air transport industry, and to explore the potential fuel consumption reduction areas in future. We cover the literature that relates to transportation, aerospace sciences, energy & fuel, and environmental sciences. It is hoped that the finding of this research study can highlight the importance of the FCO in the air transport and provide an insight into current FCO research for both academics and air transport industry. The content of this paper is organized as follows: first, the research methodology used in the study is described; second, the methods for classifying FCO research is presented; third, a simple meta-analysis of FCO research are proposed, and the results of the classification are reported; and finally, the conclusions, future research implications, and limitations of the study are discussed.

2 Research methodology

As the nature of research in the FCO in air transport is difficult to confine to specific disciplines, the relevant materials are scattered across various journals. A number of journals have very few articles on FCO to their name, making it difficult to gain credible simplistic inferences regarding the focus of research in a particular direction. Hence the research journals reviewed have been grouped discipline wise, i.e. Transportation (TP), Aerospace Sciences (AS), Fuel & Energy (F&E), and Environmental Science (ES); all of them being relevant to FCO research.

This gave us some broad fields of foray into the study of the FCO in aviation, letting us draw inferences on the trends in research and research output density in these particular fields. The studies that were selected for inclusion in this study were identified from online electronic databases since from 1973 to 2014. A computerized search of the literature was conducted utilizing Science Direct, Springer Link, Emerald Insight, Jstor, Taylor & Francis, AIAA Journal, SAE Journals, and Google Scholar. Keywords for the computerized search of the literature were: "air transportation fuel consumption optimization", "fuel efficiency in aviation", "airline fuel conservation", "aviation fuel alternatives", "energy efficiency in aviation", "aviation emission mitigation" and aviation or jet fuel consumption, which identified approximately 1200 articles. After that the full text of each article was reviewed, to eliminate those that were not actually related to FCO research in air transport. The selection process was mainly based on three criteria as follow: (1) only those articles which clearly described how the mentioned FCO techniques and strategies could be applied were selected. (2) Only those articles that had been published in transportation, aerospace sciences, energy & fuel, and environmental sciences related journals were selected, as these were the most appropriate outlet for FCO research in air transport. (3) Only the papers selected and published in the international journals were included in the study as these journals represents the highest level of research. Unpublished, working papers, conference papers, master and doctoral dissertations and text books were excluded from the study. Based on these criteria we trimmed it down to 277 articles.

Thereafter, each article was carefully reviewed and separately classified according to the four categories of FCO dimensions and seven categories of research methodologies of the FCO in air transport. Though our research may not be exhaustive, it is sufficiently representative for an understanding of FCO research. In addition, this study may suggest/bring light to some unexplored research problems in the area of air transport fuel consumption. The purpose of this paper is mainly descriptive and analytical, thereby not introducing much statistical methodology. Instead, we have conducted a simple meta-analysis to identify trends and patterns in research, in order to shed greater understanding of the development and evolution of research in fuel consumption in the air transport industry and to identify the potential research areas for further research and improvement. We present this simple meta-analysis result in the form of tables and graphs.

3 Classification method of FCO research in air transport

3.1 Classification scheme based on dimensions of FCO in air transport

Based on the literature review carried out and the nature of FCO research observed in air transport, we have introduced a classification scheme to systematically organize the published articles. From the literature survey of articles we have identified five dimensions (1) Aircraft technology & design (2) Aviation operations & infrastructure (3) Socioeconomic & policy measures (4) Aviation alternate fuels, affecting the fuel consumption in air transport. Figure 1 shows the Classification scheme based on the dimensions of FCO research in air transport. They were further classified from the four major dimensions into their respective decision variables. Hileman et al. [13] suggested the advance aircraft design, operational improvements, and alternative fuels for aviation emission reductions. The result of the study showed that the narrower body aircraft has the greatest potential for fuel burn reduction, but it would require the promotion of innovative aircraft design and extensive use of alternative fuels. Grote et al. [14] addressed the technological, operational, and policy measures for fuel burn reduction in civil aviation

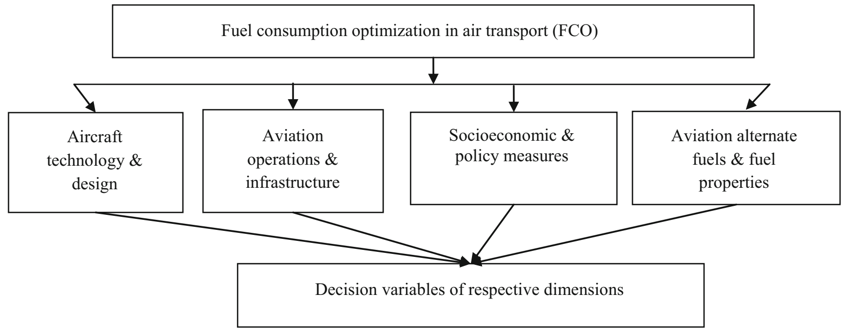

Fig. 1 Classification scheme based on dimensions of FCO

and the analysis of the study showed that some of the measures were directly implemented on the market because they directly reduce the fuel consumption and fuel cost, but some were not due to market constraints.

Sgouridis et al. [15] examined and evaluated the impact of the five policies for reducing emission of commercial aviation; technological efficiency improvement, operational efficiency improvement, use of alternative fuels, demand shift, and carbon pricing. Similarly the study of Lee & Mo [16]; Green [11]; Lee [3]; Janic [17] and Singh & Sharma [18] collectively identified the above mentioned dimensions of the FCO.

3.1.1 Aircraft technology & design

Today airlines operate in an increasingly competitive environment caused by the globalization of air transport network worldwide and therefore a necessary condition for airlines are commercially successful is the reduction of direct operating costs, which mainly depends on the technological & design characteristics of the aircraft used. Technology development is going on at a rapid rate and we can effectively make use of this technological revolution to reduce the fuel consumption of a commercial aircraft. Moreover the fuel consumption of air transport can be reduced through the variety of options such as increased aircraft efficiency, improved operations, use of alternate fuels, socioeconomic measures, and improved infrastructure, but most of the gain so far have been resulted from the aircraft technological improvement. Aircraft technological improvement mainly depends upon the three factors: structural weight, aircraft aerodynamics, and engine specific fuel efficiency [14]. Moreover the aircraft technological efficiency is described by three aircraft performance metrics: engine efficiencies are expressed in terms of thrust specific fuel consumption (TSFC), aerodynamic efficiencies are measured in terms of maximum lift over drag ratio (L_{max}/D) and structural efficiency is quantified using operating empty weight (OEW) divided by maximum takeoff weight (MTOW) [19, 20]. Further, Graham et al. [21] have considered the classical range equation in order to understand how the aircraft technology affects the fuel burn. Fuel consumption per payload range of idealized cruise, keeping the aircraft operating parameters fixed are expressed in terms of aerodynamic efficiency, structural efficiency, engine efficiency, and calorific value of the fuel.

In addition the studies of Henderson et al. [10] and Wang et al. [22] explained the fuel burn reduction by considering aircraft technology & design dimensions. Henderson et al. [10] studied the aircraft design for optimal environmental performance and the design variables considered in this study for optimization problems were from aircraft geometry, engine parameters, and cruise setting. This concludes that the aircraft optimized for minimum fuel burn encompass a high aspect ratio wing with lower induced drag, high bypass ratio engines and high core pressures and temperatures. In addition the mission range and cruise Mach number were also optimized for maximum payload fuel efficiency. Furthermore the possibility of designing larger aircraft for shorter ranges was also examined and result shown that the reduction in structural weight can be achieved by reducing fuel burn. Also, Wang et al. [22] studied the multi objective optimization of aircraft design for emission and cost reduction. A multi-objective optimization of aircraft design for the tradeoff between emission effect and direct operating cost was performed with five geometry variables (i.e. Wing area, aspect ratio, ratio of thickness to chord at root, sweep, and taper ratio), one is mass of the designed fuel for specific range 5000 Km, two flight condition parameters (i.e. cruise Mach number and initial cruise altitude) and three performance requirement as constraints (i.e. take off field length, landing field length, and the 2nd climb gradient). The result of the study showed that, a decrease of 29.8 % in direct operating cost was attained at the expense of an increase of 10.8 % in greenhouse gases. Currently the evolutionary developments of engine technology, airframe technology, and use of advance light weight alloys and composite material, have resulted in a positive trend of fuel efficiency improvements. The merging technology and optimized design dimensions finally lead to the fuel consumption optimization. Aircraft technology & design have the highest potential to optimize the aviation fuel consumption, and some of their successful applications in the FCO have been proposed in the literature [1, 3, 10, 11, 13–107].

