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THREATS TO AVIATION SAFETY CAUSED BY DEFECTS IN AIRCRAFT AIRFRAME SYSTEMS

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Abstract

Alongside the increase in air traffic and number of aircraft, the number of reported aviation events has also been increasing. We processed the data included in the European Coordination Centre for Aviation Incident Reporting Systems (ECCAIRS), analyzing small and large aircraft reliability and the safety of their operations, covering events according to ICAO aviation occurrence categories. Airframe systems are the largest contributor to the total number of reported events which occurred in Polish registered aircraft in the years 2008–2020. A detailed study of airframe systems reliability was carried out in order to assess the real reason for the failures. Airframe systems faults were assigned to specific ATA chapters and then to each of their sections. The results of this analysis may support the decisions of supervisory authorities in the areas where security threats are most important. They can also help aircraft operators with identification of the airframe units which require special attention. Identification of significant parts due to the frequency of malfunctions of particular system components may support designers. In short, these results are valuable in terms of further developments in statistical tools facilitating New Product Introduction (NPI).

Keywords: aviation transport, flight safety, safety performance indicators, airframe system, aviation occurrence
Type of the work: research article

1. INTRODUCTION

The establishment of cooperation with the Civil Aviation Authority of the Republic of Poland opened up access to the database of aviation events known as ECCAIRS (European Center for Coordination of the Accident and Incident Reporting System). It was also agreed with the Department of Safety of the Civil Aviation Authority that specialists from the Institute of Aviation would conduct a detailed analysis of aviation incidents caused by technical failures coded in the groups: System Component Failure Non Powerplant (SCF-NP) and System Component Failure Powerplant (SCF-PP). Aircraft occurrences are coded in accordance with the ICAO guidelines contained in the Aviation Occurrence Categories [1]. A detailed analysis of failing components in airframe and engine installations is based on their coding in accordance with ATA-100 [3]. Detailed identification of the failed element requires the use of a precise, four-digit coding in the ATA system [3]. The aircraft were divided into small – MTOM < 5,700 kg (Maximum Take-Off Mass) and large – MTOM > 5,700 kg. Due to the nature of aircraft operations, there are significant differences between small aircraft, primarily part of General

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Aviation, and large aircraft used in Commercial Air Transport (CAT). The CAT category also includes small general aviation airplanes for training pilots. It should be noted that each country has its own aviation culture resulting from tradition, geographic location and resources, etc. Hence it is difficult to introduce uniform standards in Europe. To meet European Union Aviation Safety Agency (EASA) requirements, it is also necessary to define the safety factors and criteria specific to Poland. ICAO Annex 19 contains the formula: "…each country should establish a safety program that it will manage in order to achieve an acceptable level of safety in civil aviation" [2, 5]. The ICAO emphasizes in its documents on aviation safety systems that such a program should be adapted to the individual nature of aviation activities in a given country. National air traffic safety improvement programs are implemented in many European countries [6, 7, 8, 12]. A methodology was developed to determine the forecast for the following year and to set alert levels for representative types of events, adopting the criterion 2σ. In order to make data analysis more objective, coefficients were introduced relating the number of events to the number of registered aircraft (per 1,000 aircraft) [9-11]. It would be more accurate to link the number of incidents to flight time, but there is no relevant data.

$$K_{1000} = \frac{1000 \cdot LZGA}{LSPGA},$$

$$K_{1000} = \frac{1000 \cdot LZK}{LSPK}.$$

where:
LZGA, *LZK* – number of occurrences concerning small aircraft (General Aviation) and large aircraft (CAT) respectively;
LSPGA, *LSPK* – number of registered small aircraft (General Aviation) and large aircraft (CAT), respectively;

Forecasting was introduced on the basis of observations of trends over several years, i.e. determination of alert levels and mean values, assuming a normal distribution of flight events [11]. These forecasts should be reviewed annually by comparing them with the actual numbers of events. The method used in Shewhart Control Diagrams has been applied to determine the alert levels, which allow for observations of the variability of the process as well as identification of the causes that trigger this increase in variability. The control limits in the Shewhart Diagrams (Figure 1) are at 3 on each side of the center line (mean values **m**), where is the standard deviation of the values in each subset of the population, estimated based on the variability of the samples. The limits set at level 3 show that approximately 99.73% of the subset value will be within the area defined by the control lines, assuming that the process is statistically regulated. The control card also shows 2 limits on both sides of the mean value m lines as warning lines (alert levels). In this area, there should be 95.4% of variability of the event being examined. Samples that appear outside the 2 limits may indicate the possibility of going beyond the set control limits [10].

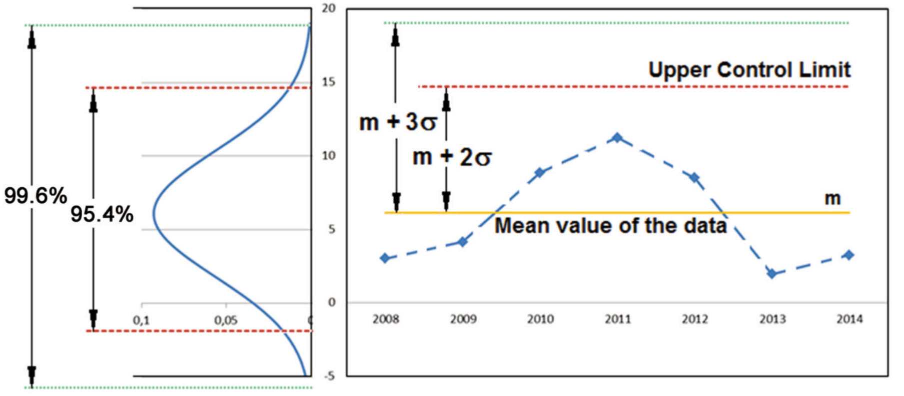

Fig. 1. Illustration of the relationship between the confidence level and the confidence interval: **m** − average sample value; σ − standard deviation of the sample.

