European Aviation Safety Agency

Study on single-engine helicopter operations over a hostile environment

Safety Risk Assessment

ALG TRANSPORTATION INFRASTRUCTURE & LOGISTICS

in consortium with

SGI AVIATION

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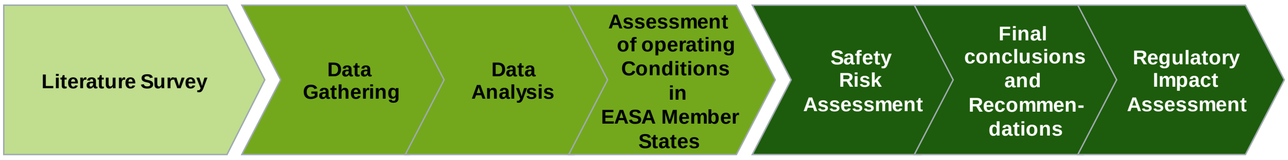
1 Introduction

The study on the single-engine helicopter operations over a hostile environment consists of the tasks included in the following scheme:



This document corresponds with the **Safety Risk Assessment**. The goal of this part of the study is to identify engine-related hazards from the database, analyse and assess their severity and frequency and subsequently, come up with measures to mitigate them.

In order to accomplish this goal, the hazards, which occurred during single-engine helicopter operations in the period between 01/01/2003 and 31/12/2012 are identified and evaluated. Mainly Commercial Air Transport (CAT) operations, but also Aerial Work and General Aviation, are included in the analysis. In order to provide a holistic risk assessment of single-engine helicopter operations, engine-related occurrences over both hostile and non-hostile environment are evaluated. After the hazard identification phase, the risk of occurrences is analysed and evaluated by comparing the registered, actual outcome of events with potential outcomes in both hostile and non-hostile environment as identified by an expert pilot. In the next phase, the events are grouped by SPS level 1 code and further clustered according to factors, which contributed to eventual failure. Finally, frequency and severity analysis of the events serves as input for mitigation measures.

2 Executive Summary

The purpose of this part of the study on the safety of single-engine commercial air transport helicopter operations in a hostile environment is assessing the safety risk.

The assessment follows three steps:

- Hazard identification
- Risk analysis;
- Risk mitigation.

The database for the assessment consists of the occurrences that are reported in an earlier part of this study. Out of a total of 4.606 occurrences that were registered for the period 2003-2012, 920 involve an accident or serious incident. Of those, there are 56 which are engine related, of which 32 involve piston powered single engine helicopters (SEH) and 24 turbine powered.

The reports for these 56 accidents and serious incidents (collectively referred to as events) are reviewed for hazards, which are classified using the SPS coding system. For each event, one or more SPS codes are allocated. The expert helicopter pilot has identified eight SPS Level 1 codes as relevant to engine-related failures. These codes are:

- Ground Duties (100);
- Safety Management (200);
- Maintenance (300);
- Pilot judgment & actions (500);
- Pilot situation awareness (700);
- Part / system failure (800);
- Ground personnel (1200); and
- Aircraft Design (1400).

The **most common hazard**, both for piston and turbine powered helicopters, **is Part / system failure** (800). The **second** most frequent category **is Pilot judgment & actions** (500), **extremely close to Maintenance group** (300) **in case of piston events**. For piston events, Safety Management (200) is also a frequent category. For turbine engine failures, Maintenance (300) and Pilot situation awareness (700) rank in third place. However, it should be noted that Pilot situation awareness (700) is the least frequent category amongst piston events.

The next phase is the risk analysis. For the **top 4 level 1 SPS codes** *[200, 300, 500 and 800 for piston-engined helicopters, and 300, 500, 700 & 800 for turbine-engined]*, a further division is made using SPS level 2 codes. For each event, an analysis is made as to whether the event occurred in a hostile environment or not and, what the actual risk severity was. In addition, and using pilot expert judgment, estimates of risk severity consequences are made for both the hostile and the non-hostile environment. Severity consequences are rated as either none, minor, hazardous or catastrophic.

This results in a total of **5 SPS categories** that are **most frequent**:

- 2090 Safety management – Inadequate pilot experience
- 3010&20 Maintenance – Maintenance management & Performance of maintenance duties
- 5010&30&40&60 Pilot judgment and actions – Pilot's decision & Flight profile & Landing procedure & Procedure implementation
- 7020 Pilot SA – Environment awareness
- 8020 Part / system failure – Power plant

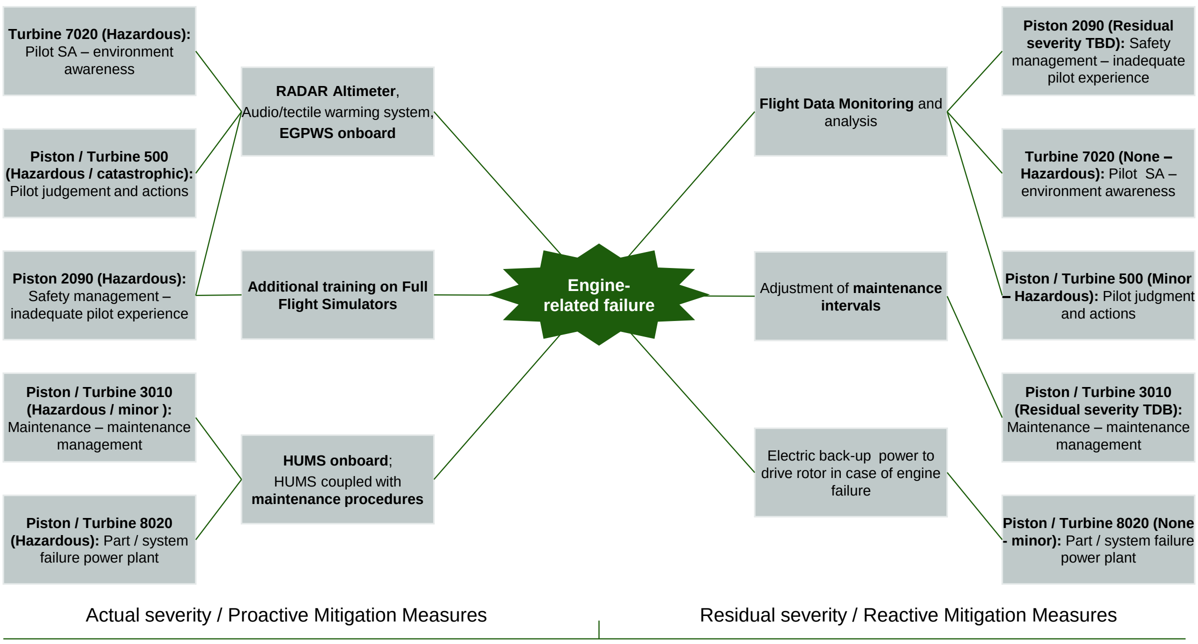
For these categories, risk mitigations are discussed. A total of **9 mitigation measures** are proposed, as follows:

- Student pilot training to be conducted on uncomplicated helicopters with typical helicopter characteristics;
- Additional training on Full Flight Simulators
- EICAS systems;
- Tactile warning systems;
- Quality improvements in education and recurrent training;
- Introduction of radar altimeters to warn for unintended loss of altitude;
- Introduction of EGPWS to provide the pilots with a complete flight path view with respect to terrain;
- HUMS;
- Hybrid power systems providing electric back-up power in case of engine failure; and
- Flight data monitoring.

In addition, recommendations are considered for:

- removing administrative constraints for pilots making a precautionary landing; and
- further investigation of events to determine root causes.

Finally, the proposed mitigation measures for both piston- and turbine-engined helicopters are graphically summarised in a **bowtie diagram** depicted in next figure, where average actual severity of the occurred engine-related events grouped per SPS Level 2 is mitigated by proactive measures (on the left side of the figure) and reactive measures (on the right side of the figure, together with residual severities of respective SPS groupings).



Bowtie diagram

3 Methodology and scope

This chapter presents an overview of the methodology applied for completing safety risk analysis tasks. This methodology is comprised of three analysis steps: Hazard identification (Chapter 4), Risk Analysis (Chapter 5) and Risk Mitigation (Chapter 6).

3.1 Hazard identification

The hazard identification task consists of several steps as elaborated below. The list of these steps is as follows:

1. Determine the number of Flight Hours for piston and turbine single-engine helicopter operations during timeframe of interest;
2. Calculate occurrence ratios per 100.000 FH for piston and turbine SEH;
3. Identify engine-related accidents and serious incidents for further analysis;
4. Calculate the occurrence rates per SPS Level 1 code for both piston and turbine SEH operating in both hostile and non-hostile environment

The gathered events in the database represent occurrences reported in the single engine helicopter sector over the past 10 years. These events have a variety of causes. This risk assessment is conducted in order to support a possible revision of EASA requirements regarding CAT operations with single engine helicopters over hostile environment. Therefore this part of the study focuses on events, which, in case of a similar mishap or failure, would lead to a significantly different outcome between multi- and single-engine helicopters. Events with identical consequences for both multi- and single-engine helicopters (e.g. flight control issues, obstacle strike, atmospheric conditions etc.) would not justify regulatory restrictions for one or the other type of helicopter.

Although the alleviation in JAR OPS 3 is only applicable for CAT operations over hostile environment, all other types of operations, as well as operations over non-hostile environment, are relevant for analysis of risks associated with single-engine helicopter operations. Therefore this part of the study incorporates events regardless of type of operations or environment.

3.2 Engine related events

In order to capture differences in risk between single- and multi-engine helicopter operations, the main focus lies in engine-related mishaps or failures, which directly or indirectly contributed to the final outcome of the event. Power degradation, loss of power or even intermittent power problems, demand different actions and/or decisions from the pilot when operating a single-engine helicopter rather than a multi engine helicopter. Consequently, the risks associated with such events are different for both types of helicopters. Besides the engine itself, several other parts of the single-engine helicopter are identified as unique to its design and could potentially result in more severe outcomes may problems occur. The following items are identified:

- Engine air intake, can be part of engine or airframe system. Both are included.

- The engine output driveshaft (between engine and main gearbox) or drive belts are non-redundant parts on a single engine machine together with freewheel units (enabling the rotor to rotate freely when the power is interrupted).

- Fuel system failures are likely to have a different impact on single engine helicopters, as multi engine helicopters mostly have provisions to prevent simultaneous flame out of both engines, giving the pilot at least a little extra time to manage the problem or prepare for complete loss of power.

- Pilot vehicle interface (PVI or HMI) problems can result in an unintended manipulation of engine controls or a delayed response. These are more likely to affect the performance of a single engine helicopter than multi engine machines.