3.1.2 Aviation operations & infrastructure

The amount of fuel consumed by an aircraft during its operation from start-up through to taxi and takeoff, to cruise, to approach for landing and taxiing on arrival, depends upon several factors. Many of the factors can be influenced by airlines with proper operations planning and strategies. The current operational practices are not always optimal from the fuel consumption point of view and hence there is need for operational improvements. Operational improvement can be expressed in term of operational efficiency, which is the combination of ground and airborne efficiency. In general the actual aircraft performance can be determined by how the aircraft is operated subject to operational constraints and the efficient operational procedures are those, in which the actual fuel burn used falls close to the theoretical minimum [14]. Furthermore the operational efficiency can be expressed in term of operational and payload-fuel energy intensity, and the payload factor [13]. Also the operational factors to reduce the fuel consumption per passenger-km include the increasing load factor, optimizing the aircraft speed and fuel weight, limiting the use of auxiliary power, eliminating the non essential weight, and reducing taxiing. In addition, highly sophisticated flight-planning system also improves the aircraft fuel efficiency because this allows pilots to exploit prevailing wind conditions, calculate precise fuel loads & set different flight levels and speeds for the aircraft to achieve the most economic performance. For a typical flight there are a number of factors such as cruise altitude and speed, mass, and weather conditions that affects the fuel consumption [108]. Therefore, by optimizing the aircraft operations from start-up through to taxi and takeoff, to cruise, to approach for landing and taxiing on arrival, have the significant to reduce the fuel burn.

Aviation infrastructure also plays an important role in fuel consumption optimization. Infrastructure improvements present a major opportunity for fuel consumption reduction in aviation. The design of an airport, including the location of the runways and taxiways relative to terminal buildings, clearly has an effect on aircraft fuel burn, because reduction of delays and decreased taxiing time can provide significant aircraft fuel burn reduction. Airport congestion and improper air traffic management increase the fuel consumption. Airport congestion occurs whenever the actual traffic demand is greater than what the system can handle without the delay. According to Simaiakis et al. [109] airport surface congestion at major airports in the United States and Europe is responsible for increased taxi-out times, fuel burn and emissions. Air Traffic Management (ATM) plays an important role in reducing the environmental impacts of air transportation by reducing the inefficiencies during the operations of an aircraft [110]. Ryerson et al. [111] analyzed the possible fuel savings from Air Traffic Management (ATM) improvements and the study explored the impact of the airborne delay, departure delay, and excess planned flight time, and terminal efficiency in fuel consumption using econometric techniques. In addition the better terminal design can also reduce the fuel consumption. There are a number of ways that airports, airlines and ATM providers can improve the air transportation system to minimize fuel burn and emissions. These include improving the use of the airspace, air traffic control and operations and further improving the use of airspace and air traffic control includes the flexible use of airspace, route redesign, using the new tools and programmes to find most effective route, and reduced separation between the aircraft. Salah [112] developed the model of optimal flight paths taking into consideration jet noise, fuel consumption, constraints and extreme operational limits of the aircraft on approach. The results of this study showed that, the environmental impacts and fuel consumption are reduced by the use of aircraft trajectory optimization during arrivals. Beside this there are some constraints to the improved ATM which includes the air traffic controller (ATC). ATC prevents the ideal trajectory of the aircraft to be flown due to a number of reasons such as safe separation, congested airspace, restricted airspace, delay management and weather avoidance etc. The priorities of controller are also taken into the account. For air traffic controller the safety comes first thereafter the performance. Therefore, by optimizing the aviation infrastructure, there is the potential to reduce fuel consumption. A comprehensive list of the reviewed studies of aviation operations & infrastructure affecting FCO is presented in the literature [1, 3, 7, 11–20, 32, 33, 38, 40–42, 44, 48, 53, 54, 61, 67, 69, 70, 72–75, 85, 86, 94, 95, 98, 104–182].

3.1.3 Socioeconomic & policy measures

Aviation is the fastest growing sector of the economy. It provides the number of socioeconomic benefits. There are many socioeconomic & political factors which affect the airline fuel consumption optimization. If these factors are carefully managed then a significant amount of fuel can be saved. Also the social awareness levels of the society, regarding the impact of the aviation emission on climate change plays a key role in fuel consumption reduction. According to Lee & Mo [16] currently, the scientific knowledge and the social demand for low-emission aircraft is not strong enough because the general public is not well aware of the harmful impacts of aviation emissions on the global climate. The strong social pressure sends the signal to the government and the government takes the necessary action after scientifically confirming the problem. As in the cases of the automobile emission and aircraft noise significant technological and operational improvements have been reported, because the general public was well aware of the health damages caused by these [3]. Also, the education and awareness are very important social measure in air transport and there will be many airline customers who have never thought of aviation emission as an environmental problem. Information should be widely available regarding the impact of flying, so that airlines have the background information they need to understand the changing circumstances of aviation. Informed choice is a key component of the transport demand and environmental policy implication. Furthermore, the economic/policy measures for reducing the fuel consumption includes the emission trading, taxes on aviation fuel, and carbon emission charges [17]. Beside this there are some constraints on the airline operations, training, maintenance & reservations, planning & routes, scheduling, airways, and labour, these constraints should be removed for fuel burn reduction [183]. In addition, the economic and policy measures should be introduced in an incremental fashion to give the air transport and consumers time to adjust to the changes. So therefore, by optimizing the socioeconomic & political factors, we can improve the air transportations fuel efficiency. Studies related to socioeconomic & policy measures have been proposed in the literature [2, 3, 14–20, 29, 33, 41, 42, 44, 53, 54, 73, 74, 94, 113, 114, 150, 154, 158–160, 172, 183–224].

3.1.4 Aviation alternative fuels & fuel properties

Aviation alternative fuels can also play an important for the optimization of aviation fuel consumption. Since the energy crises of the 1970s, all the aircraft companies, aviation sectors, engine companies, and other government organization are working for practicality of using alternative fuel in aircraft. A viable alternative aviation fuel can stabilize fuel price fluctuation and reduce the reliance from the crude oil. According to Hileman & Statton [225] economic sustainability, environmental concerns, energy supply diversity, and competition for energy resources are the main drivers for alternative jet fuels development. The replacement for current alternative fuels need no aircraft modifications and can be used with the current aviation system, encompassing existing distribution and refueling infrastructure [226]. Hileman & Statton examined the criteria for the potential alternative jet fuels and highlighted that the synthetic liquid alternative fuels were compatible with current aircraft fleet, but the economic cost of production and the current lack of feedstock availability limits their near term availability to air transport. In addition the study explored the potential of the alternative aviation fuels: conventional jet fuel from petroleum resources, synthetic jet fuels, biodiesel and bio-kerosene, ethanol and butanol, liquefied natural gas and hydrogen and highlighted the technical feasibility parameters: high energy density, high specific energy, high flash point, low freezing point and vapor pressure, high thermal stability, adequate lubricity, and sufficient aromatic compound content. Janic [17]; Pereira et al. [227], Verstraete [228], and Yılmaz et al. [229] studied the liquid hydrogen as an alternative fuel for air transport and these studied identifies the important parameters affecting the fuel consumption. Chuck & Donnelly [230] tested the compatibility of the potential aviation bio-fuels with the Jet A-1 and viscosities, cloud point temperature, flash points, energy content, effect of fuel burn in the range vs. the payload were studied. The result of the study shown that, only the hydrocarbons, matched the range vs. payload of Jet-A1 and the limonene was found to fulfill the required specification. Therefore a suitable alternative fuel can be selected on the basis of a variety of criteria, societal priorities, economic viability, and sustainability considerations, which will further reduce the aviation fuel consumption. Aviation alternative fuels & fuel properties studies related to FCO have been proposed in the literature [3, 11, 13–18, 32, 33, 40–42, 53, 54, 59, 79, 86, 94, 104, 140, 150, 194, 225–282].

