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Energy efficiency in aircraft cabin environment: Safety and design

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ABSTRACT

Nowadays, aviation industry has been faced with technology challenges and safety requirements. Therefore, aircraft manufacturers give special attention to environmental building capacities regarding to passenger comfort and safety. This paper aims measuring safety and comfortability level of passenger accommodation during the flight. Since the environmental and safety issues could affect humans on a different level significance, this paper is based on the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method as a decision making tool for balancing those two inputs. With the aim of defining rank of existing world market aircraft the Saaty scale was used for developing the weight of different criteria whilst the improved TOPSIS method is used for ranking six aircraft: A320, A330, A340, B737, B747, B767 based on cabin environmental efficiency and safety.

1. Introduction

Nowadays, aircraft cabins have environmental problems similar to those of modern buildings, homes, offices, commercial places, etc. On the other hand, safety requirements are defined by more rigid measures. Some similarities could be found in fire protected systems. This issue is concerned by different regulatory standards worldwide since the studies show that people spend, on average more than 90% time indoors. As buildings, aircraft attempt to balance energy efficiency with other needs such as clean and fresh air, adequate ventilation and acceptable level of temperature and humidity. Different strategies such is mixturing outside air with recilculated air could result in increasing concentration of carbon dioxide (CO_2), volatile organic compounds (VOCs) or similar. On the other hand, contaminants may originate from cabin indoor sources such as panels, carpeting, etc. All this contaminants could impose building related symptoms by decreasing cabin air quality with health complaints of crew and passengers. Passengers could be affected by different health conditions depending on the time of exposure, while flight crew exposure could degradate pilot flight performance and reduce flight safety.

There is no such investigation within the literature that consider environmental stressors influence on passengers during the flight. The majority of authors analysed human performance and limitation related to flight and cabin crew or ATC [1] and airport [2] buildings. This paper explained other effects on passengers since there were recorded cases of panic due to the lower level of environmental conditions in cabin which directly mitigate flight safety. Some authors investigate influence of environmental on military pilots performances during the missions. The importance of the issue could be explained by 2P's dilemma, described as management dilemma of balancing protection (safety) versus productivity or level of service [3]. According to Hunt and Space [4], the role of predominant stressors has been changed during the time. Following figures present replacement of some stressors (Figs. 1 and 2).

2. Cabin safety

Cabin operations play a critical role in the safety of air transport worldwide. Historically, the role of cabin crew was seen as limited to evacuations in a post-accident scenario. Although this remains an essential duty of cabin crew, today the role of cabin crew goes beyond passenger evacuations. Cabin safety deals with all activities that cabin crew must accomplish during the operation of an aircraft to maintain safety in the cabin. Cabin crew contribute to safe, effective, and efficient operations in normal, abnormal and emergency situations. As demonstrated in numerous events, cabin crew play an important role in preventing accidents and serious incidents, including but not limited to events such as an in-flight fire, unruly passenger or decompression.

It is for this reason that international aviation organizations worldwide (EASA, ICAO, IATA, FAA, etc.) focus on cabin safety and continue to develop standards, procedures and best practices

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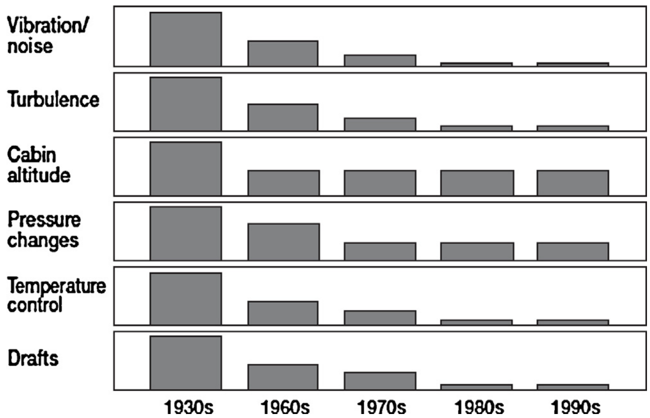

Fig. 1. Predominant stressors of the past.