Based on the methodology proposed by the ICAO in its “Safety Management Manual” [4], an analysis of the safety level threat caused by individual airframe systems was applied. Examples of such assessment are presented in the form of tables. The drawings showing the changes in the K_{1000} coefficient in the years 2008–2020; the 2020 axis also contains values forecast in 2019: <u>the mean for a given parameter is marked in magenta and the previously described maximum (2σ) is marked in red, determining the alert level.</u>

2. SAFETY ANALYSIS OF LARGE AIRCRAFT OPERATIONS

Figure 2 shows the percentage of different event categories defined in the ICAO [1]. The cases in the SCF-NP group are dominant, and account for over 18% of the total. There is also a significant share of collisions with birds (about 17%).

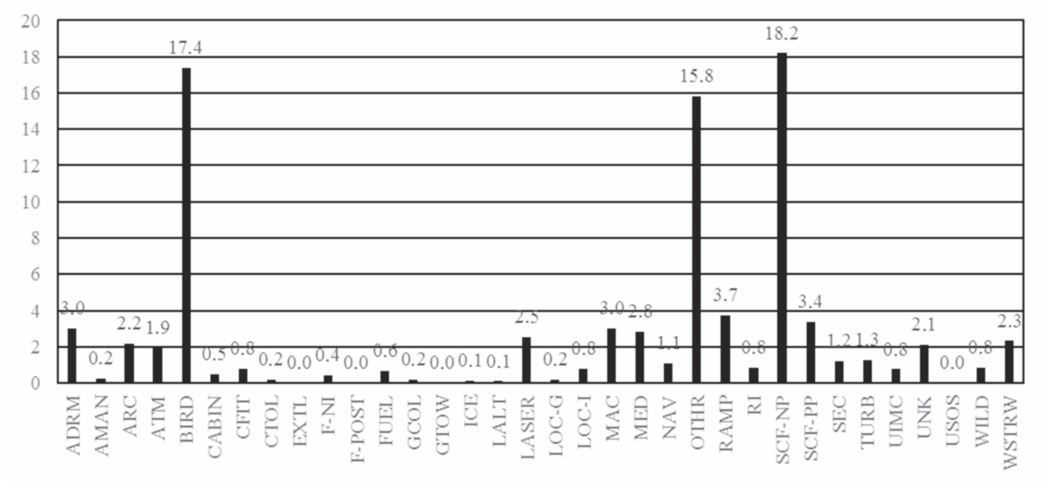

Fig. 2. Reported occurrences by aviation occurrence category (according to the ICAO [1]) in Poland for large aircraft as a percentage in 2008–2020.

2.1. Non Powerplant events (SCF-NP) caused by failures of airframe systems for large aircraft

Figure 4 shows the changes in the K_{1000} coefficient for events in the SCF-NP category in the period 2008–2020. Since 2016, there has been a slight decrease in this factor and in 2020 there was a jump in its value, because the number of events in this group is systematically growing (Figure 3). The value of the K_{1000} coefficient in 2020 far exceeded the alert level forecast for this year (Figure 4).

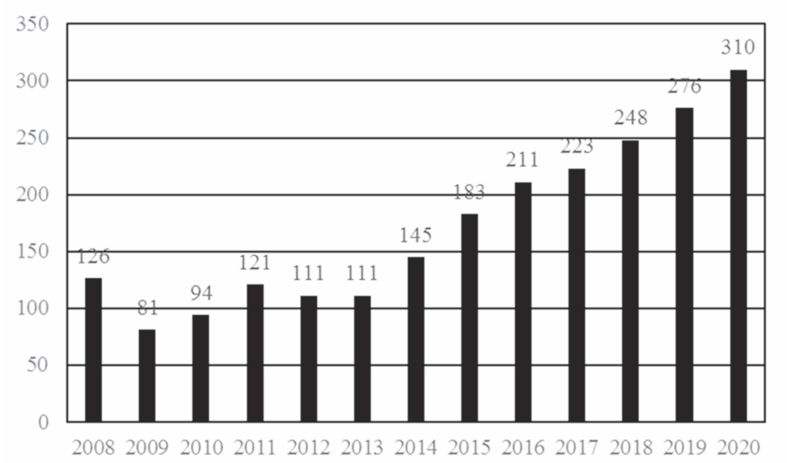

Fig. 3. Number of events for the SCF-NP category for large aircraft in 2008–2020.

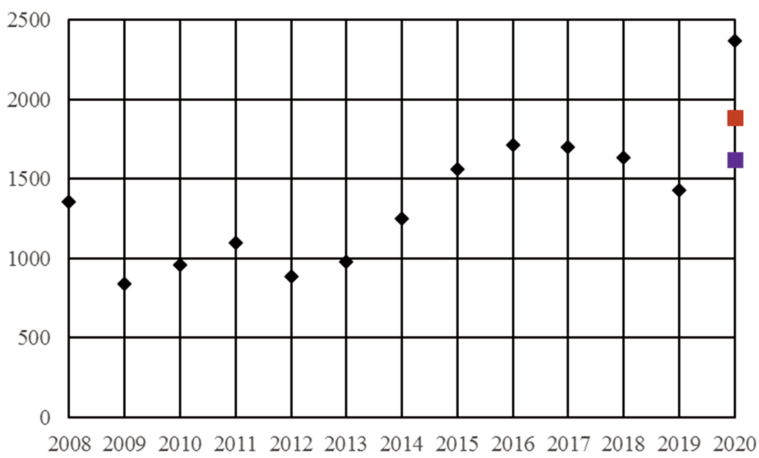

Fig. 4. K_{1000} values for the SCF-NP category for large aircraft in 2008–2020. Values forecast in 2019: the average for K_{1000} marked in magenta; and the maximum that determines the alarm level marked in red.

SCF-NP events reported by crews are grouped according to ATA-100 qualifications (Air Transport Association). This revealed which airframe system was the cause of the greatest number of incidents. Figure 5 shows the percentage share in each group according to the ATA. Two systems dominate: flight controls (ATA-27) and landing gear (ATA-32). In much smaller numbers, there are incidents caused by failures in the following airframe systems: Air conditioning (ATA-21), electrical power (ATA-24), hydraulic power (ATA-29) and indicating/recording (ATA-31).