3.1.5 Identifications of decision variables based on FCO dimensions

Further, the decision variables of respective dimensions of FCO were selected from the literature on the basis of the description and examination of the relationships between fuel consumption and respective dimensions & their variables, logical reasoning, conceptual basis, and strong influence on fuel burn. Theses dimensions & their respective decision variables affect the fuel consumption in an air transport indirect way and indirectly. As clearly evident from the literature these dimensions are closely related to each other so care has been taken that, a single decision variable cannot be repeated more than one time under the two different dimensions. Table 1 shows the decision variables based on the identified dimensions and the reviewed literature. Table 2 shows the number of decision variables of respective dimension and their percentage. From Table 2 it is clear that the A had the highest percentage of decision variables (48.99 %), while B dimension has 23.47 %, and C has 13.26 % and D has 14.28 % each.

3.2 Classification scheme based on research methodologies of FCO research

Figure 2 shows the classification scheme 2 based on the research methodology related to fuel consumption & optimization studies in air transport. The fuel consumption & optimization research in air transport on the basis of research methodology could be grouped broadly into two major classifications of analytical and empirical research. Further, they are classified into three subcategories of each major classification, i.e. analytical-conceptual, mathematical, statistical, and empirical-experimental, statistical, and case studies. Furthermore analytical- mathematical techniques include the linear programming, mixed integer programming, dynamic programming, gradient based algorithms, simulation modeling, and nature based algorithms. Analytical research uses the deductive

Table 1 Identified the decision variables based on the FCO dimensions

Identified dimension	Identified decision variables of FCO	References
(A) Aircraft technology & design	1)Aircraft structural weight 2)Wing reference area 3)Wing leading edge sweep 4)Wing quarter chord sweep 5)Wing aspect ratio 6)Wing mid span 7)Wing dihedral 8)Wing root thickness to chord ratio 9)Wing tip height 10)Wing span 11)Wing fuel weight 12)Wing exposed root chord 13)Wing quarter chord sweep 14)Wing average thickness to chord ratio 15)Ultimate load factor 16)Maximum design speed 17)Fuselage seat abreast 18)Fuselage cargo height 19)Maximum height of fuselage 20)Effective maximum diameter of fuselage 21)Maximum cabin width of fuselage 22)Fuselage nose length 23)Fuselage parallel length 24)fuselage tail length 25)Fuselage cabin length 26)Fuselage fineness ratio 27)Horizontal tail area 28)Horizontal tail span 29)Horizontal tail aspect ratio 30)Horizontal tail taper ratio 31)Vertical tail area 32)Vertical tail span 33)Vertical tail aspect ratio 34)Vertical tail taper ratio 35)Drag type factor 36)Critical mach number 37)Aircraft wetted area to wing reference area ratio 38)Cruise lift to drag ratio 39)Oswald efficiency factor 40)Effective wing aspect ratio 41)Takeoff thrust sea level 42)Engine bypass ratio 43)Number of engines 44)Engine dry weight 45)Operating specific fuel consumption 46)Static margin 47)Centre of gravity position of aircraft from leading edge of wing 48)Aerodynamic centre of aircraft from leading edge of wing	[1, 3, 10, 11, 13–107]
(B) Aviation operations & infrastructure	49)Maximum takeoff weight 50)Stage length 51)Fuel weight 52)Reserve fuel weight 53)Payload 54)Cruise speed 55)Maximum number of passenger 56)Mission passenger 57)Maximum cabin altitude differential 58)Maximum payload weight 59)Mission payload weight 60)Takeoff field length 61)Maximum ceiling 62)Initial cruise altitude 63)Landing field length 64)Weather condition 65)Flight profile 66)Pilot Techniques 67)Aircraft maintenance 68)Terminal area 69)Runway 70)Taxiway 71)Apron	[1, 3, 7, 11–20, 32, 33, 38, 40–42, 44, 48, 53, 54, 61, 67, 69, 70, 72–75, 85, 86, 94, 95, 98, 104–182]
(C) Socioeconomic & policy measures	72)Aircraft scheduling 73)Fuel prices 74)Ticket prices 75)Economic incentives 76)Labour & Work Rule 77)Voluntary Measures 78)Community Awareness 79)Social and political pressure 80)R & D funding for technology 81)Government regulations 82)Charges and taxes 83)Emission trading scheme 84)Political obstacles	[2, 3, 14–20, 29, 33, 41, 42, 44, 53, 54, 73, 74, 94, 113, 114, 150, 154, 158–160, 172, 183–224]
(D) Alternative fuels & fuel properties	85)Types of alternate fuels 86)Fuel availability 87)Energy per unit volume 88)Energy per unit mass 89)Aromatics content 90)Sulphur content 91)Additives 92)Boiling point 93)Flash point 94)Density 95)Viscosity 96)Lubricity 97)Freezing point 98)Smoke point	[3, 11, 13–18, 32, 33, 40–42, 53, 54, 59, 79, 86, 94, 104, 140, 150, 194, 225–282]

methods while the empirical research uses the induction method to arrive at conclusions. Analytical-research consists the logical, mathematical, and statistical methods [283]. Table 3 shows the research methodologies FCO in air transport.

Table 2 Percentage of identified decision variables of FCO dimensions

Key	Dimension	No. of Decision Variables	Percentage (%)
A	Aircraft technology & design	48	48.99
B	Aviation operations & infrastructure	23	23.47
C	Socioeconomic & policy measures	13	13.26
D	Alternative fuels & fuel properties	14	14.28

3.2.1 Analytical research methodology

In this study, the analytical research includes the case studies for conceptualization, intro-respective research, and conceptual modeling for fuel consumption research in air transport [1, 3, 4, 11, 13, 14, 16, 19, 21, 32, 34, 38, 40, 41, 43–45, 49, 50, 52–54, 57, 59, 61, 73, 79–83, 87, 92, 94, 96, 97, 100, 101, 103, 105, 106, 110, 128, 140, 146, 148, 151, 155, 163, 164, 168, 174, 175, 183, 187, 193, 201, 209, 211, 213, 215, 218–220, 225, 231, 232, 236, 258, 267, 273]. Analytical mathematical research develops the new mathematical relationships between closely defined concepts and uses the simulated data to draw the conclusions [284, 285]. Here the analytical-mathematical research for fuel consumption in aviation includes the; fuel burn and emission prediction and forecast for future scenario studies which primarily consist of logical and descriptive modeling [2, 22, 25, 29, 35, 37, 42, 46–48, 55, 63–65, 67, 69, 70, 72, 75–78, 84, 85, 88–91, 93, 95, 98, 99, 102, 104, 107, 113–115, 117, 132, 133, 136, 138, 147, 149, 152, 153, 165, 178–182, 184, 188, 190, 191, 199, 212, 244]. Additionally the analytical-mathematical techniques can further be classified into the linear programming [24, 28, 39, 62, 108, 116, 122–125, 129, 134, 150, 157, 160, 162, 166, 170, 177, 185, 192, 197, 198, 203, 216, 217, 221, 224], mixed integer programming [12, 135, 197, 221, 224], dynamic programming [17, 75, 76, 107, 119, 154, 159, 161, 171, 186, 189], gradient based methods [26, 27, 30, 31, 36, 51, 56, 60, 71], simulation modeling [15, 112, 121, 142, 227, 228], and nature based algorithms [10, 58, 66, 68, 118, 120, 176]. These techniques mainly deal with the FCO models that are the main thematic area of this study. Each of these techniques has its own strengths and weaknesses and can be helpful in solving certain types of FCO problems. Mathematical programming models have been demonstrated to be useful analytical tools in optimizing decision-making problems such as those encountered in air transport fuel consumption.