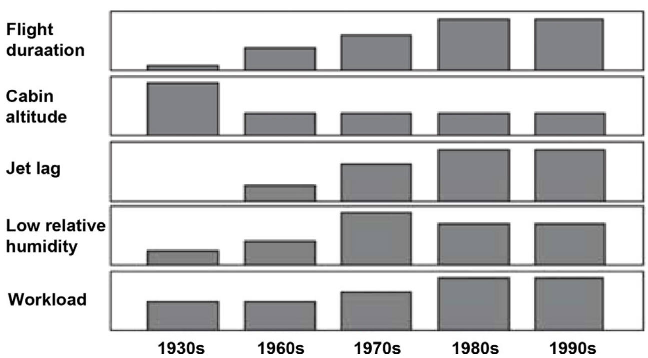

Fig. 2. Predominant stressors of the present.

to ensure safety in all aspects of cabin operations. Those organizations work with airlines, manufacturers and other industry partners in raising standards and implementing best practices. Cabin safety is a critical component of aviation safety as is an airline's safety management system which includes proactive data collection and the ensuing prevention activities regarding: cabin design and operation, equipment, procedures, cabin crew training, human performance and crew resource management and passenger management.

Aviation community seeks to continuously contribute to the reduction of incidents/accidents, and costs associated with ensuring the safe operation of commercial aircraft. This is achieved through the:

- development and promotion of recommended practices for the industry;
- analysis of worldwide trends and the initiation of corrective actions which offer tangible solutions;
- cooperation with aircraft manufacturers in developing technical installations, equipment and design;
- improving safety management system implementation and practice.

From the statistical point of view IATA [5] recorded findings are as follows:

- Out of the 81 total accidents in 2013, 37 contained a cabin safety dimension 62% of these accidents occurred on turboprop aircraft;
- 57% of these accidents occurred during the landing phase;
- 49% of these accidents resulted in a hull loss;
- 38% of these accidents occurred on jet aircraft;
- 30% of these accidents involved IATA members;
- 16% of these accidents resulted in fatalities.

In terms of cabin-related events, the breakdown is as follows:

- The predominant cabin-related event was evacuation, which accounted for 95% of all cabin-related events;
- 2 accidents involved a ditching.

Aviation industry has forced strong measures to provide safer air transportation by three blocks of defence [6] defined by professor Reason [7]. Those are regulation, procedures and training. This paper obtained results from other studies considered under those circumstances [8–10].

3. Cabin environment conditions

Cabin environment conditions are regulated by the supplied outside air. Fig. 3 presents typical modern aircraft ventilation system based on cabin of the Boeing B767 airplane which is provided by the engine compressors, cooled by air-conditioning packs located under the wing center section, and mixed with an equal quantity of filtered recirculated air.

Average air per passenger is 20 cubic feet per minute (half is filtered recirculated air and half is outside air) which provides complete cabin air exchange every 2–3 min. High air exchange rates are important due to maintenance of temperature, cabin pressurization, air flow, etc.

Cabin environmental conditions could generate in some cases hazards which are the basis for safety risks casual factors. In the literature, aviation hazards are always present in 3 possible states: acceptable, acceptable with monitoring actions and not acceptable under any condition [11]. It is important to understand that hazards are always present but the difference is by their nature: meteorological conditions, human factor, technical procedure, operational procedure, etc.

This paper analyses typical cabin environmental conditions during the flight time of occupants. Main comfort capabilities could be measured by total air supply to cabin, flow of outside air, cabin air temperature, volume per passenger, cabin noise and CO_2 cabin exhaust. Table 1 presents some results provided by simulation time for the aircraft Boeing B767 [12].

Physical measurements show that the data recorded from the instrumentation of the cabin and ventilation system were normally distributed and therefore tabulated as means and standard deviations (SD). Table 1 shows a summary of the quantities held constant during the 4 conditions (Columns 2–6), and of the resulting RH and CO_2-levels (Columns 7–9). The daily averaging period was from the time when steady conditions had been reached for RH and CO_2 until the end of the simulated flight.