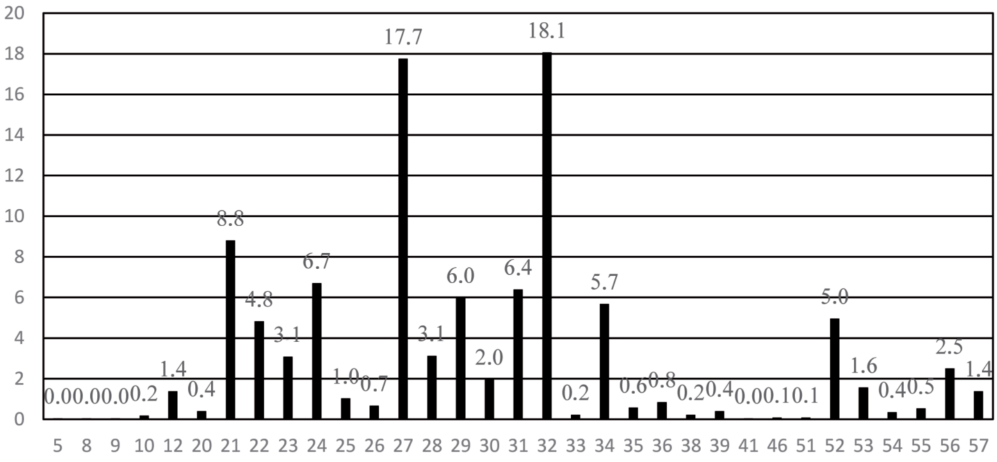

Fig. 5. Percentage share of individual ATA groups in the SCF-NP category for large aircraft in 2008–2020.

Tab. 1. Safety risk probability [4].

Likelihood	Meaning	Value
Frequent	Likely to occur many times (has occurred frequently)	**5**
Occasional	Likely to occur sometimes (has occurred infrequently)	**4**
Remote	Unlikely to occur, but possible (has occurred rarely)	**3**
Improbable	Very unlikely to occur (not known to have occurred)	**2**
Extremely Improbable	Almost inconceivable that the event will occur	**1**

Tab. 2. Safety risk severity [4].

Severity	Meaning	Value
Catastrophic	- Equipment destroyed - Multiple deaths	**A**
Hazardous	- A large reduction in safety margins, physical distress or workload such that the operators cannot be relied upon to perform their tasks accurately or completely - Serious injury - Major equipment damage	**B**
Major	- A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of an increase in workload, or as a result of conditions impairing their efficiency - Serious incident - Injury to persons	**C**
Minor	- Nuisance - Operating limitations - Use of emergency procedures - Minor incident	**D**
Negligible	- Few consequences	**E**

When analyzing potential threats to aviation safety, it was found that, based on ECCAIRS data from 13 years, landing gear defects (chapter ATA-32) pose a great threat to aviation safety in Poland. Table 4 shows the results of this analysis. The failure frequency is shown in Table 1. The consequences are dangerous in the event of a landing gear failure, see Table 2. There have been several serious incidents for Polish registered aircraft due to such landing gear faults.

It seems that only confining oneself to the theoretical probabilities of the impact of a given system failure on flight safety is insufficient. It is necessary to take into account the failure frequency of individual systems for a specific aircraft structure and the specific conditions of its operation. When assessing security risks in virtually every area of human activity, the history of events and their actual consequences for a particular area must always be taken into account.

Tab. 3. Safety risk assessment matrix [4].

Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Tab. 4. Safety risk assessment matrix for large aircraft airframe systems.

ATA chapter		
No	Contents	Index
27	Flight controls	5D
32	Landing gear	5C
24	Electrical Power	4D
21	Air conditioning	4E
31	Indicating/ recording system	4E
23	Communication	3D
29	Hydraulic power	3C
52	Doors	3D
22	Auto flight	3D
28	Fuel	2E
56	Windows	2D
57	Wings	2D
8	Leveling and weighing	1E
12	Servicing – routine maintenance	1D
25	Equipment/ furnishings	1E
26	Fire protection	1D
30	Ice and rain protection	1D
35	Oxygen	1E
46	Information systems	1E
53	Fuselage	1E
54	Nacelles/ pylons	1E
55	Stabilizers	1E

The red box in the Table 3 and 4 indicates that immediate action should be taken to eliminate the safety risk. All airframe systems described in cells with a yellow background do not require immediate action; however, it is advisable to observe their operation and, if necessary, take the necessary action to improve safety.

2.2. An example of a detailed malfunction assessment for the landing gear system of a large aircraft

The value of the K_{1000} coefficient in 2020 (Figure 7) for the landing gear did not exceed even the mean level projected in 2019. However, due to the frequency of incidents and the consequences of a malfunction in the landing gear system, the safety hazard is assessed as serious (see Table 4), despite the fact that number of failures has been systematically decreasing since 2018. The consequences of a failure in this system for an airline are very significant. Interrupting taxi or take-off may result in a minimal flight delay, but often requires a change of aircraft or even the cancellation of the flight. The financial consequences of these disruptions to passenger or cargo operations are kept secret by operators. Landing gear failures in 2008–2020 caused the following operational problems: Emergency landings – 12, Canceled flight – 11, Aborted taxiing – 37, Flight turning back – 62 and Aborted take-off – 18.

Figure 6 shows the change in the number of aircraft events caused by landing gear failures in 2008–2020.