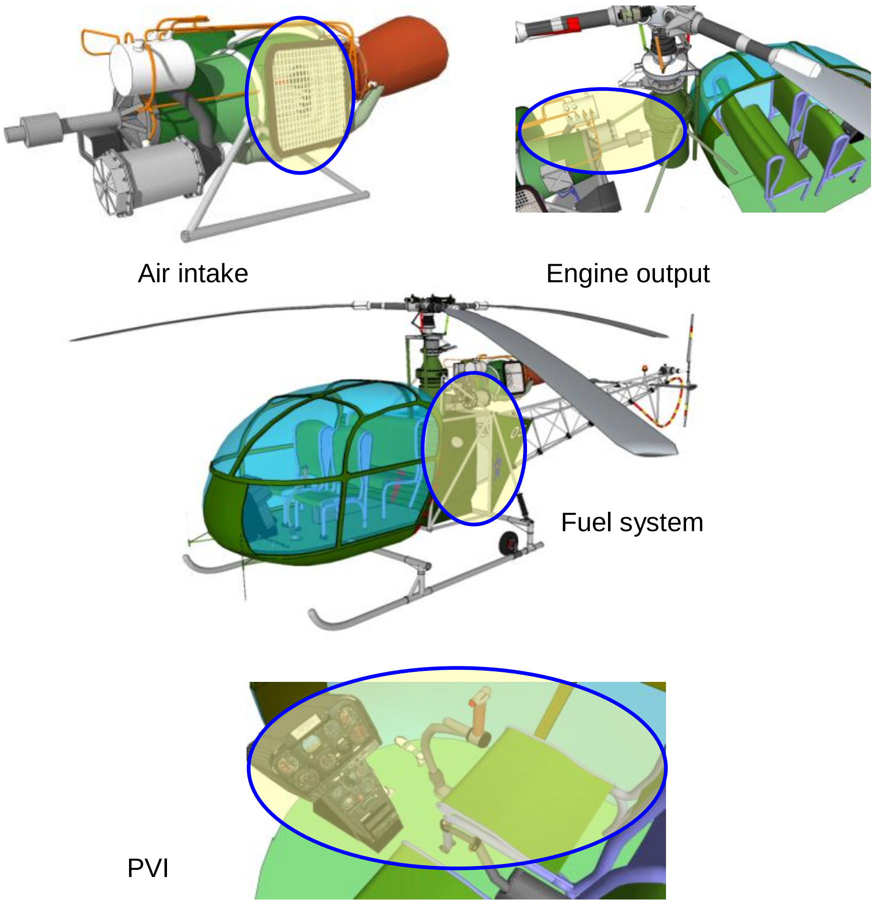


Figure 1: Components with indirect engine relation

3.3 Risk assessment

The risk assessment task consists of several steps as elaborated below. The list of these steps is as follows:

1. Isolate the primary / initial cause of engine-related accidents and serious incidents during SEH operations from the multitude of assigned SPS codes by analysing original occurrence reports;
2. Based on primary / initial causes, assign events to clusters in order to set priorities for mitigation measures;
3. Break-down the event chains by SPS Level 2 codes;
4. Determine the occurrence rates of each SPS Level 2 code per 100.000 FH for both piston- and turbine- engine SEH;
5. Determine the actual and estimated (potential) severity of an event based on its primary cause for operations over hostile and non-hostile environment;
6. Based on combination of frequency, severity and respective distribution over clusters, select several SPS Level 2 code groups for piston- and turbine-engined SEH as input for mitigation strategies.

The original accident reports are analysed by an expert helicopter pilot in order to determine primary causes of accidents and serious incidents. For both piston- and turbine-engined SEH, the events are assigned to nine clusters presented in next table. Furthermore, each event is further broken down into SPS Level 2 codes in order to narrow down the factors, which contributed to the accident/incident.

Cluster	Definition	Examples
Design	Factors which are specific to the design and prescribed maintenance schedules and procedures of single-engine helicopters	Gear failure due to fatigue.
Maintenance	Possible flaws which occurred during maintenance, use of wrong parts, early signs of imminent failure missed by maintenance personnel or not reported by ground personnel or pilot	Wrong type of drive belt installed; Cylinder clearances adjusted incorrectly.
Inadequate handling of engine failure	In case of engine failure, incorrect employment of standard procedures, pilot situation awareness	Wrong iginition switch selection
Environment	Environmental factors[1], which contributed to an event	Carburettor icing, compressor blade failure due to ingestion of ice/snow
Pilot induced	Potential errors in piloting techniques, operation outside of the prescribed flight envelope	Accidental engine shutdown by switch error
Flight preparation	Factors which are missed by pilot or ground personnel during routine pre-flight checks	Insufficient fuel
No Fault Found	In case of engine-failure, detailed investigation revealed no probable cause of the event	Intermittent loss of power during flight
Fuel pollution	Contamination of fuel, leading to a failure	Fuel polluted with a polymer
Other	Any and all other factors contributing to an accident / incident	Irregular poorly performed maintenance, pilot not licensed to fly at nigh

Table 1: Clusters of primary engine-related failures

In order to provide a holistic risk analysis of SEH occurrences, both quantitative and qualitative approaches are used. The occurrence rate per 100.000 FH of each SPS Level 2 category and the actual severity of the accident is determined quantitatively based on available data. Furthermore a distinction is made between occurrences in piston and turbine helicopters, since different engine types do not only presuppose different problems, but also represent different leagues of aircraft within the single-engine helicopter fleet. For example, turbine helicopters (generally) offer a greater seating capability and are capable of operating in a wider range of atmospheric conditions.

The severity of the events is assessed by using the ADREP 2000 taxonomy coding for damage and injury levels as presented in Table 2. Furthermore, the ALG severity code is comprised of the combination of the assigned ADREP codes by adding up injury and damage codes, which results in a 'severity matrix' presented in Table 3.

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[1] *Physical Environment* is a *factor "in a mishap if environmental phenomena such as weather, climate, whiteout or brown out conditions affect the actions of individuals and result in human error or an unsafe situation."*
Technological Environment is a factor "in a mishap when cockpit / vehicle / control station / workspace design factors or automation affect the actions of individuals and result in human error or an unsafe situation."
Related to maintenance situations: inadequate natural light, inadequate artificial lighting, dusk/nighttime, high noise levels, housekeeping/cleanliness, and hazardous/toxic substances. For instance, a maintenance worker who is working at night does not see a tool he left behind or an operator working on a pitching deck falls from a ladder

Both assignment of events to one of the eight clusters and estimation of potential severity of an event based on its primary cause for operations over both hostile and non-hostile environment, are qualitative judgments provided by an expert helicopter pilot. The results of both approaches help establish a priority list for mitigation measures.

Standard		Severity level				
ICAO / ADREP	**Value**	1	2	3	98	99
	Damage	Destroyed	Substantial	Minor	None	Unknown
	Injury	Fatal	Serious	Minor	None	Unknown

Table 2: Severity codes

Material damage / Injury	Destroyed	Substantial	Minor	None
Fatal	Catastrophic	Catastrophic	Hazardous	Hazardous
Serious	Catastrophic	Hazardous	Hazardous	Minor
Minor	Hazardous	Hazardous	Minor	Minor
None	Hazardous	Minor	Minor	Minor

Table 3: Severity matrix

3.4 Limitations of employed risk analysis methodology

During processing of the data the following limitations were encountered:

- Severity of events. Although the total number of gathered events for this study would allow for proper statistical analysis, the number of confirmed engine related events is relatively low. This implies that there is a reasonable chance that the results may exceed a reasonable standard deviation.
- Occurrence rates. The database does not represent all events. Only reported events are processed. Events with minor or no damage/injury are not always reported or remain at operator level. It is expected that a significant number of these 'low impact' events can therefore not be assessed. It would require a change of reporting system and/or reporting culture, to have all required data available for future use. The absence of numerous 'low impact' events in the database, calls for use of 'frequency of reported events' instead of actual occurrence frequency.