Different cabin condition could provide variety of reaction on passengers on board. Some research [12] has detected following passenger reaction on provided conditions based on their subjective assessments. Data from subjective assessments and objective physiological tests could not be assumed to be normally distributed, and were therefore analyzed using the non-parametric Friedman two-way analysis of variance by ranks, followed by the Wilcoxon matched-pairs signed-ranks test for those cases in which the Friedman P-value was <0.05. Subjects with missing data were omitted from the analysis. Table 2 shows the significant results that were obtained.

4. Method for aircraft ranking based on measuring safety and comfort parameters

Presented paper describes a decision making methodology for aircraft ranking based on the TOPSIS (Techniques for Order Preference by Similarity to Ideal Solution) method. The TOPSIS method

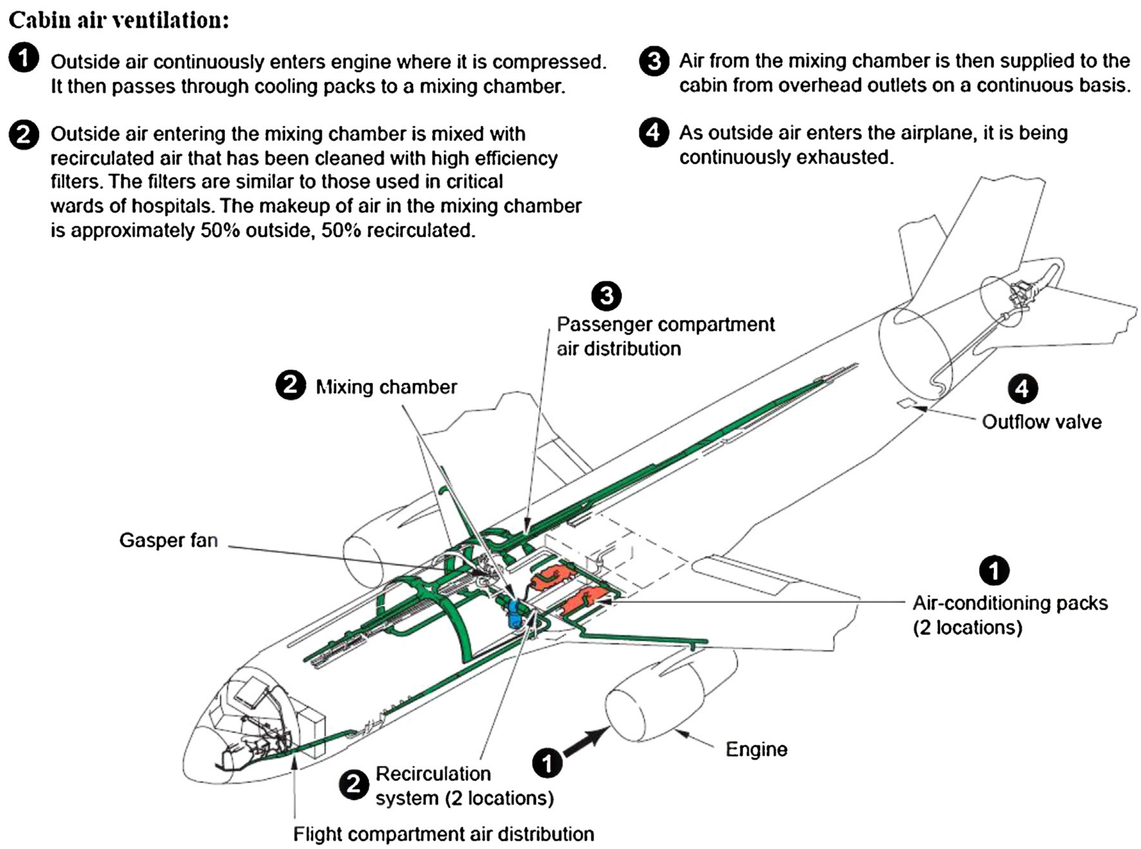

Fig. 3. Aircraft ventilation system based on cabin of the Boeing B767.

Table 1
System data averaged over conditions and daily periods from 9:45 to 15:45.