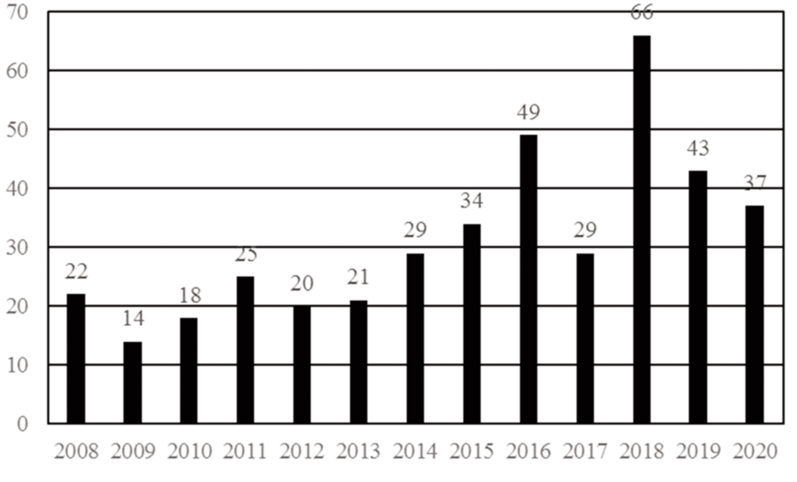

Fig. 6. Number of landing gear events for large aircraft in the years 2008–2020.

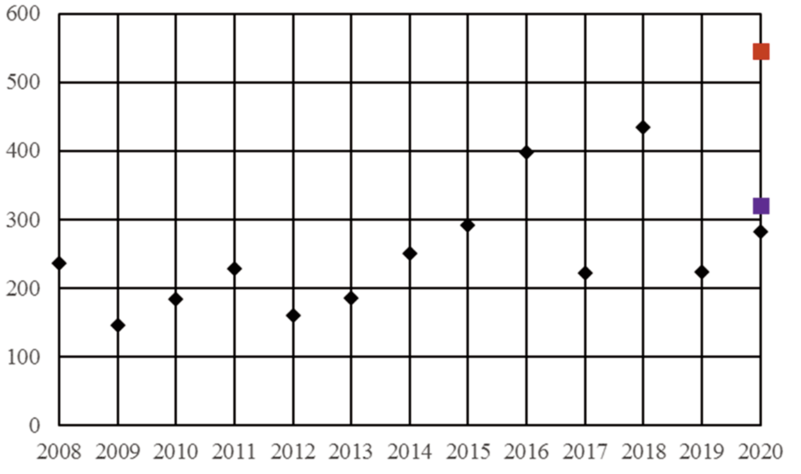

Fig. 7. Values of K_{1000} for landing gear system malfunctions for large aircraft in the years 2008–2020.

2.3. Landing gear in detail

The ATA-100 numbering system divides chapter ATA-32 (Landing Gear) into sections as follows:

32-00 GENERAL
32-10 MAIN GEAR AND DOORS
32-20 NOSE GEAR / TAIL GEAR AND DOORS
32-30 EXTENSION AND RETRACTION
32-40 WHEELS AND BRAKES
32-50 STEERING
32-60 POSITION, WARNING, AND GROUND SAFETY SWITCH
32-70 SUPPLEMENTARY GEAR – SKIS, FLOATS

Figure 8 shows the percentage share of the particular units of the landing gear that caused aviation events in the years 2008–2020.

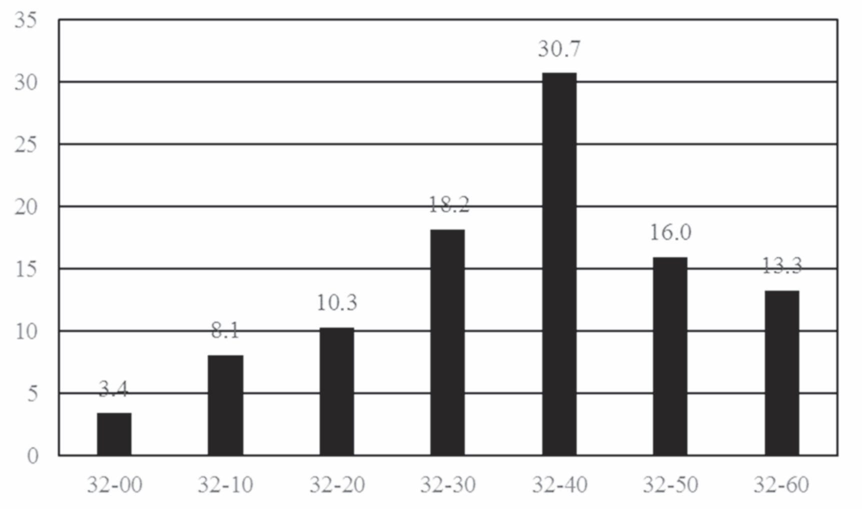

Fig. 8. Percentage share of events in individual sections of landing gear system (ATA-32) for large aircraft in 2008–2020.

It should be noted that the dominant ATA section, 32-40 (wheels and brakes), covers a very broad range of faults that cause aircraft incidents. The brakes caused 44 events, and wheels 56. Parts of the wheel and brake subassembly, due to the high level of faults, cause the largest number of aviation incidents compared to other components of the landing gear system. In 2020, as compared to 2019, there was an increase in the number of malfunctions of wheel and brake components. The values of the K_{1000} coefficient and the number of component failures in ATA 32-40 are presented in the following Figures 9 and 10 respectively.

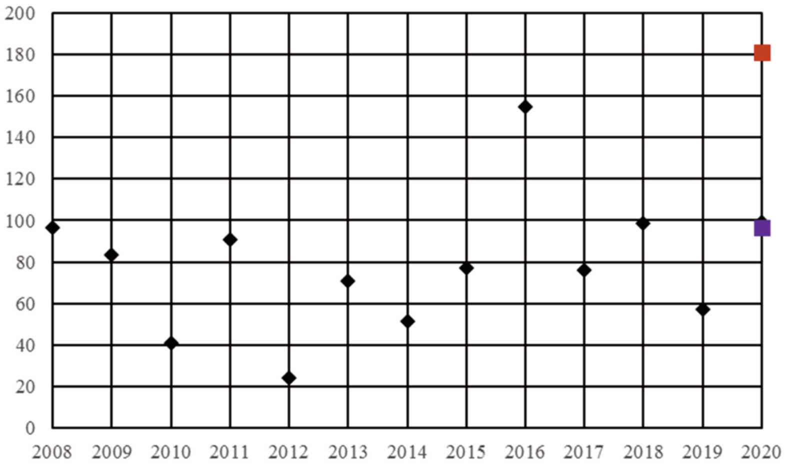

Fig. 9. Values of K_{1000} for wheel and brake failures (ATA 32-40)
for large aircraft in 2008–2020.