As a consequence of the mentioned limitations, the study reverts to a more qualitative approach for both severity and frequency of occurrence. To be able to identify unrealistic results, an estimated severity category will be established (what was likely to happen) for each engine related event, for both a hostile and non-hostile environment. The actual severity of each occurrence is evaluated against the estimated severity based on expert helicopter pilot's experience.

3.5 Risk mitigation

Mitigation measures are established for the most critical events on the priority list of engine related risks in single-engine helicopter operations. The principles applied for mitigation measures are:

- Low cost solution
- Supporting as much as possible the complete range of operations
- Uncomplicated, easy implementation
- Expected effect (residual risk) of the mitigation measure must be significant compared to existing situation

Only mitigations with estimated significant reduction of risk will be presented in this report. Risk reduction can either be an expected reduction of severity and/or a reduction of frequency of events.

Furthermore, mitigation measures are applied to the relevant events and reassessed by expert judgment (qualitative) on the residual risk over hostile environment. Reduction of severity by one level will be considered significant. The effect of the mitigation on frequency of events can only be qualitatively assessed. The expected effect on frequency of events will be motivated for each mitigation measure. As it is not possible to quantify the effects on frequency in advance, a reasonable likelihood of a mitigation measure to lower the frequency of an event is considered sufficient. Finally, the mitigation measures and their respective residual risks will be presented using a bowtie diagram.

4 Hazard identification

The following analysis is intended to identify the proportion of most common generic causes of accidents and serious incidents of single-engine helicopters due to engine failure. For this purpose, it will be necessary to provide occurrence ratios per 100.000 flying hours, evaluating turbine and piston events separately. These ratios are necessary for further estimation of frequency of engine-related failures.

Engine	Flight Hours
Piston	3.990.000
Turbine	6.000.000
Total	**9.990.000**

Table 4: Estimated flight hours for the European fleet (2003-2012)

Occurrence ratios per 100.000 FH for all registered events (4.606), all accidents and serious incidents (920) and, finally, accidents and serious incidents related to engine failure (125) - (56) of them with report available - are collected in next figures. It also shows the ratios of engine-related accidents and serious incidents by engine type using the respective flight hours.

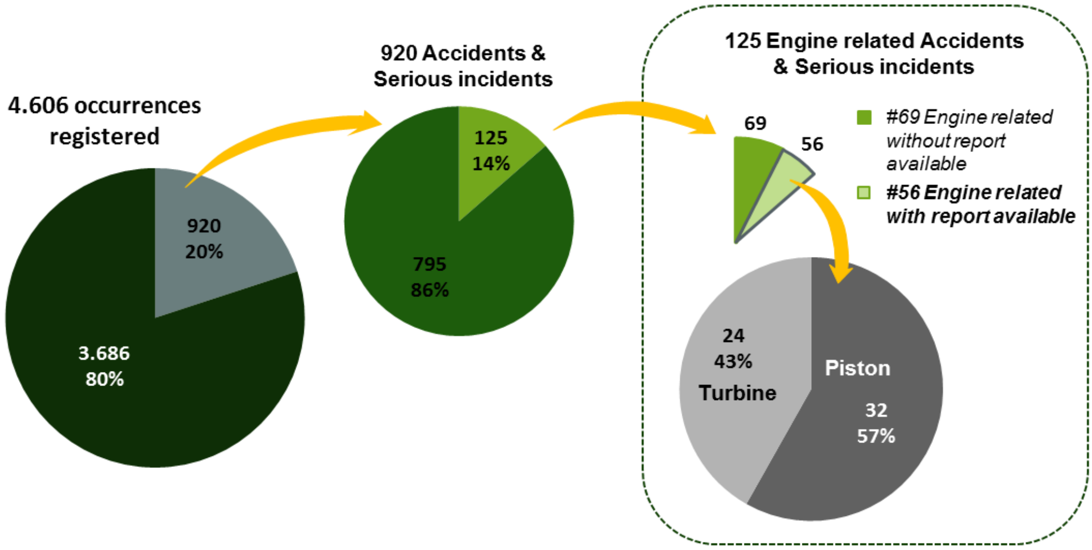

Figure 2: Occurrences categorization

Concept	Total occurrences		Total occurrences with reports available	
	Number of occurrences	Ratios per 100.000 FH	Number of occurrences	Ratios per 100.000 FH
Occurrences registered	4.606	**46,01**		
Accidents & Serious incidents	920	**9,21**		
Accidents & Serious incidents **engine related**	125	**1,25**	56	**0,56**
- *Piston*	*76*	***1,90***	*32*	***0,80***
- *Turbine*	*49*	***0,82***	*24*	***0,40***

Table 5: General ratios

Piston and turbine events will be separately evaluated and categorized by level 1 SPS codes. The reading of engine related accidents and serious incidents reports was required to develop the identification of SPS codes (see methodology in *EASE SEH 3 – Data Analysis and Member States Assessment*). So that, the safety risk assessment is based on the 56 engine related accidents and serious incidents with report available[2].

Eight different categories have been identified as possible causes of engine failure by the expert helicopter pilot: Ground Duties (100), Safety Management (200), Maintenance (300), Pilot judgment & actions (500), Pilot situation awareness (700), Part / system failure (800), Ground personnel (1200) and Aircraft Design (1400). Analysis of available data confirmed that all engine-related events were assigned to at least one of the indicated SPS Level 1 categories, with exception of Ground personnel (1200), which has not occurred at all. Next bar graphs represent the number of engine-related occurrences per 100.000 FH with an SPS category appearing at least once. These bar graphs show that piston- and turbine-engined helicopters have a different distribution of causes of an engine-related failure.