Condition [L/s per person]	Total air supply to cabin		Flow of outside air [L/s]		Flow of outside air*		Cabin air temperature [°C]		Window panel temperature		RH, cabin air [%]		CO_2, cabin exhaust		CO_2, outside air [ppm]	
	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
1.4	198.0	0.33	1.43	0.04	0.102	0.00	23.3	0.09	18.4	0.23	28.4	1.83	2490	124	425	9
3.3	200.0	0.29	3.33	0.02	0.238	0.00	23.3	0.07	18.7	0.24	16.0	1.20	1632	103	427	11
4.7	200.0	0.33	4.72	0.02	0.337	0.00	23.3	0.07	18.4	0.21	11.2	0.57	1317	66	406	11
9.4	200.0	0.30	9.43	0.02	0.674	0.00	23.3	0.06	18.8	0.18	6.8	0.40	893	37	421	13

* Present requirement of fresh air per occupant according to the FAR 25 is 0.25 kg/min.

is a multiple criteria method that identifies a solution from a finite set of points.

The basic principle is that the chosen points should have the "shortest" distance from the positive ideal and the farthest "distance" from the negative ideal solution. In the TOPSIS model, the measurement of weights and qualitative attributes do not consider uncertainty associated with mapping human perception to a number.

Table 2
VA-scale assessments with significant differences between conditions.

Period of exposure	VA-scale	Friedman test All		Wilcoxon matched-pairs signed-ranks test					
	1.4 vs			1.4 vs	1.4 vs	3.3 vs	3.3 vs	4.7 vs	
1st	10 min	Throat Irritation	0.043	0.425	0.053	0.009^	0.298	0.127	0.314
2nd	$3^{1/4}$	Air	0.014	0.165	0.071	0.010∨	0.812	0.053	0.183
		Noise	0.015	0.010∨	0.359	0.628	0.003^	0.009^	0.364
		Eye Dryness	0.016	0.010∨	0.515	0.055	0.021^	0.287	0.051
		Claustrophobia	0.012	0.007^	0.008^	0.002^	0.815	0.448	0.663
3rd	6 h	Noise	0.031	0.051	0.893	0.089	0.010^	0.335	0.038∨
		Headache	0.025	0.181	0.114	0.029^	0.397	0.104	0.357
		Dizziness	0.004	0.009^	0.007^	0.002^	0.738	0.081	0.639
		Claustrophobia	0.006	0.390	0.002^	0.001^	0.009^	0.011^	0.589

^ Means that scale value of first condition is higher than second condition.

Table 3
Estimation of aircraft design and safety related parameters.

Max/min	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11
	Max	Max	Max	Min	Min	Min	Min	Max	Max	Min	Min
Criteria	(A) Total air supply to cabin	(B) Cabin air temperature	(C) Volume per passenger	(D) Cabin noise	(E) W/SCLmax	(F) W/aCLtoST	(G) Fuel/pax/nm	(H) Seat × range	(I) Structural efficiency	(J) Accident rate	(K) Cabin evacuation time
A320-200	198	24	0.22	80	1962.27	2423.85	0.0443	405000	0.261088	0.24	85
A330-200	200	25.5	0.36	78	2269.21	3146.34	0.046	1866410	1.582609	0.3	90
A340-200	200	23.5	0.31	74	2445.04	4224.13	0.0502	2227050	0.192218	0.69	87
B737-200	205	26	0.19	80	1845.48	2537.71	0.0632	218500	0.294808	0.54	85
B747-400	202	24.5	0.26	79	3117.51	4579.9	0.05	3521600	0.154187	0.93	75
B767-200	200	26.5	0.34	75	1970.87	2347.53	0.0305	695520	0.250334	0.45	90

Table 4
Estimation of environment-design related parameters of aircraft.