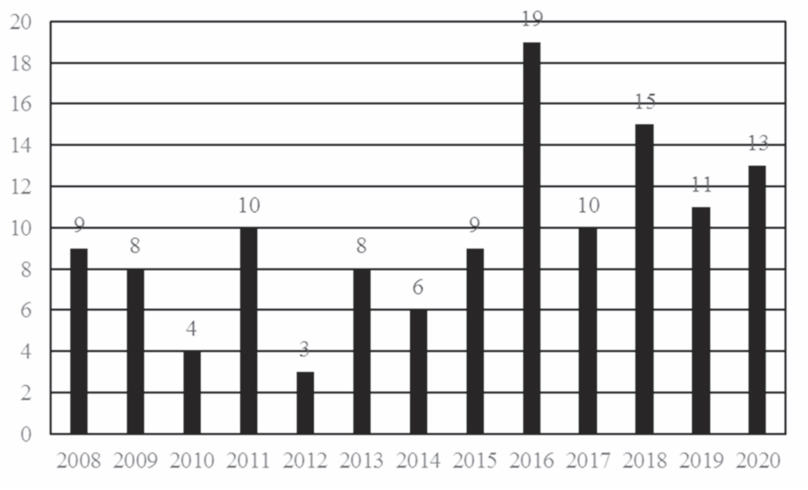

Fig. 10. Number of events caused by wheels and brakes for large aircraft
in the years 2008–2020.

2.4. Example of short-term analysis

The above analysis of landing gear system failures was carried out on the basis of thirteen years of observations of air incidents caused by such failures. However, short-term analyses should not be forgotten. A typical example would be 2020. Just as Figure 5 for 2008–2020 shows that landing gear and flight control failures have the largest share, Figure 11 – presenting data only for one year – 2020, shows that failure of the navigation system (chapter ATA-34) was the cause of the largest number of aviation events.

Figure 12 shows the change in the value of the K_{1000} coefficient for the aviation events caused by failures of the navigation system, ATA-34 in the years 2008–2020.

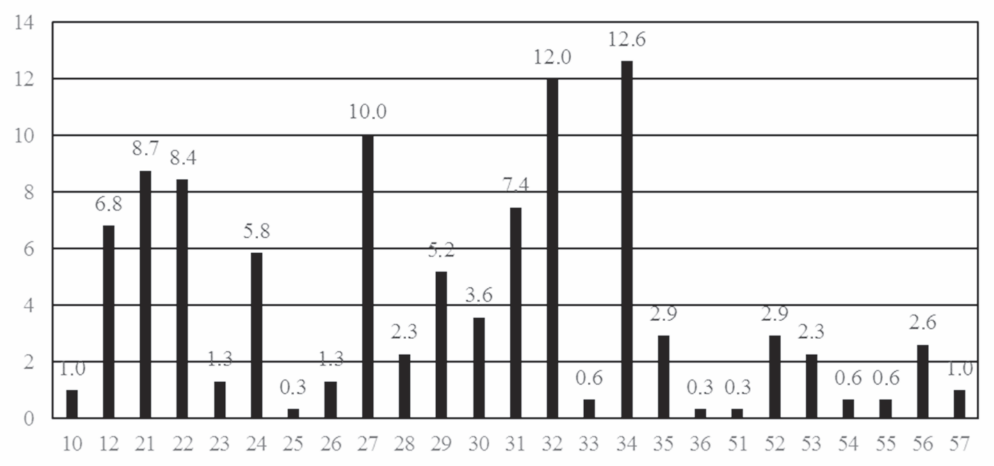

Fig. 11. Percentage share of particular ATA chapters in the SCF-NP category for large aircraft in 2020.

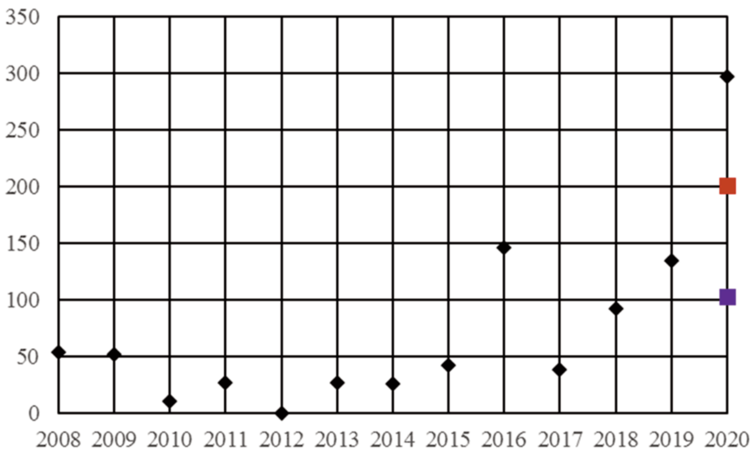

Fig. 12. Values of K_{1000} for navigation system malfunctions for large aircraft in the years 2008–2020.

The K_{1000} coefficient significantly exceeded the alert level forecast in 2019. Its change in subsequent years compared to the previous year should be observed. There was a surge in the number of failures causing aviation incidents in 2020. Unfortunately, they cannot be assigned to one dominant aircraft type.

ATA-34 chapter (navigation) is divided into sections as follows:

34-00 GENERAL
34-10 FLIGHT ENVIRONMENTAL DATA
34-20 ATTITUDE AND DIRECTION
34-30 LANDING AND TAXIING AIDS
34-40 INDEPENDENT POSITION DETERMINING
34-50 DEPENDENT POSITION DETERMINING
34-60 FLIGHT MANAGEMENT COMPUTING

The analysis of the total number of failures in individual sections of the navigation system is shown in Figure 13, in which it can be observed that units included in section ATA 34-50 (dependent position determining) take the greatest share. This is the part of the system which provides information to determine position and is mainly dependent on ground installations or orbital satellites. This section includes items such as DME, transponders, radio compass, LORAN, VOR, ADF, OMEGA and GLOBAL POSITIONING, etc. It should be emphasized that the K_{1000} coefficient significantly exceeded the alert level forecast in 2019. Its value was mainly caused by malfunctions in DME (Distance Measuring Equipment) and transponders. Figure 14 shows the change in K_{1000} for ATA 34-50 in the years 2008–2020.