Linear programming (LP) models consist of a linear fuel consumption function which is to be minimized subject to a certain number of constraints [157, 162]. Mixed integer programming (MIP) is applicable when some or all of the variables are restricted to be integers [286]. Dynamic programming is used when sub problems are not independent and we solve the problem by dividing them into sub problem [284]. As the aircraft fuel consumption during its operation is not always linear in nature, therefore complex mathematical relationships are used for the FCO. The mathematical techniques, i.e. linear programming and MIP may not be very effective in solving real world FCO problems, because of the large

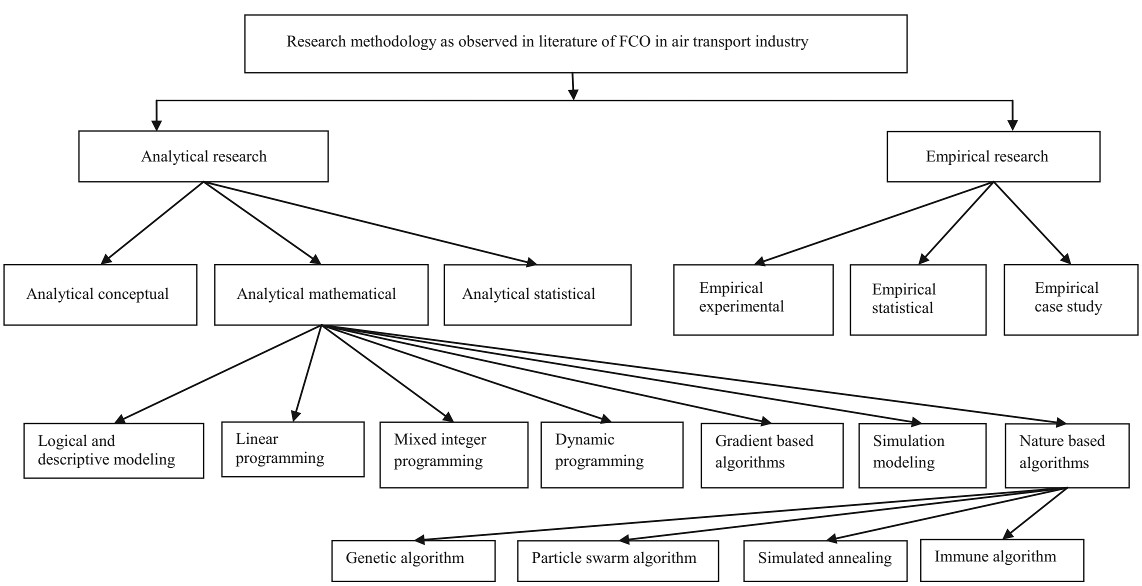

Fig. 2 Classification scheme based on research methodology on fuel consumption & optimization studies

Table 3 Research methodologies for FCO research in air transport

Reference	Research methodology
[1, 3, 4, 11, 13, 14, 16, 19, 21, 32, 34, 38, 40, 41, 43–45, 49, 50, 52–54, 57, 59, 61, 73, 79–83, 87, 92, 94, 96, 97, 100, 101, 103, 105, 106, 110, 128, 140, 146, 148, 151, 155, 163, 164, 168, 174, 175, 183, 187, 193, 201, 209, 211, 213, 215, 218–220, 225, 231, 232, 236, 258, 267, 273]	Analytical conceptual research
[2, 22, 25, 29, 35, 37, 42, 46–48, 55, 63–65, 67, 69, 70, 72, 75–78, 84, 85, 88–91, 93, 95, 98, 99, 102, 104, 107, 113–115, 117, 132, 133, 136, 138, 147, 149, 152, 153, 165, 178–182, 184, 188, 190, 191, 199, 212, 244]	Analytical mathematical research-Logical and descriptive modeling
[24, 28, 39, 45, 62, 108, 116, 122–125, 129, 134, 157, 160, 162, 166, 170, 177, 185, 192, 197, 198, 203, 216, 217, 221]	Analytical mathematical - Linear programming
[12, 135, 197, 221, 224]	Analytical mathematical -Mixed integer programming
[17, 75, 76, 107, 119, 154, 159, 161, 171, 186, 189]	Analytical mathematical -Dynamic programming
[26, 27, 30, 31, 36, 51, 56, 60, 71]	Analytical mathematical- Gradient based algorithms
[10, 58, 66, 68, 118, 120, 176]	Analytical mathematical- Nature based algorithm:
	Genetic algorithms
	Particle swarm algorithms
	Simulated annealing
	Immune algorithm
[15, 112, 121, 142, 227, 228]	Analytical mathematical- Simulation modelling
[20, 23, 109, 111, 130, 137, 144, 145, 156, 158]	Analytical statistical research
[18, 126]	Empirical statistical research
[86, 204, 229, 230, 233–235, 238–240, 243, 245–247, 250–252, 256, 259, 261, 263–265, 268–271, 281, 282]	Empirical experimental research
[131, 138, 141, 167, 169, 172, 187, 194, 195, 205–208, 210, 214, 222, 223, 226, 237, 241, 242, 248, 253–255, 257, 260, 262, 266, 272, 274–280]	Empirical case study

number of variables and constraints involved. These are only suitable for solving the FCO problems with limited variables and constraints and also LP require high computer memory and long CPU time in order to process complex mathematical algorithms [287]. Linear programming has shown to be incapable of describing the actual complexity of realism of FCO models. Also the dynamic programming has the limitations: lack of general algorithms and dimensionality [284].

Gradient based methods are mainly used for aerodynamic design optimization of aircraft and they minimize the convex differential functions. Gradient-based methods provide a clear convergence criterion. The limitations of gradient-based methods are; high development cost, noisy objective function spaces, inaccurate gradients, categorical variables, and topology optimization [285]. This limits their use for global FCO. Simulation modeling in the area of the FCO is used to observe how an aircraft performs, diagnose problems and predict the effect of changes in the aircraft system, evaluates fuel consumption, and suggest possible solutions for improvements. Simulation techniques can be ideal for reproducing the behaviors of a complex design system of the aircraft. Many previous studies have analyzed the capability of simulation modeling in fuel consumption modeling and optimization [15, 112, 121, 142, 227, 228]. One of the major limitations of simulation techniques is its inability to guarantee optimality of the developed solution. Also the simulation technique is very expansive.

The nature based algorithms can be based on swarm intelligence, biological systems, physical and chemical systems [288]. The researchers have learned from biological systems, physical and chemical systems to design and develop a number of different kinds of optimization algorithms that have been widely used in both theoretical study and practical applications. Since the nature is the main source of inspiration of these algorithms, so they are called nature based algorithms [288, 289]. In FCO problems the nature based algorithms are classified into the genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing, and immune algorithm. GA is an evolutionary based stochastic optimization algorithm with general-purpose search methods which simulate the processes in a natural evolution system [290]. GA is an efficient algorithm with flexibility to search the complex spaces such as the solution space for the global air transport fuel consumption. GA algorithms are well suited to multi-objective optimization problems because they can handle large populations of solutions [58]. The advantages of using GA techniques for solving large optimization problems are its ability to solve multidimensional, non-differential, non-continuous, and even nonparametric problems [291]. Moreover, it solves the problem with multi solutions. GAs has been proven to be a highly effective and efficient tool in solving complex aircraft design, and some of their successful applications in the optimization of fuel consumption models have been proposed in the literature [58, 68, 176]. There are, however, a number of challenges when designing a customized GA procedure to solve a certain FCO problem. The first difficulty is the construction of customized genetic operators to perform the mating process on the chromosomes. Secondly, designing a constraint handling mechanism is generally a complicated task in order to ensure the effective implementation of the model constraints. In addition, when populations have a lot of subjects, there is no absolute assurance that a genetic algorithm will find a global optimum [290]. PSO has been extensively used to many engineering optimization areas due to its simple conceptual framework, unique searching mechanism, computational efficiency, and easy implementation [290]. In order to find the optimal solution, the PSO algorithm simulates the movement of a set of particles in the search space under predetermined rules [292]. The particles use the experience accumulated during the evolution, for finding the global maximum or minimum of a function [118]. The PSO algorithm does not require sorting of fitness values of solutions in any process and this might be a significant computational advantage over GA, especially when the population size is large [293].

Simulated annealing (SA) is a one of the most common meta-heuristics techniques, and has been successfully applied to solve several types of combinational optimization problems [294]. The main advantages of SA are; it deals with arbitrary systems and cost functions, relatively easy to code, even for complex problems. But its main disadvantage is that, it cannot tell whether it has found an optimal solution, it requires some complimentary bound [295]. Pant, R. [66] used SA for the aircraft configuration and flight profile optimization. In case of aircraft fuel consumption, the objective function was found to be highly nonlinear and discontinuous, with several combinations of design variables not having a feasible solution. Hence, gradient-based optimization methods could not be applied to obtain the optimal solution, and the SA approach was adopted [66]. Ravizza, S. et al., [120] adopted the population based immune algorithm for tradeoff between the taxi time and fuel consumption in airport ground movement. Immune Algorithms are related to the Artificial Immune Systems field of study concerned with computational methods. Immune Algorithms are inspired by the process and mechanisms of the biological immune system. The main advantages of the algorithm are dynamically adjustable population size, combination of local with global search, defined convergence criterion, and the capability of maintaining stable local optimum solutions [296]. More knowledge about the fuel-based objective function is needed to formulate the combined FCO function. Lastly the analytical-statistical research integrates logical, mathematical models from analytical-research and statistical models from empirical research for fuel consumption & optimization research. Table 2 shows the list of analytical statistical studies [20, 23, 109, 111, 130, 137, 144, 145, 156, 158]. Summarily, the main objective of analytical statistical research is to provide, the more cohesive model for empirical statistical testing [283].