Parameter	Description	Equation	Source
Total air supply to cabin	An adult breathe some 0.5 L of air in normal conditions 20 times per minute (up to 2 L in deep gasps, and the rate varies from 12 breath/min at rest to 120 breath/min on panting)	Intake composition (fresh air) is 77% N_2 + 21% O_2 + 1% H_2O + 1% Ar + 0.04% CO_2, and exhalation is 74% N_2 + 17% O_2 + 4% H_2O + 1% Ar + 4% CO_2. Maximum environmental CO_2 for comfort: 0.17 vol% (1700 ppm)	Martinez [14]
Cabin air temperature	People comfort demands air supply at T = 18.26 °C depending on heating or cooling needs, without thermal chocks	Normal cabin temperature is 24 °C ± 2.5 °C	Martinez [14]
Volume per passenger	Volume per passenger has its variations due to the class and comfort airline offer to the certain destination and passenger attraction	Regional airlines are designed by 0.2–0.4 m^3 volume per passenger	Report No. DOT-P-15-89-5 [16]
Cabin noise	These noise levels consist of both continuous and discontinuous types. range. As a general tendency, continuous noise levels were seen to be 60–65 dB(A) prior to takeoff, and 80–85 dB(A) and 75–80 dB(A) during flight and landing, respectively	Discontinuous in-cabin noise levels were observed to reach levels as high as 81–88 dB(A)	Ozcan et al. [17]
Design parameters	W/SC_{Lmax}	Wing loading is the weight of the aircraft divided by the wing area. It normally refers to take-off but W/S affects stall speed, climb rate, take-off and landing distances and turn performances. It is the wind loading that determines the design lift coefficient and also impact drag	Jenkinson et al. [18]
	W/aCL_{toST}		
	Fuel/pax/nm (kg)	–	Raymer
	Seat × range (seat nm)	–	[19]

Generally, the alternative (aircraft) comparison is based on different criteria the weights of which are normalized and evaluated subjectively. This method reviews an ideal and non-ideal solution from the perspective of criteria matrix. Finally, the TOPSIS method is used for order preference taking into account similarity to an ideal solution. This paper aims setting aircraft rank from the design/safety principles. Detailed analysis is presented below.

This paper analyses typical safety and comfort parameters during the flight time of occupants. Main comfort capabilities could be measured by economy class pitch, aircraft accident rate, cabin evacuation time, ground efficiency, climb capabilities and structural efficiency.

4.1. Assessing design and safety parameters of an aircraft applying the multi attribute decision making method

This research presents outputs obtained from the research dedicated to aircraft risk model development provided on the University of Belgrade, Division of Aircraft. The goal of the research was to establish measurement system related to design and safety relationship on the sample of contemporary regional aircraft. Moreover, aircraft ranking was based on environmental-design and safety related parameters. Following results of contemporary papers [13], data collection is based on the following parameters (Table 3).

Table 5
Estimation of safety related parameters of aircraft.

Parameter	Description	Equation/value	Source
Accident rate	Accident rates are defined by airplane type from the period 1959 through 2013. Those date are related to hull loss accidents for worldwide commercial jet fleet.	Hull loss accident rate (per million departures)	Boeing [20]
Cabin evacuation time	In accordance with Federal Aviation Regulation (FAR) 25, aircraft manufacturers must conduct full-scale demonstrations to show an airplane's evacuation capability. All passengers and crew must be evacuated from the aircraft to the ground within 90 s.	The 90-s limit is a certification standard. Internationally, industry accepts 90 s as a reasonable estimate of the survivable time in an evacuation where fire is present.	NTSB [21], Butcher [22]
Structural efficiency	Aircraft structural efficiency (σ) could be defined from the rate of max useful load–max payload (P/L) and max structural load (MTOW).	$\sigma = \text{Payload}_{max}/\text{MTOW}$	Čokorilo et al. [13]

Table 6
The evaluation of criterion weight.

W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11
0.070	0.240	0.077	0.132	0.021	0.021	0.038	0.051	0.047	0.142	0.161

Table 7
The estimation of relationship between criteria.