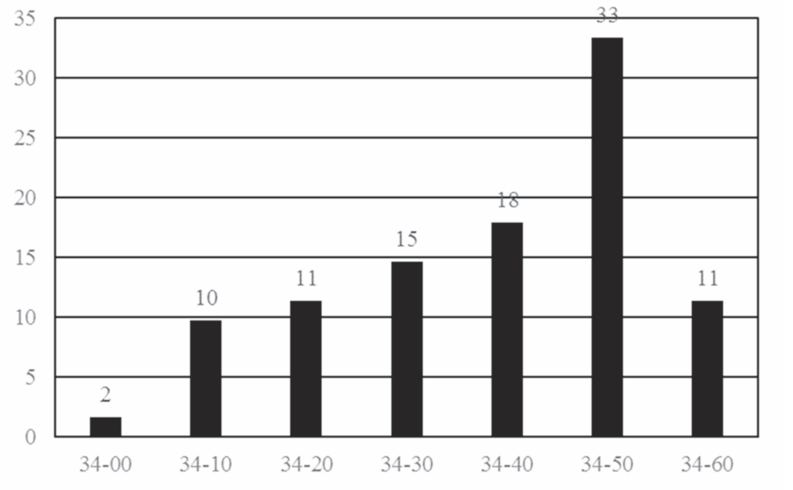

Fig. 13. Percentage share of events in individual sections of navigation system (ATA-34) for large aircraft in 2008–2020.

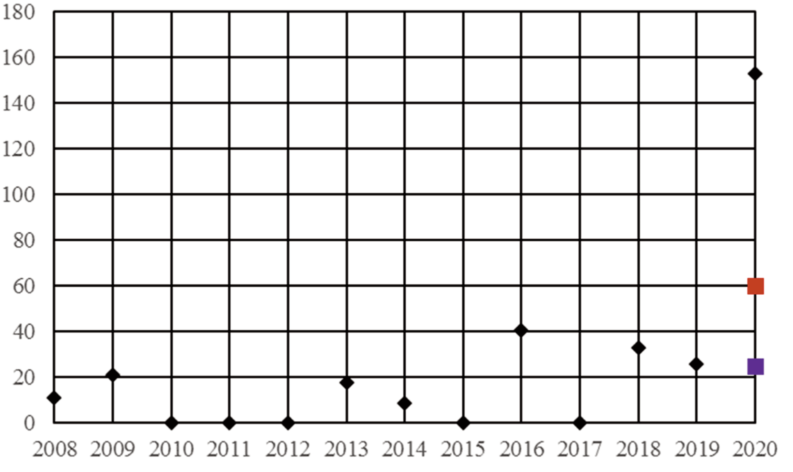

Fig. 14. Values of K_{1000} for failures in dependent position determining (ATA 34-50) for large aircraft in 2008–2020.

If the safety risk caused by the navigation system could have been in the "green field" as per Table 4 in the long-term analysis, then for the year 2020 this risk has to be placed in the "yellow field", with a strong recommendation that the failures in its components be carefully observed. Table 5 shows the change in the risk level for the navigation system if short-term analysis is performed.

Tab. 5. Safety risk assessment matrix.

34	Navigation for years 2008–2020	**2D**
34	Navigation for 2020 only	**5D**

3. SAFETY ANALYSIS OF SMALL AIRCRAFT OPERATION

General aviation flight operations are different from those specific for the CAT category. Flights are often made between small grassy airfields and very rarely between airports. General aviation aircraft also perform commercial flights: for towing gliders, transporting parachutists and training pilots. Aircraft are sometimes operated by students and inexperienced people [13]. For this reason, the share of technical defects (SCF-NP and SCF-PP) is greater than in the case of large aircraft. This is shown in Figure 15.

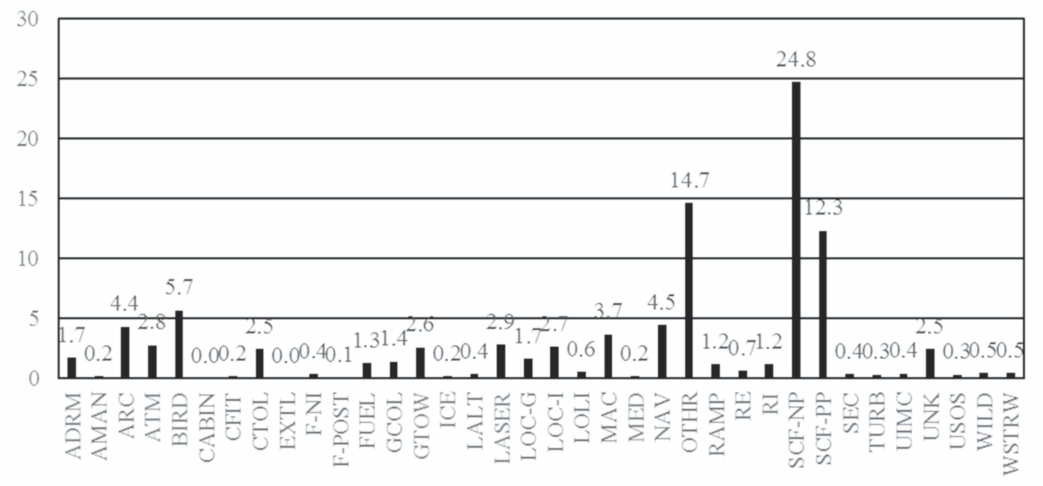

Fig. 15. Percentage of individual occurrences as defined by ICAO [1]
for small aircraft in 2008–2020.

Apart from airframe systems (about 25%), the share of aviation incidents caused by aircraft engines is high (12.3%).