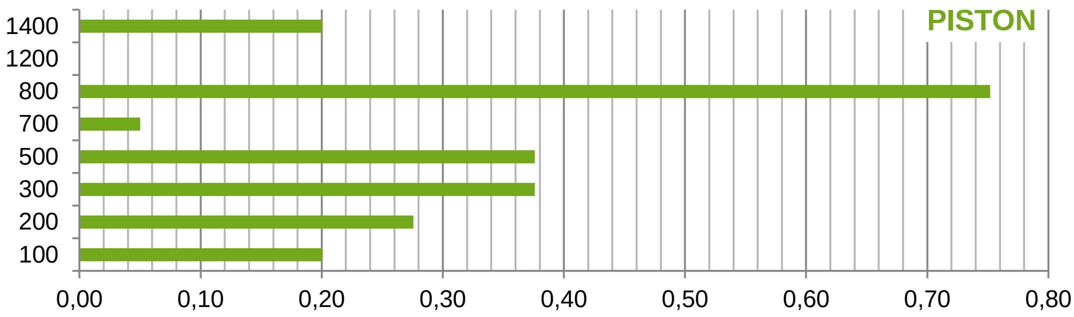

Figure 3: PISTON Engine related occurrences per 100.000 FH in which SPS level 1 category was identified at least once

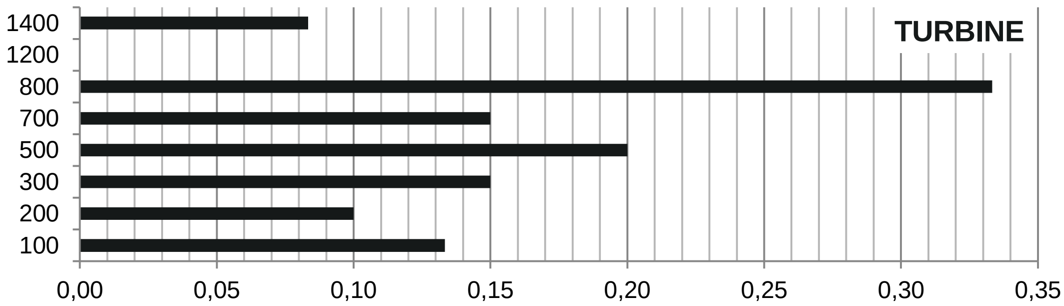

Figure 4: TURBINE Engine related occurrences per 100.000 FH in which SPS level 1 category was identified at least once

The absolute values of occurrence ratios are higher for the piston engine. Comparing the SPS Level 1 categories, the most common cause of failure, both for piston and turbine, is Part / system failure (800). The second most frequent category is Pilot judgment & actions (500), extremely close to Maintenance group (300) in case of piston events. For piston events, Safety Management (200) is also a frequent category. For turbine engine failures, Maintenance (300) and Pilot situation awareness (700) rank in third place. However, it should be noted that Pilot situation awareness (700) is the least frequent category amongst piston events.

[2] The absolute ratios are related to the total number of engine related event: 76 piston engine related occurrences vs 49 turbine engine related occurrences. So, final occurrence ratios per 100.000 FH to be used in the rule assessment will be: 1,9 piston engine related occurrences per 100.000 FH and 0,82 turbine engine related occurrences per 100.000 FH. It is the result after extrapolate safety risk assessment ratios:

$$0{,}80\, piston\ engine\ related\ (with\ report\ available)\ x\ 100.000FH \cdot \frac{76\ (total)}{32\ (with\ report\ available)} = 1{,}90\, piston\ engine\ relatedx\ 100.000FH$$

$$0{,}40\, turbine\ engine\ related\ (with\ report\ available)\ x\ 100.000FH \cdot \frac{49\ (total)}{24\ (with\ report\ available)} = 0{,}82\, piston\ engine\ relatedx\ 100.000FH$$

The same graphs are presented below, but now with two colour bars depending on number of accidents and serious incidents in hostile and non-hostile environment[3]. The occurrence ratios show a greater number of accidents in hostile environment per 100.000 FH for turbine helicopters.

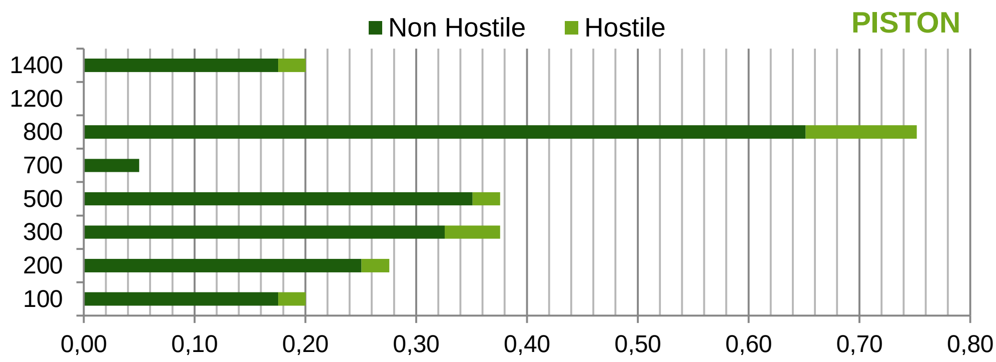

Figure 5: PISTON Engine related occurrences by type of environment per 100.000 FH in which SPS level 1 category was identified at least once

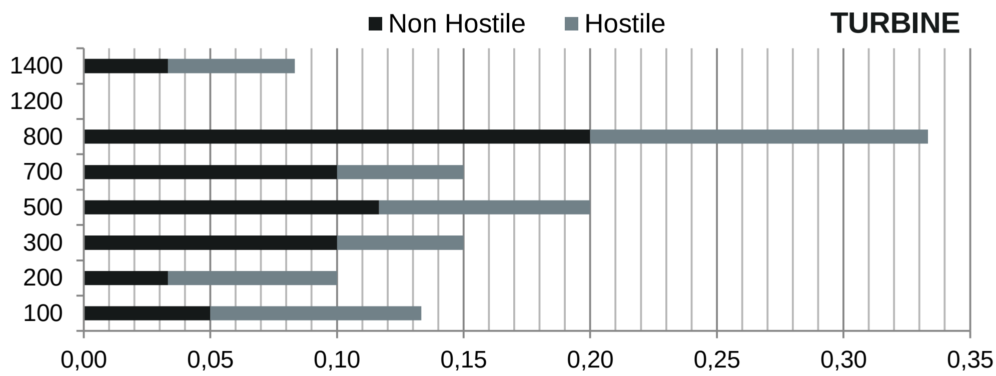

Figure 6: TURBINE Engine related occurrences by type of environment per 100.000 FH in which SPS level 1 category was identified at least once

[3] The ratio is obtained dividing by the flying hours for piston and turbine. The two colour bars only distinguish the number of occurrences according to the environment at the moment of the accident or serious incident registered

5 Risk analysis

In this chapter further analysis will be performed on most frequent SPS Level 1 occurrences for piston- and turbine-engined helicopters as identified in Chapter 4. Furthermore, relative frequency, severity of the event and its primary cause is evaluated both quantitatively (by analysing the actual event) and qualitatively (by estimation of severity provided by an expert helicopter pilot).