3.2.2 Empirical research methodology

The empirical research methodology uses data from external organizations or businesses to test if relationships hold in the external world [283]. Empirical research methods for fuel consumption & optimization studies are classified into three sub-categories, namely; empirical-experimental [86, 204, 229, 230, 233–235, 238–240, 243, 245–247, 250–252, 256, 259, 261, 263–265, 268–271, 281, 282], empirical statistical [18, 126], and empirical case studies [131, 138, 141, 167, 169, 172, 187, 194, 195, 205–208, 210, 214, 222, 223, 226, 237, 241, 242, 248, 253–255, 257, 260, 262, 266, 272, 274–280]. The empirical-experimental research examines the relationships by manipulating controlled treatments to determine the exact effect on specific dependent variables [283, 297]. The empirical- experimental research methodology for fuel consumption & optimization studies are mainly consist of fuel properties and optimization studies. The main advantage of using the empirical-experimental research is, it may understand and respond more appropriately to dynamics of situations of fuel consumption. The main purpose of empirical statistical research methodologies is to empirically verify theoretical relationships in larger populations from actual practices for reducing the number of relationships for future application [283, 297]. Literature reports the two empirical statistical analyses [18, 126], in which fuel consumption models are tested for their reliability and validity. Lastly, the empirical case study examines the organizations across time and provides the dynamic dimension to theory for promoting the theoretical concepts [283]. Moreover, the empirical case studies provide new conceptual insights by empirically investigating individual cases of complex fuel consumption relations of the real world.

4 A simple meta-analysis

In general, the nature of data available in the studies reviewed determines the type of meta-analytic method that can be applied. In this paper, we perform summary counts of the determinants of the article studied, fuel prices, and evolution of fuel efficiency trends. Though this simple meta-analysis provides only descriptive information with no statistics, it is expected to shed greater understanding of the development and evolution of FCO research trends in the air transport industry and to identify potential research areas for further research and for improvement. Accordingly, we analyzed 277 articles related to FCO research in air transport by (1) Yearly distribution of articles, and evolution of fuel prices and fuel efficiency trends (2) Distribution of research methodologies (3) Journal wise (Discipline) distribution.

4.1 Yearly distribution of research articles, fuel prices and evolution of fuel efficiency trends

Progresses in literature related to fuel consumption have been started since after 1973–74 Arab oil embargoes. After that, the oil crises fuel conservation and efficiency became the main focus of the aviation industry. Table 4 Yearly distributions of research articles, fuel prices, and evolution of fuel efficiency trends of air transport from 1973 to 2014 [298]. The major growth in optimum use of fuel occurred after the 1973 Arab oil embargo. During the period 1973–1980, the oil prices increased sharply and U.S. economy had focused the need for more fuel efficient transportation [98]. The first oil shock was in 1973–1974 and the second one in 1978–1980 [16]. During the period 1973–1975, the oil prices increased sharply as shown in Table 4, while the airline jet fuel prices stabilized in 1976 compared to sharply rising prices in the three preceding years. The jet fuel price in 1975 rose to about 2.01 dollar/ million BTU, from the 1.54 dollar/ million BTU in 1974. During the period 1973–1975, the net average percentage change in fuel prices was 51 % and during the period 1976–1978, the fuel prices increased by an amount 8-13 %, this shows the stability of jet fuel prices. But, again during the period (1978–1980) second oil shock the jet fuel prices increased sharply, by net average percentage 49 % and this was only 2 % less than the 1973–1975 time periods. Also increased air travel volume was one more main reason behind the rising fuel prices, because the passengers were relatively unconcerned to the ticket price because the benefits of faster travel and this was a very interesting trend in that period [16]. Table 4 shows the distribution of research articles during the period 1973–1980. Total number of articles from 1973 to 1980 were 38 and most of the studies have been found in 1978 i.e.9. It is clear from the Table 4, that the numbers of the articles during the first oil shock (1973–1975) were 9 and after first oil shock and second oil shock, they have been increased to 29. Figure 3 shows the yearly distribution of a number of articles and fuel prices.

In the early 1980s, the non OPEC countries had also started production of oil therefore oil consuming counties decreased their oil demand from OPEC countries. As a result the OPEC production declined after 1981 and in response to declining production. Furthermore, Iran and Iraq war, and ceasing of oil production by Saudi Arabia were the main reasons for fuel price decline [299]. During the period 1981–1985 the US airline jet fuel prices declined from 7.49 to 6.51 dollar/ million BTU and also the net average % decline in fuel prices was 3.4 %. But, the biggest decline in jet fuel prices occurred in 1986, during this year the jet fuel prices decreased by 32 % as compared to 1985 prices. After, the 1986 to 1989 the fuel prices stabilized with net average % change of only 2 %. Again, in 1989 the fuel prices increased by 28 % as compared to 1988 prices. The 1990 spike was mainly attributable to the first Gulf War, but the price spike was only for shorter periods [299]. It is clear from the Fig. 3 that the fuel prices from 1973 to 1981 increased continuously and from 1981 to 1989 decreased continuously. The total numbers of articles during this period were 23. Most of the studies have been found in 1987 i.e. 8. During the period 1981–1990, the number of articles also decreased as compared to 1973–1980.

In the period 1991–2003 the jet fuel prices remained relatively low and stable. During the period 1991–1995, the fuel prices continuously decreased and they fell from 5.18 to 4.04 dollar/million BTU. In 1998 oil prices were affected by the Asian financial crisis. They fell to below 25 % as that of 1997 jet fuel prices. But, the Asian economies recovering from the financial crisis, prices increased during 2000. The fuel prices rose by 63 % as compared to that of 1999 prices. The total number of articles from 1991 to 2003 were 61 and most of the studies have been found in 2003 i.e.9. The numbers of the articles were more than the last two decades.

During 2004–2014 world aviation fuel consumption and its production increased to a greater extent. The rising demands of countries such as China and India, and political instability in Venezuela, Nigeria, Russia and particularly Middle East have troubled oil supplies and raising prices [300]. From Fig. 3 it is clear that the fuel prices rose sharply from 2002 to 2008 and during the period 2004–2009, the fuel prices experienced large fluctuations from 2004 to 2009. In 2008 jet fuel prices reached levels more than three times those of 2003. While in 2009 fuel prices fell from their 2008 high, and it all most reached half of 2008 fuel prices. This spike and decline in jet fuel prices have demonstrated uncertainty in the magnitude of future fuel prices. Again, in 2011 the jet fuel prices rose by 6.34 dollar/million BTU more than those of 2010 and after that from 2012 to 2014 they decline net average % of 6.20. During the period 2004–2014 the numbers of research studies have also been increased. Table 4 shows, the

Table 4 Yearly distributions of research articles, fuel prices, and evolution of fuel efficiency trends [298]