3.1. SCF-NP category events for general aviation aircraft

Defects in general aviation airframe systems do not in practice pose a threat to the safety of operations. Over the past two years, a decrease in the number of aviation incidents in this category has been observed. The actual value of the K_{1000} coefficient for 2020 is lower than the mean value forecast for that year (Figure 16) and is systematically lower from year to year.

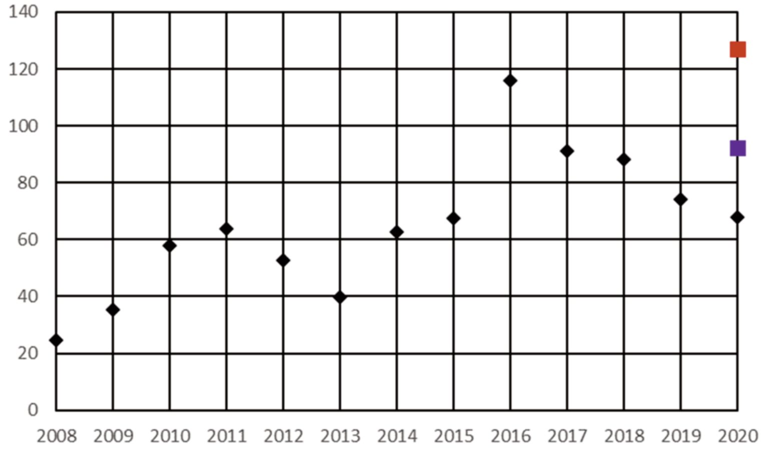

Fig. 16. K_{1000} factor for the SCF-NP category for general aviation aircraft in 2008–2020.

Landing gear system (chapter ATA 32) defects dominate, counting for as much as 39% of all airframe system failures (Figure 17).

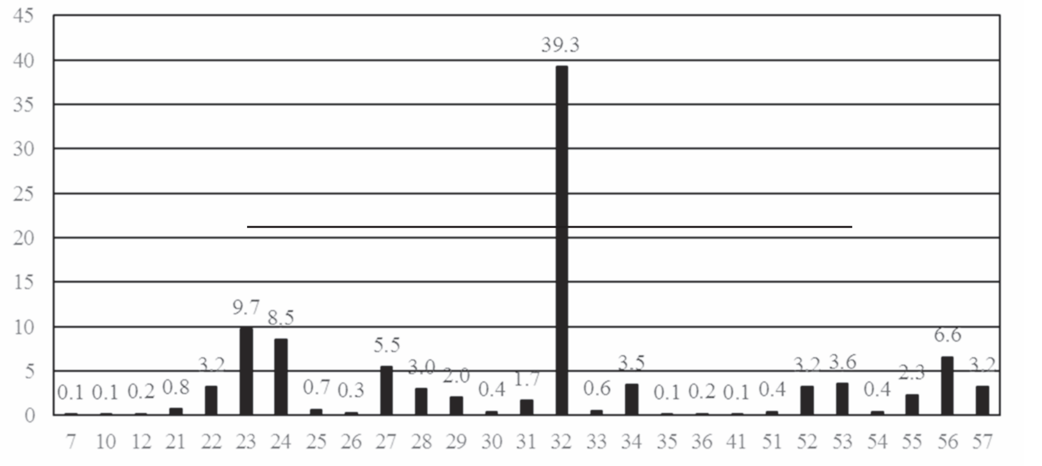

Fig. 17. Percentage share of individual ATA groups in the SCF-NP category for general aviation aircraft in 2008–2020.

3.2. Detailed assessment of general aviation landing gear system malfunctions

Landing gear failures were the cause of most of the incidents caused by failures in the general aviation airframe systems. Others, such as communications (ATA 23), electrical power (ATA 24) or windows (ATA 56) have no significant impact on aviation safety hazards. The landing gear caused the following operational perturbations: Emergency landings – 8, Aborted taxiing – 8, Flight turning back – 65, Aborted take-off – 24.

Figure 18 shows the changes in the K_{1000} value of the landing gear system in the years 2008–2020. The actual K_{1000} coefficient in 2020 has a value between the mean forecast in 2019 and the alert level.

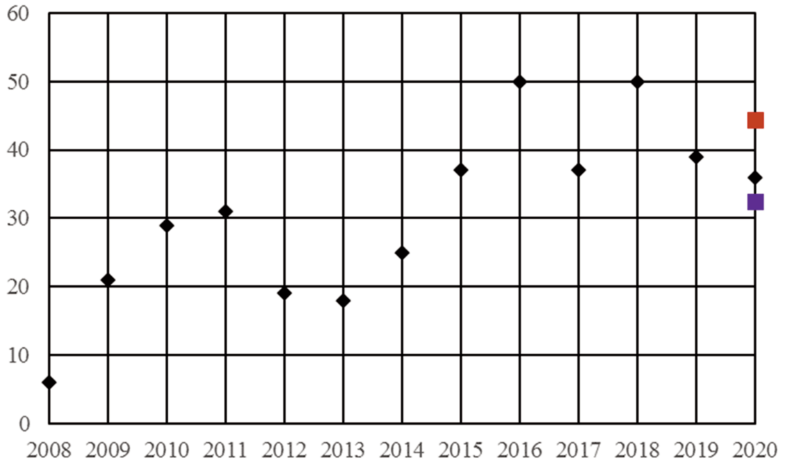

Fig. 18. K_{1000} values for landing gear system malfunctions (ATA-32) for general aviation aircraft in 2008–2020.

The analysis of events related to the landing gear category, taking into account the subgroups, showed that as many as 57% of the failures were related to wheels and brakes (ATA 32-40). Figure 19 shows the percentage share of malfunctions of individual sections in the years 2008–2020.