	Total air supply to cabin	Cabin air temperature	Volume per passenger	Cabin noise	W/SCLmax	W/aCLtoST	Fuel/ pax/nm	Seat × Range	Structural efficiency	Accident rate	Cabin evacuation time
Total air supply to cabin	1	0.2	0.5	0.25	5	5	3	3	2	0.25	0.33
Cabin air temperature	5	1	3	2	7	7	6	5	5	3	3
Volume per passenger	2	0.33	1	0.33	5	5	3	1	3	0.2	0.33
Cabin noise	4	0.5	3	1	7	7	3	3	3	1	0.33
W/SCLmax	0.2	0.14	0.2	0.14	1	1	0.5	0.33	0.2	0.16	0.33
W/aCLtoST	0.2	0.14	0.2	0.14	1	1	0.5	0.33	0.2	0.16	0.33
Fuel/pax/nm	0.33	0.16	0.33	0.33	2	2	1	1	2	0.2	0.2
Seat × range	0.33	0.2	1	0.33	3	3	1	1	3	0.33	0.2
Structural efficiency	0.5	0.2	0.33	0.33	5	5	0.5	0.33	1	0.33	0.33
Accident rate	4	0.33	5	1	6	6	5	3	3	1	0.5
Cabin evacuation time	3	0.33	3	3	3	3	5	5	3	2	1

4.2. Environment—Design related parameters of aircraft

Environment designed parameters of aircraft include variety of parameters which could significantly influence on aircraft operations and passengers subjective perception. Therefore, authors intended to select the most appropriate and important parameters to be analysed (Table 4):

4.3. Safety related parameters of an aircraft

Safety related parameters important for the multi attribute assessment are shown in Table 5.

5. Aircraft energy efficiency by multi-attribute analysis of the safety and design parameters

Obtained results were discussed based on the method of the normalized weight of criteria based on the Saaty scale explained by Čokorilo et al. [13]. The final outputs from this method are the normalized weights of criteria. The following algorithm performs a methodology for weight normalization presented in following equation:

(1) Define the total number of criteria for alternative ranking (n_k).
(2) Estimate relationship between each pair of criteria (k_i, k_j; $i,j = 1...m$) applying the Saaty scale (1–9).
(3) Apply the following formula (Eq. (1)) to calculate normalized weight for certain criteria:

$$w_i = \frac{\sum_{j=1}^{m} k_{ij} / \sum_{i=1}^{m} k_{ij}}{n_k} \quad (1)$$

The proposed algorithm considers the following steps:

(1) select 2 or more aircraft (alternatives);
(2) select safety and design aircraft parameters (criteria);
(3) apply the method of the normalized weights of criteria based on the Saaty scale to compare each pair of criteria by transforming subjective linguistic expressions into the normalized weights;
(4) apply the TOPSIS method for the chosen alternatives (aircraft), defined criteria (safety and design parameters) and the normalized weights of criteria;
(5) analyze the obtained results and propose countermeasures (the obtained aircraft rank presents an aircraft sorted list from the best to the worst solution for the settled energy efficiency conditions).

An expert evaluation of criteria based on the Saaty scale is shown in Table 6. Provided research is based on sensitive analysis of above mentioned parameters. Comfort and safety are two important aspects of aircraft operations from the user's perspective. Some market analyses show that European airlines are more oriented to comfort aspects, whilst for example Middle East and Asian markets are more safety promotion oriented.

The method of the normalized weight of criteria provides the following results for a certain aircraft (Table 7).

Aircraft rank based on the assessment of previous weight of criteria and the TOPSIS method is (from the best to the worst solution) as follows:

(1) A330-200;
(2) A320-200;
(3) B767-200;
(4) B737-200;
(5) A340-200;
(6) B747-400.

6. Conclusions

There is a variety of possibilities to compare different aircraft characteristics. This paper is focused on the most important safety and design parameters particularly related to cabin environmental conditions. Leading manufacturers, such are Airbus and Boeing constantly and rapidly improve the aircraft production lines regarding technology development. On the other hand, personal perception of occupants during the flight, both cabin and flight attendants and passengers could differ depending on personal health condition, cultural issues, gender, and other equity assessments. This papers aims providing clear methodology for measuring safety and comfortability level of passenger accommodation during the flight. Basically, by weighting criteria, some parameters were given certain advantage: cabin air temperature, cabin noise, cabin evacuation time, accident rate, etc. The final result shows aircraft rank, based on above mentioned TOPSIS method, but it could be evaluated with some more cabin efficiency parameters in some future work.

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