Year	No. of Articles	Evolution of fuel efficiency trends research trends	References	Jet fuel prices (dollar/million BTU)
1973	3	Turbojet revolution, fuel burning rate study	[102, 103, 281]	0.89
1974	5	Operational efficiency, socioeconomic and political measures, aircraft size	[174, 175, 183, 222, 223]	1.54
1975	1	Hydrogen fuel	[280]	2.01
1976	7	Turbofan 1st generation, policy measures, Hydrogen fuel, operational efficiency	[101, 171–173, 220, 221, 279]	2.18
1977	7	Aircraft size, turboprop potential, fuel management model	[96–100, 170, 278]	2.51
1978	9	Fuel combustion requirement, future turbofan, hydrogen fuel, airport and terminal design,	[92–95, 168, 169, 275–277];	2.86
1979	2	Engine efficiency, airport capacity	[91, 167]	3.85
1980	4	Turbofan 2nd generation, and 3rd generation aircraft design, hydrogen fuel	[88–90, 274]	6.27
1981	1	Fuel allocation model	[166]	7.49
1982	3	Fuel burn estimation	[85–87]	7.02
1983	1	Hydrogen fuel	[182]	6.94
1984	2	Aircraft design, fuel consumption estimation	[106, 165]	6.87
1985	1	Turbofan performance estimation	[84]	6.51
1986	2	Advance turboprop, Aircraft material potential	[82, 83]	4.42
1987	8	Alternative fuels, hydrogen fuel, fuel prices, modern turboprop, optimal cyclic cruise	[79–81, 107, 219, 270–272]	4.55
1988	1	Variable wing camber	[78]	4.15
1989	3	Aerodynamic efficiency, fuel properties	[77, 268, 269]	4.70
1990	1	Ground efficiency	[164]	6.03
1991	2	Hydrogen fuel, terminal area traffic management	[163, 267]	5.18
1992	5	Hydrogen fuel, endurance performance optimization, fuel management model, optimum cruise lift	[1, 75, 76, 162, 266]	4.84
1993	1	Thermal stability of jet fuel	[282]	4.47
1994	5	Fuel properties, taxation policy, fuel consumption modeling	[161, 218, 263–265]	4.14
1995	2	Policy measures	[73, 74]	4.04
1996	5	Wave rotor optimization, hydrogen fuel & fuel properties, engine design	[71, 72, 105, 261, 262]	4.88
1997	5	Alternatives fuels & fuel properties, cruise range performance and prediction	[70, 257–260]	4.53
1998	2	Terminal airdrome, policy measures	[69, 160]	3.40
1999	5	Turbofan engine design and flight profile optimization, incentive based regulations	[65–68, 217]	4.23
2000	2	Aircraft turnaround efficiency, chemical kinetic model	[159, 256]	6.90
2001	5	Technological and operational efficiency, policy options, turbofan and turbojet engine	[20, 63, 158, 216, 255]	5.79
2002	5	Airport infrastructure, technological and operational efficiency, socioeconomic and policy options	[7, 19, 157, 214, 215]	5.54
2003	9	Biodiesel and fuel properties, aircraft size, socioeconomic and policy options, engine performance optimization	[61, 62, 154–156, 213, 252–254]	6.76
2004	5	Blended wing body, technological measures, alternative fuels, infrastructure, socioeconomic & policy options	[59, 60, 152, 153, 212]	9.06
2005	6	Aircraft design optimization, fuel management model, alternative fuels, operational and socioeconomic & policy measures	[57, 58, 150, 151, 211, 251]	13.10
2006	8	Technological and operational efficiency, fuel properties optimization, turbofan engine optimization	[55, 56, 113, 114, 148, 149, 249, 250]	14.89
2007	13	Airport infrastructure, alternative fuels & fuel properties, SAGE model, operational efficiency, aircraft size	[52–54, 143–147, 209, 210, 246–248]	16.46
2008	12	Hydrogen fuel and fuel properties, operational and technological efficiency, aircraft landing scheduling	[48–51, 142, 178–181, 224, 244, 245]	23.13
2009	13	Socioeconomic & policy measure, alternative fuels & fuel properties, technological and operational efficiency	[11, 42–47, 137–140, 208, 243]	12.64

Table 4 (continued)

Year	No. of Articles	Evolution of fuel efficiency trends research trends	References	Jet fuel prices (dollar/ million BTU)
2010	21	Technological & operational efficiency, Socioeconomic & policy measure, alternative fuels & fuel properties	[2, 3, 37–41, 104, 134–136, 202–207, 240–242]	16.43
2011	18	Technological & operational efficiency, Socioeconomic & policy measure, alternative fuels & fuel properties	[15, 16, 34–36, 129–133, 199–201, 236–239]	22.77
2012	16	Technological & operational efficiency, Socioeconomic & policy measure, alternative fuels & fuel properties	[10, 32, 33, 123–128, 196–198, 229, 233–235]	24.44
2013	22	Geared turbofan, Technological & operational efficiency, Socioeconomic & policy measure, alternative fuels & fuel properties	[13, 29–31, 118–122, 177, 187–195, 228, 231, 232]	23.30
2014	28	Technological & operational efficiency, Socioeconomic & policy measure, alternative fuels & fuel properties	[12, 14, 17, 18, 21–28, 108–112, 115–117, 176, 184–186, 225–227, 230]	22.58
Total	277			

total numbers of articles from 2004 to 2014 were 165, which is more than the number of articles than from 1973 to 2003. Most of the studies have been found in 2014 i.e. 28. Figure 3 shows the increasing trend of number of articles from 2004 to 2007 and during the same period the oil prices had also increased. But in the last 2 years the total numbers of articles were 50, and this represents the 18 % of the total number of articles. From Table 4 it is observed that the number of published articles between the period 1973 and 2000 is less (90 articles), than that of the period 2001–2014.

Historically, jet fuel prices have been the main driver for improvements in aircraft fuel efficiency [16]. Table 4 also shows the yearly evolution of the fuel efficiency trends from 1973 to 2014. Evolution of fuel efficiency trends has explored the four factors .i.e. technological efficiency improvement, operational efficiency improvement, socioeconomic & policy measures, and alternate fuel use, similar as that identified earlier. But, the alternative fuels have only shown the future potential options for fuel efficiency improvement, because of concerns regarding their economic cost of production and the current lack of feedstock availability limits their near term availability of aviation [225]. So, only the improvement in aircraft fuel efficiency from 1960 to 2014 were mainly due to technological factors, operational factors, load factors, and aircraft size. The various trends evolved in the Table 4 are also grouped under these four factors. From Table 4 it is clear that the entire fuel efficiency factor have been evolved continuously from 2007 to 2014, as compared to other time span. According to Grote, [14] average fuel-efficiency improvement between 1960 and 2008 was 1.5 % per annum, but over the time it has slowed down. Lee et al. [20] predicted that the reduction in energy intensity during the period 1959–1995 were mainly due to improvement in engine efficiency (57 %), aerodynamic efficiency (22 %), aircraft capacity (17 %), and other changes such as increased aircraft size (4 %). Owen, [301] showed a 70 % improvement in fuel efficiency as fuel per RPK between 1970 and 2006 and these improvements were mainly due to improvements in load factor (20 %), aircraft size (26 %) and finally technical and operational improvements to the fleet (24 %). However a great part of this improvement was gained during the 1970–1980 (40 %) and rest of improvements had been achieved during 1980–1990 (22 %), 1990–2000 (23 %), and 2000–2006 (15 %). Figure 4 shows the evolution of fuel efficiency trends in US domestic and international aviation from 1970 to 2013. It is clear from Fig. 4 that the US domestic and international airlines passengers' air traffic, fuel consumption decreased from 9 liters/100Km to 3 liters/100Km and 10 liter/100Km to 4 liters/100Km during the time period from 1970 to 2013.

Table 5 Percentage (%) of research methodologies for FCO research

Research methodology of FCO research	Percentage (%) of research methodologies
A. Analytical research :	
1) Analytical conceptual research	26
2) Analytical mathematical:	22
a) Logical and descriptive modeling	10
b) Linear programming	2
c) Mixed integer programming	4
d) Dynamic programming	3
e) Gradient based algorithms	2
f) Nature based algorithm	2
h) Simulation modeling	4
3) Analytical statistical research	
B. Empirical research	
1) Empirical statistical research	1
2) Empirical experimental research	10
3) Empirical case study	14
Total:	100

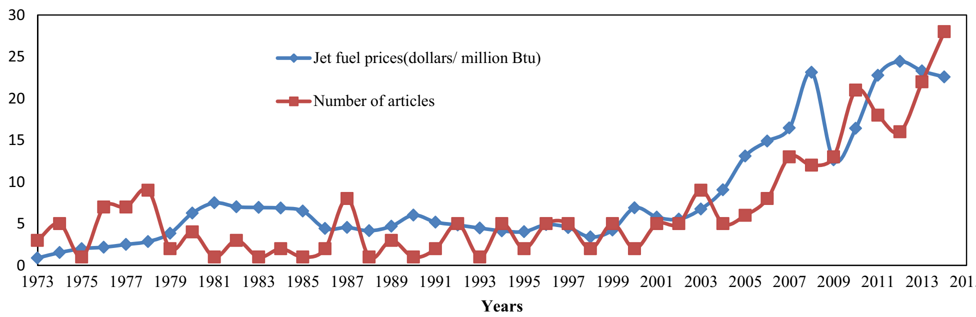

Fig. 3 Yearly distribution of number of articles and jet fuel prices

Improvements were particularly rapidly during the 1970s, when wide body aircraft came into the service and in the early to mid-1980s, when mid-range aircraft like turbofan 2nd and third generation entered into the service. Figure 4 shows the 60 % and 52 % reduction of fuel burn of US domestic and international airlines on a seat-Km (passengers only) during the time period 1970–1985. The flattening slope of the fuel burns curve in Fig. 4 suggests a notable decrease in the rate of fuel efficiency improvement over the time period 1985–2000. Through 1985–2000, we estimate that the efficiency of aircraft improved 15 % for both airlines. Lastly, the figure shows that the fuel efficiency improvement of 9 % and 11 % for the domestic and international US airlines during the time period 2001–2014.