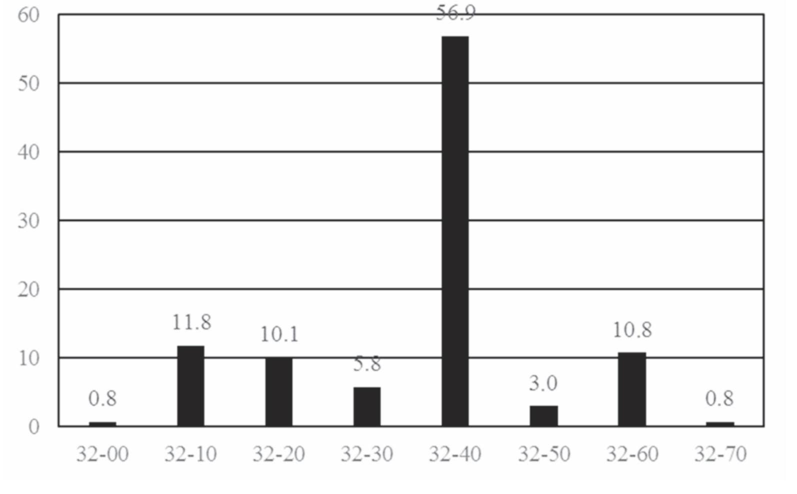

Fig. 19. Percentage share of events in individual sections of landing gear systems (ATA-32) for general aviation aircraft in 2008–2018.

The ATA section 32-40, wheels and brakes, includes components that enable rolling and stopping the aircraft on the ground. It includes devices to stop the rotation of the wheels of the landing gear after their retraction, as well as bearings, tires, valves, rotary seals, anti-skid devices, pressure gauges and hydraulics, etc. Incidents caused by the failure of wheel and brake components are dominant in landing gear faults. The K_{1000} coefficient in 2020 was below the average forecast for this year, as shown in Figure 20. It should be noted that the number of malfunctions decreased in 2020, continuing the decrease that had been seen in 2019 from the level in 2018 (as shown in Figure 21).

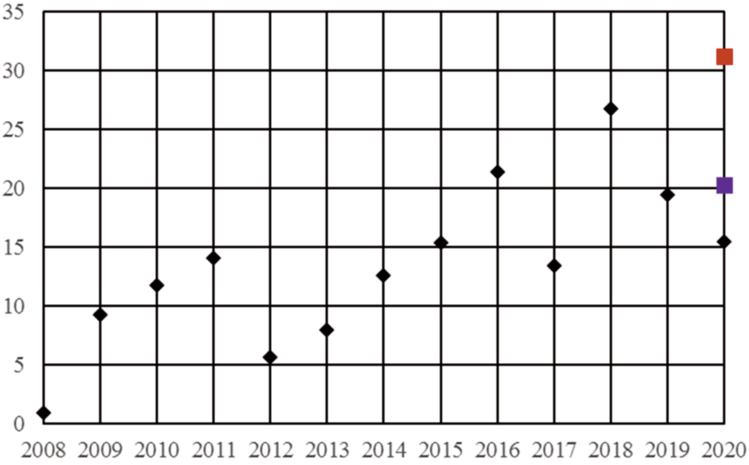

Fig. 20. K_{1000} values for failures of wheels and brakes (ATA 32-40) for general aviation aircraft in 2008–2020.

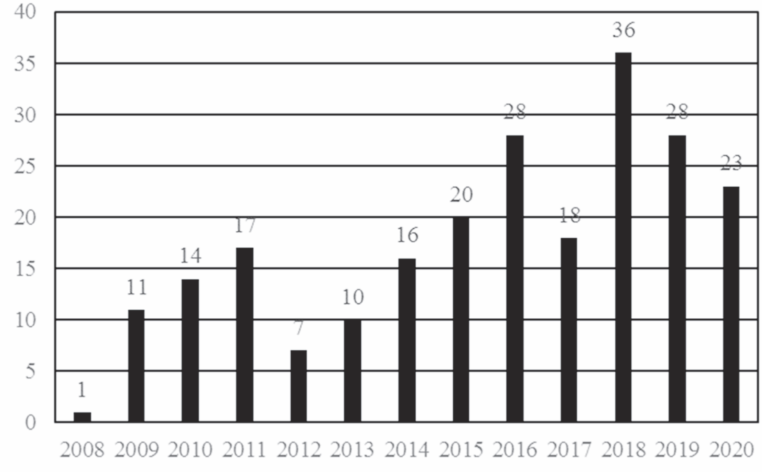

Fig. 21. Number of events caused by wheels and brakes for general aviation aircraft in the years 2008–2020.

A large number of faults are due to the lack of tire pressure. It can be assumed that these failures are caused by tire damage due to metal elements scattered around the airport. General aviation aircraft often operate from small airports that do not have runway and taxiways cleaned. This is information crucial for the relevant authorities to take appropriate action to eliminate this phenomenon.

CONCLUSIONS

Statistical analyses of the data contained in the ECCAIRS database are an important tool:
– supporting assessment of trends in changes in the level of aviation safety,
– assisting national aviation safety management authorities by identifying risks in individual ICAO categories of threats,

– indicating the need to intervene in aviation organizations for which there are indications of a decrease in the quality of their work (in the performance of periodic inspections, repairs),
– providing guidance to aircraft designers regarding assumptions for new projects or the need to modify the structure of the operation of aircraft,
– tracking the occurrence of faults in a specific aircraft or security threats at a selected airport.

The analyses of aviation events caused by failures in individual airframe systems are very important, both short-term and long-term. Airport infrastructure should be improved and prepared for intense air traffic. In particular, attention should be paid to the condition of the runways. Runway debris should not be allowed to damage tires or propeller tips.

Multidisciplinary analysis of data on the reliability of air traffic components and aircraft structural systems can help in the appropriate preparation of SAT auxiliary equipment, in the design of new aircraft and the improvement of existing airframe systems. The data processing presented may be useful for the further development of statistical tools facilitating the supervision of the introduction of new designs. As in many cases the fault causing the occurrence is repeated on the same type of aircraft, it is necessary to amend maintenance organization procedures. These changes should ensure effective removal (during technical inspections) of defects entered by the crew into the logbook.

Diagnostic systems are necessary to increase the detection of faults in aircraft systems (at an early stage of their emergence). In order to eliminate the safety risks posed by the most defective aircraft systems, aviation authorities should implement effective modification programs for these systems in close cooperation with manufacturers.

More broadly, the methodology presented in this paper is universal and can be used for similar analyses in other countries.

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