The actual severity of the assessed events is compared to an estimated severity for each individual event. By comparing the two, it is possible to avoid conclusions based on unrealistic figures as a result of low number statistics. The 'estimated severity' columns present the estimated severity bandwidth in which the majority of the events as described would be expected.

The tables in paragraphs 5.1 and 5.2 show significant discrepancies between the actual outcome of events in a non-hostile environment. Loss of engine power in non-hostile environment results in a significant number of event in fatalities and/or destroyed helicopters. From detailed analysis, it was found that, although the general area was non-hostile, the actual local position of the helicopter at the moment of the event, could be considered hostile. Examples are insufficient altitude to be able to manoeuvre to a proper emergency landing area, operating to or from confined areas, or sloping grounds and obstacles. Also a number of these events occurred in combination of altitude and airspeed, at which it is unlikely to accomplish a safe landing. This part of the flight envelope (published by the OEM in a Height-Velocity diagram) is therefore considered hostile for a single engine helicopter.

When taking these local conditions into account, the actual severity regarding the assessed engine related events could be considered realistic.

5.1 Piston single-engine helicopters

In this section the accidents and incidents of the piston-engined helicopters are analysed based on the most frequent SPS Level 1 categories.

5.1.1 SPS Level 1: 200 (Safety Management)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 200 category (Safety Management). The events are assigned to respective 'hazard clusters'. Furthermore, for each event, the actual severity is compared to an expert estimation. The occurrence rates per 100.000 FH of the associated SPS Level 2 codes are presented in the figure below.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
7	Engine shutdown due to ignition failure (magneto break)	Design	2030	Y	hazardous	catastrophic / hazardous	hazardous / minor
132	Spark plug issues caused loss of power	Maintenance	2030	N	catastrophic	catastrophic / hazardous	hazardous / minor
344	Ignition issues, pilot SA, suspected drive belt failure	Inadequate handling of engine failure	2010	N	catastrophic	minor / none	None
352	Suspected ignition issues, power loss, delayed pilot reaction	Inadequate handling of engine failure	2090	N	catastrophic	catastrophic / hazardous	hazardous / minor
610	The camshaft had fractured; engine failure	Design	2090	N	minor	catastrophic / hazardous	hazardous / minor
624	Sudden power loss at low altitude, possibly fuel supply problem	No Fault Found	2090	N	minor	hazardous / minor	minor
681	Engine failure during autorotation exercise handled inadequately	Inadequate handling of engine failure	2090	N	hazardous	catastrophic / hazardous	Minor
724	Engine failure due to damaged valves, probably result of previous overspeed, student pilot, IGE hover.	maintenance	2090	N	hazardous	Minor / none	Minor / none

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
764	ignition failure, maintenance issues	Maintenance	2010	N	minor	catastrophic / hazardous	hazardous / minor
797	carburator icing	Environment	2090	N	minor	catastrophic / hazardous	hazardous / minor
815	bearing failure drive belt pulley	Design	2090	N	minor	catastrophic / hazardous	hazardous / minor

Table 6: PISTON List of events within SPS Level 1 = 200 (Safety Management)

Analysis shows that within Safety Management category (SPS Level 1 200), the most severe events (catastrophic) are attributed to the 'Inadequate handling of engine failure' and 'maintenance' initial cause clusters.

Out of ten events in previous table, only one has occurred over hostile environment with relatively severe consequences. Events 132, 344 and 352 all had catastrophic consequences, which according to the expert pilot's judgment, is not necessarily to be expected based on initial cause of the accident. Even though, the occurrence rates are relatively low, the 2090 SPS Level 2 code associated with 'Inadequate Pilot Experience' occurs in multiple clusters and therefore dominates the Safety Management category. The 2090 SPS code is therefore seen as a priority for mitigation measures to follow in the next chapter.

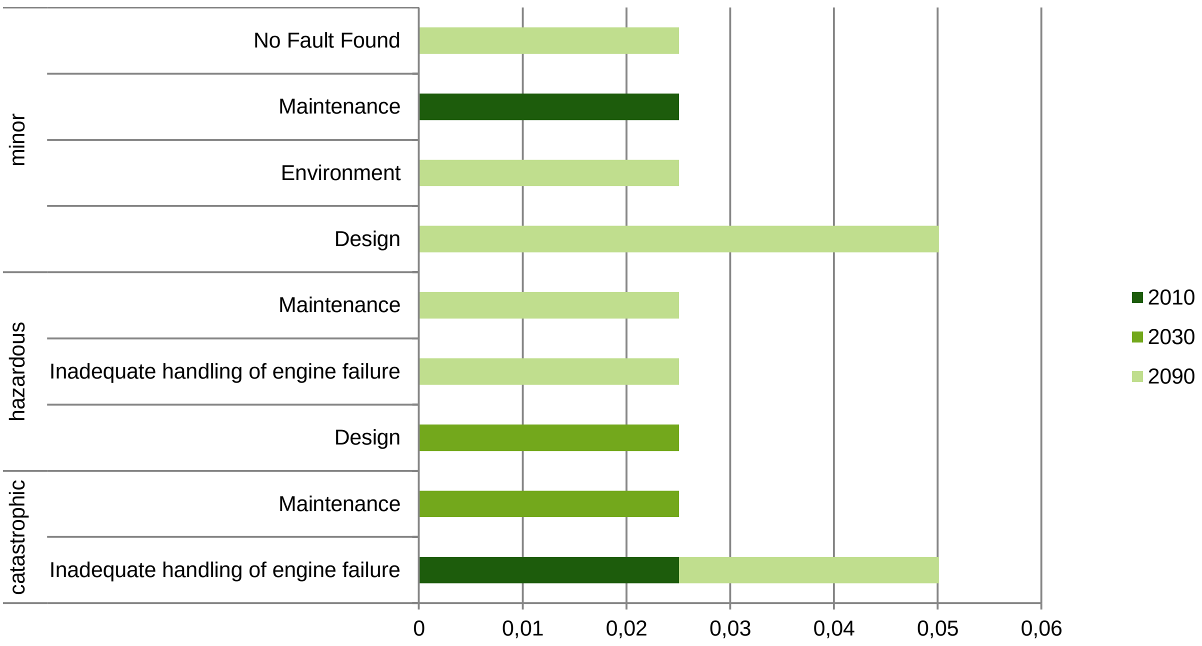

Figure 7: PISTON Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the "Safety Management" category