4.2 Distribution of articles by research methodologies of FCO research

Table 5 shows the percentage distribution of research methodologies for the FCO research in air transport. It is clear from the Table 5 that the analytical research methodologies have the higher percentage (75 %) than the empirical research methodologies (15 %). Also, the near about haft of the research methodologies are from the analytical- conceptual, logical, and descriptive modeling. These studies mainly include the; fuel burn and emission calculation, prediction and forecast for future scenario. Moreover, the analytical-conceptual, logical, and descriptive modeling, empirical-experimental and, empirical case studies are more predominately proposed by many researchers 72 % of methodologies rather than 21 % methodologies of optimization modeling. It is also observed from Table 5 that the optimization modeling research techniques, i.e. Linear programming, dynamic programming, MIP, gradient based methods, and natural algorithms have very low percentage (21 %).

4.3 Distribution of articles by journals (discipline wise)

The journal wise the number of FCO research articles in international journals is computed and the same is shown in Table 6. During the period 1973 to 2014 there are 277 research articles on FCO research appeared in 69 journals and most of the article have been found in Journal of Air Transport Management (9 %) followed by Transportation Research Part D: Transport and Environment, and International journal of Hydrogen Energy both having 7 % each. Since the numbers of articles against many journals are few to get some simple inferences, the research journals reviewed are grouped with respect to disciple wise, i.e. Transportations (TP), Aerospace Sciences (AS), Fuel & Energy (F&E) and Environmental Science (ES). Table 6 shows the discipline wise total % of the articles. Accordingly, distribution of articles of journals (discipline wise) is computed and shown in Fig. 5. It is observed that the Transportation (TP) related journals have far the most articles i.e. 111. This indicates that TP is a major important field affecting the FCO in air transport. Followed to TP related journals, the Aerospace sciences (AS) are having more articles on FCO research. The differences between the

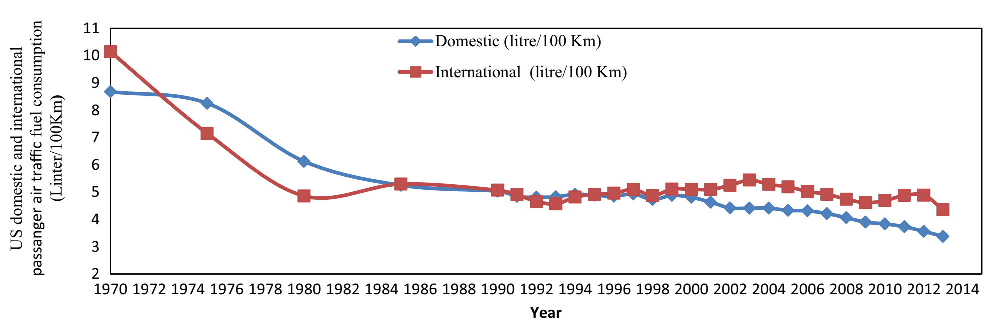

Fig. 4 Evolution of fuel efficiency trends in US domestic and international aviation from 1970 to 2013 [302]

Table 6 The discipline wise total % of articles

SI. No.	Journal name	No. of articles	Discipline code	Discipline total & % articles
1.	Journal of Air-Transport Management	26	TP	111 [40 %]
2.	Transportation Research Part D: Transport and Environment	19	TP	
3.	Transport Policy	10	TP	
4.	Transportation Research Part A: Policy and Practice	6	TP	
5.	Journal of Transport Economics and Policy	6	TP	
6.	Transportation Research	5	TP	
7.	Transportation Journal	4	TP	
8.	Transportation Planning and Technology	4	TP	
9.	Transportation Research Part E: Logistics and Transportation	3	TP	
10.	European Transport Research Review	3	TP	
11.	Journal of Air Transportation	2	TP	
12.	Transportation Research Part B: Methodological	2	TP	
13.	Transportation Research Part C: Emerging Technologies	2	TP	
14.	Transportation Science	1	TP	
15.	Transport Reviews	1	TP	
16	Journal of Advance Transportation	1	TP	
17.	Public Transport	1	TP	
18.	Journal of Transport Geography	1	TP	
19.	Technology Analysis & Strategic Management	4	TP	
20.	Interfaces	3	TP	
21.	Operations Research	2	TP	
22.	European Journal of Operational Research	1	TP	
23.	Journal of Technology Management & Innovation	1	TP	
24.	Management Science	1	TP	
25.	The Journal of Operational Research Society	1	TP	
26.	Industrial Engineering Letter	1	TP	
27.	Aircraft Engineering and Aerospace Technology	14	AS	89 [32 %]
28	Journal of Aircraft	14	AS	
29.	Progress in Aerospace Sciences	12	AS	
30.	Aerospace Science and Technology	10	AS	
31.	Journal of Propulsion and Power	8	AS	
32.	The Aeronautical Journal	6	AS	
33.	AIAA Journal	4	AS	
34.	Acta Astronautica	4	AS	
35.	Proceeding of Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering	2	AS	
36.	SAE : International Journal of Aerospace	2	AS	
37.	Aircraft Design	2	AS	
38.	Chinese Journal of Aeronautics	2	AS	
39.	Journal of Engineering for Gas Turbines and Power	2	AS	
40.	Canadian Aeronautics and Space Journal	1	AS	
41.	Technology and Culture	1	AS	
42.	Material & Design	1	AS	
43.	Advance Material Research	1	AS	
44.	Technological Forecasting and Social Change	1	AS	
45.	Automatica	1	AS	
46.	Fuzzy Sets and Systems	1	AS	
47.	International Journal of Hydrogen Energy	19	F & E	64 [23 %]
48.	Fuel	11	F & E	

Table 6 (continued)

SI. No.	Journal name	No. of articles	Discipline code	Discipline total & % articles
49.	Energy Conversion and Management	5	F & E	
50.	Energy	5	F & E	
51.	Energy Policy	4	F & E	
52.	Progress in Energy and Combustion Science	3	F & E	
53.	The OPEC Energy Review	3	F & E	
54.	Proceedings of the Combustion Institute	2	F & E	
55.	Journal of Energy (AIAA)	2	F & E	
56.	Fuel Science and Technology International	2	F & E	
57.	Annual Review of Energy and the Environment	2	F & E	
58.	Applied Energy	2	F & E	
59.	Renewable and Sustainable Energy Reviews	1	F & E	
60.	Combustion and Flame	1	F & E	
61.	Fuel Processing Technology	1	F & E	
62.	Journal of Energy Technologies and Policy	1	F & E	
63.	Atmospheric Environment	6	ES	13 [5 %]
64.	Journal of Cleaner Production	2	ES	
65.	Environment Science and Policy	1	ES	
66.	International Journal of Environmental Research and Public Health	1	ES	
67.	Philosophical Transactions: Mathematical, Physical and Engineering Sciences	1	ES	
68.	Climate Policy	1	ES	
69.	Carbon Management	1	ES	
	Total	277		100

TP and AS articles are only 8 %. This could be due to the fact most of the articles reported in TP are also related to road and rail transport and those were not included in the study. The number of articles that appeared in discipline F&E and ES are relatively low with discipline TP, and AS. This could be due to the low correlation between the objectives of various studies reported on FCO research in air transport and scope of the respective journals.