5.1.2 SPS Level 1: 300 (Maintenance)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 300 category (Maintenance). The majority of events in this group have occurred over non-hostile environment with minor consequences. The two catastrophic events both occurred over non-hostile environment and have been attributed to inadequate handling of engine failure by the pilot and helicopter's design characteristics. Furthermore it can be said, that events with minor actual severity went according to the 'best case' scenario estimated by the expert pilot.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
7	Engine shutdown due to ignition failure (magneto break)	design	3010	Y	minor	catastrophic / hazardous	hazardous / minor
241	Failure of carburettor and electrical issues; Metal shards were found in the engine oil	maintenance	3020	Y	minor	catastrophic / hazardous	hazardous / minor
352	Suspected ignition issues, power loss, delayed pilot reaction	inadequate handling of engine failure	3020	N	catastrophic	catastrophic / hazardous	hazardous / minor
387	No direct engine malfunction, but exhaust pipe was detached from the turbocharger (due to fatigue	design	3020	N	minor	catastrophic / hazardous	hazardous / minor
391	Engine malfunction; possibly because the mixture control cable may have become disconnected from the mixture lever on the fuel injector servo.	design	3010	N	catastrophic	catastrophic / hazardous	hazardous / minor
529	Drive belt broke, wrong type of drive belt installed, not spotted during routine maintenance	maintenance	3010 3020	N	minor	catastrophic / hazardous	hazardous / minor
596	Intermittent loss of power during transition from hover to forward flight; the engine had exceeded its rated speed on the previous day; not reported to maintenance	flight preparation	3010	N	minor	catastrophic / minor	hazardous / minor
606	Cylinder clearances adjusted incorrectly; cylinder exhaust valve was blocked in closed position, loss of power	maintenance	3040	N	minor	catastrophic / hazardous	hazardous / minor
674	Driveshaft failure due to fatigue	design	3020	N	minor	catastrophic / hazardous	hazardous / minor
681	Engine failure during autorotation exercise. Applied wrong techniques during autorotation.	inadequate handling of engine failure	3040	N	minor	catastrophic / hazardous	minor
724	Engine failure due to damaged valves, probably result of previous overspeed, student pilot, IGE hover.	maintenance	3010	N	hazardous	Minor / none	Minor / none
764	ignition failure, maintenance issues	maintenance	3040 3010	N	minor	catastrophic / hazardous	hazardous / minor
781	engine component fail, possible maintenance flaw	maintenance	3040 3020 3010	N	minor	catastrophic / hazardous	hazardous / minor
810	Polluted fuel (polymer)	fuel pollution	3040 3020 3010	N	minor	catastrophic / hazardous	hazardous / minor
815	bearing failure drive belt pulley	design	3010	N	minor	catastrophic / hazardous	hazardous / minor

Table 7: PISTON List of events within SPS Level 1 = 300 (Maintenance)

Next figure depicts the breakdown of the SPS Level 2 codes associated with the accidents and incidents in the table above. The list of accidents is represented by three SPS Level 2 codes: 3010 (MX Procedures / Management), 3020 (Performance of MX Duties) and 3040 (Quality of Parts). The 3010 code occurs most frequently and is assigned to several clusters. Therefore failure modes associated with this code are a priority for mitigation measures.

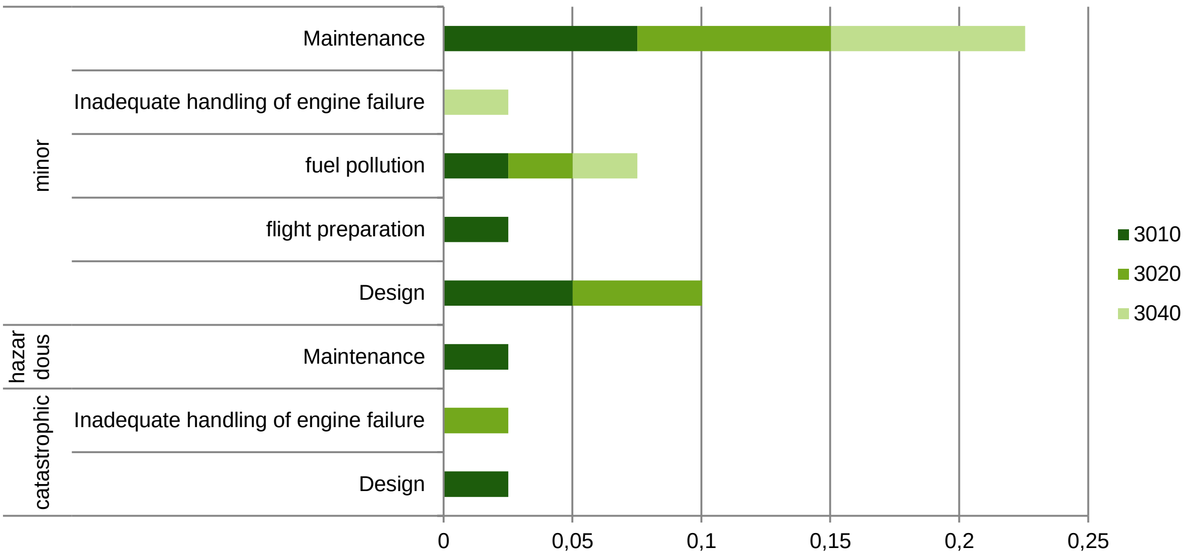

Figure 8: PISTON Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the "Maintenance" category