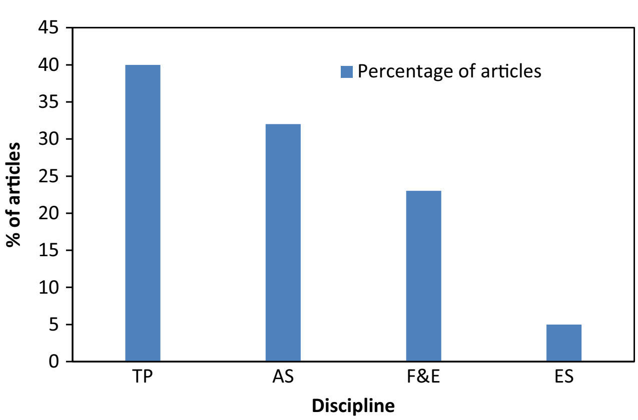

Fig. 5 Discipline wise percentage of articles

5 Findings, conclusions, direction for future research implications, and limitations

It is known that the history of the FCO research is not long compared with other industries. To the best of our knowledge, so far, no attempt has been made to classify and analyze the literature dealing with FCO with air transport research. Thus, in this paper we have attempted to review and classify the FCO research. Accordingly, an extensive literature review has been attempted from various journals and web based articles that are possible outlets for this research. This resulted in the identification of 277 articles from 69 journals by year of publication, journal, and topic area based on the two classification schemes related to FCO research, published between, 1973 to December- 2014. In addition, the study has identified the 4 dimensions and 98 decision variables affecting the fuel consumption. Also, this study have explained the six categories of FCO research methodologies (analytical - conceptual, mathematical, statistical, and empirical-experimental, statistical, and case studies) and optimization techniques (linear programming, mixed integer programming, dynamic programming, gradient based algorithms, simulation modeling, and nature based algorithms). The findings of this study indicate that the analytical-mathematical research methodologies represent the 47 % of FCO research. The results show that there is an increasing trend in research of the FCO. It is observed that the number of published articles between the period 1973 and 2000 is less (90 articles), so we can say that there are 187 articles which appeared in various journals and other publication sources in the area of FCO since 2000. Furthermore there is increased trend in research on FCO from 2000 onward. This is due to the fact that continuously new researchers are commencing their research activities in FCO research. This shows clearly that FCO research is a current research area among many research groups across the world. Lastly, the prices of jet fuel have significantly increased since the 2005. The aviation sector's fuel efficiency improvements have slowed down since the 1970s–1980s due to the slower pace of technological development in engine and aerodynamic designs and airframe materials.

From the matching of published articles according to our proposed classification schemes and according to performance metric, it seems there are considerable untouched research problems in FCO research. Over the last four decades, the significance of FCO at tactical and operational levels has been recognized by academics and practitioners as a competitive advantage for the better performance of airlines. This study reviewed the state of the art in optimization modeling of fuel consumption. Our findings have some important conclusions of FCO research and suggest the following directions for future research in the area:

- We classified the current literature into four dimensions based on the degree of complexity and identified 98 decision variables affecting the FCO. This classification of dimensions and their respective decision variables could be of potential value to future researchers in the field and is also capable of further refinements. These parameters, if addressed, could result in a consistent, and comparable database of the FCO research.
- We conclude that FCO models need to address the composite fuel consumption problem by extending models to include all the dimensions, i.e. aircraft technology & design, aviation operations & infrastructure, socioeconomic & policy measures, and alternative fuels & fuel properties. FCO models typically comprise all the four dimensions and this reality need to be taken into account in global FCO models. In addition, these models should have objectives or constraints to evaluate the aircraft sizes according to market structure, impact of various policy measures on fuel burn, and near term potential alternative fuel options in the global FCO problem. In the models reviewed, we evaluated that, only the few authors considered these factors.
- We also conclude that the performance measures (.i.e. technological efficiency and operational efficiency) adopted in FCO models need to be broadened in definition to address socioeconomic & political and alternative fuels potentials. Although real FCO models emphasize a variety of performance measures in practice—none of FCO models allow for this variety.
- A second classification was also presented in the paper based on the research methodologies and techniques used for tackling the proposed fuel consumption problems. One perpetual concern is the development of appropriate research approaches for tackling large fuel consumption and optimization problems. Various research techniques have been used to deal with aircraft design, operations, infrastructure, socioeconomic & political, and alternate fuel problems ranging from mathematical models; gradient based algorithms, simulation modeling, and to the latest nature based algorithms. Hence, there is a need to further extend the effectiveness of the existing solution techniques to be capable of handling realistic FCO problems with large numbers of variables and constraints. Heuristics and meta-heuristic techniques are still the dominant solution techniques in the literature of FCO [10, 58, 66, 68, 118, 120, 176]. Genetic algorithms (GAs), particle swarm optimization (PSO), simulated annealing (SA), and immune algorithm (IA), has been recognized by several researchers as the most promising techniques. There is still a need to further extend the effectiveness of the existing research methodologies and to test the new arrivals such as Ant Colony Optimization (ACO), Bee Colony Optimization (BCO) techniques, and Firefly optimization techniques (FA).
- Only 1 % and 2 % articles discussed the empirical statistical methodology and analytical-mathematical methodology based on the natural algorithms within the context of the FCO. As far as the empirical statistical research methodology is concerned, it verifies models for their empirical validity in larger populations to reduce the number of relationships in future research, while the nature based algorithms has been considered the most powerful tool for optimization. More research could be done on this issue. Therefore, we observed that, the combination of empirical statistical methodology followed by analytical- mathematical nature based algorithms could be of potential research methodologies to future researchers in the field.
- It is observed that the number of published articles between the period 1973 and 2000 is less (90 articles), so we can conclude that there are 187 articles which appeared in various journals and other publication sources in the area of FCO since 2000. With this it is possible to comment that on an average 13 articles per year appeared in journals/other publication sources related to FCO research since 2000. Furthermore there is increased trend in research on FCO from 2000 onward. This is due to the fact that continuously new researchers are commencing their research activities in FCO research. This shows clearly

that FCO research is a current research area among many research groups across the world.

- The prices of jet fuel have significantly increased since the 2005. If air transport improves their fuel efficiency in response to increase in jet fuel prices, then some of the increases in the cost of air travel can be reduced. The aviation sector's fuel efficiency improvements have slowed down since the 1970s-1980s due to the slower pace of technological development in engine and aerodynamic designs and airframe materials. Technological improvements will take a long time for development, while the operational change is most near-term, could lead to significant reduction in air fares in the face of much higher oil price, but it may not achieve a significant option given the fast increase in air travel demand. Also the study has evolved the various trends of aircraft technological factors, and operational factors for fuel efficiency improvement. These factors could be potential options for the FCO.
- Also an important outcome of the analysis of trends in literature output was that we noticed clear parallels between interest in FCO research and global occurrences related to the oil and energy industry, whether social, political or economic, whether scheduled or sudden; whether positive or degrading to the energy sector. And hence, ultimately, oil prices seem closely related to interest in the FCO.
- In addition a total of 277 articles were classified according to our classifications. We analyzed the identified articles from the 69 journals by year of publication, journal, and topic area. This particular analysis could provide guidelines for the pursuit of future research on FCO and its applications by explaining the chronological growth of aviation fuel efficiency over the years, the challenging areas of fuel efficiency improvement and application, and the major issues surrounding environmental impact, fuel prices, and competitions among the airlines.
- Finally, we acknowledge that this review cannot be claimed to be exhaustive, but it does provide a reasonable insight into the state-of-the-art on FCO research. Thus, it is hoped that this review will provide a source of reference for other researchers/readers interested toward FCO research and help stimulate further interest. Future work will concentrate on the development of an appropriate information framework for FCO research in air transport. After that, this informational framework should be checked for reliability and validity. This leads to the development of a structural model of fuel consumption in the air transport industry and further knowing the relationships among the variables an optimization model will be constructed. Furthermore, this study will also provide the base for fuel conservation, energy efficiency, and emission reduction (As CO_2 emission are proportional to aircraft fuel burn) in the aviation sector.

This study might have some limitations. Readers should be cautious in interpreting the result of this study, since the findings are based on the data collected only from the international journal articles. The journals articles were mainly from; Transportations (TP), Fuel & Energy (F&E), Aerospace Sciences (AS), and Environmental Sciences (ES). Only, the 69 journal of these disciplines were included in the study. There might be other academic journal which may be able to provide a more comprehensive picture of the articles related to the application of the FCO in air transport. Second, we have reviewed academic/professional journals articles only; conference proceedings and dissertation were excluded, as we assumed that high quality research eventually published in academic/professional journals. Lastly, non-English publications were excluded from this study. We believe research regarding the application of FCO techniques have also been discussed and published in other languages.

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