5.1.3 SPS Level 1: 500 (Pilot judgment & actions)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 500 category (Pilot Judgment & actions). This category includes several events with catastrophic consequence. Catastrophic consequences of these events have been attributed to a variety of SPS Level 2 codes: 5010 (Human Factors - Pilot's Decision), 5030 (Flight Profile), 5040 (Landing Procedures) and 5060 (Procedure Implementation). Having reviewed the primary / initial causes, the majority of events with catastrophic consequences have been placed into 'Inadequate handling of engine failure' and 'Maintenance' clusters.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
132	Spark plug issues caused loss of power	maintenance	5010 5060 5030 5040	N	catastrophic	catastrophic / hazardous	hazardous / minor
273	Cylinder blocking the exhaust valve and the valve push rod broke	design	5040	N	minor	catastrophic / hazardous	hazardous / minor
344	Ignition issues, pilot SA, suspected drive belt failure	inadequate handling of engine failure	5040 5010	N	catastrophic	minor / none	none
345	probable engine stall during reduction of power, fuel warning light inoperable	No Fault Found	5040 5030	N	catastrophic	catastrophic / hazardous	hazardous / minor
352	suspected ignition issues, power loss, delayed pilot reaction	inadequate handling of engine failure	5020	N	catastrophic	catastrophic / hazardous	hazardous / minor
371	Possible unidentified transient defect in the fuel or ignition systems may have prevented the engine from producing adequate power. Possible flight technique issues (tail wind, rotor droop, vortex ring state)	inadequate handling of engine failure	5030	N	hazardous	hazardous / none	minor / none
374	Failure of one of the two drive belts transmitting power from the engine to the main transmission	design	5010	Y	hazardous	catastrophic / hazardous	hazardous / minor
387	no direct engine malfunction, but exhaust pipe was detached from the turbocharger (due to fatigue), producing smoke and excessive heat	design	5040	N	minor	catastrophic / hazardous	hazardous / minor
529	Drive belt broke, wrong type of drive belt installed, not spotted during routine maintenance	maintenance	5010	N	minor	catastrophic / hazardous	hazardous / minor

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
596	intermittent loss of power during transition from hover to forward flight; the engine had exceeded its rated speed on the previous day; not reported to maintenance	flight preparation	5010	N	minor	catastrophic / minor	hazardous / minor
610	The camshaft had fractured; engine failure	design	5040	N	minor	catastrophic / hazardous	hazardous / minor
681	Engine failure during autorotation exercise. Applied wrong techniques during autorotation.	inadequate handling of engine failure	5060 5040 5010	N	minor	catastrophic / hazardous	minor
797	Carburettor icing	environment	5060 5050	N	minor	catastrophic / hazardous	hazardous / minor
717	Most likely belt tension problem, gradual power loss, delayed pilot response.	maintenance	5060	N	catastrophic	catastrophic / hazardous	hazardous / minor
724	Engine failure due to damaged valves, probably result of previous overspeed, student pilot, IGE hover.	maintenance	5010 5060	N	minor	minor / none	minor / none

Table 8: PISTON List of events within SPS Level 1 = 500 (Pilot Judgment & actions)

Next figure depicts the distribution of events over clusters, their severity and relative occurrence rates. It is clear that the SPS Level 1: 500 category is not dominated by any of the Level 2 codes, therefore mitigation measures will be drawn up for this category as a whole.

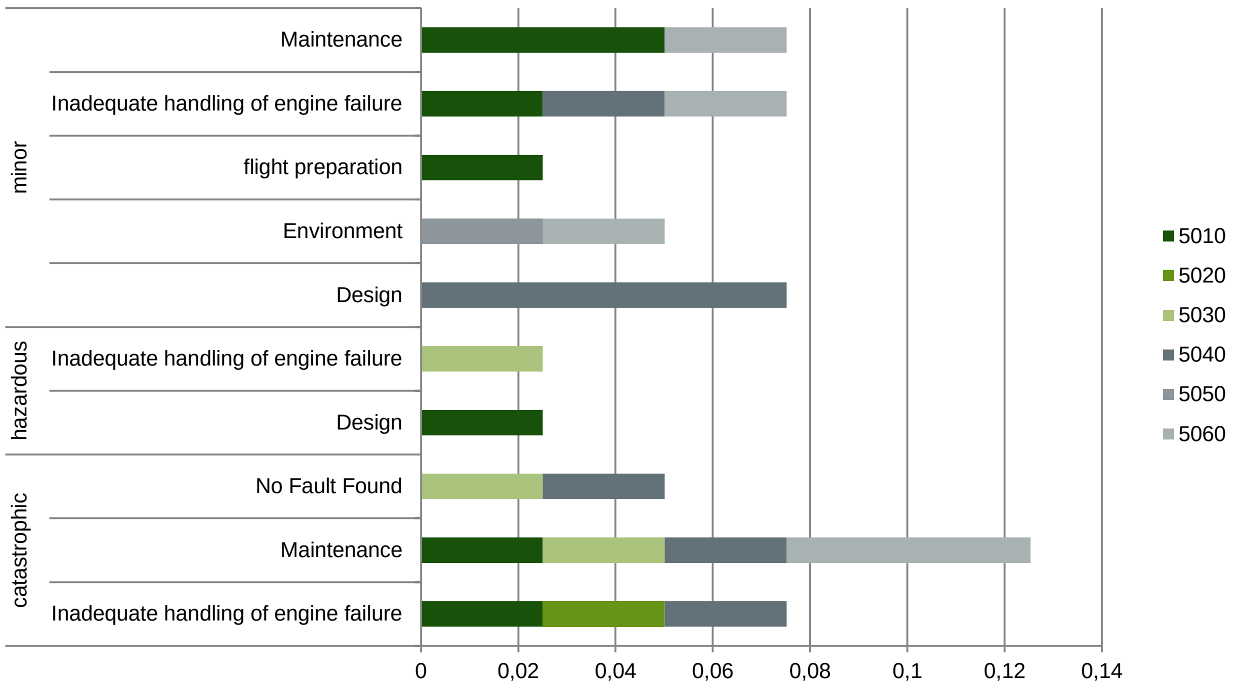

Figure 9: PISTON Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the "Pilot judgment & actions" category

5.1.4 SPS Level 1: 800 (Part / system failure)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 800 category (Part / system failure). Since only engine-related causes of events are reviewed, this list is quite extensive. The events in this category range from none to catastrophic severity and can attributed to a variety of clusters.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
7	engine shutdown due to ignition failure (magneto break)	design	8020	Y	minor	catastrophic / hazardous	hazardous / minor
95	insufficient oil for cooling, engine failure	flight preparation	8020	N	minor	catastrophic / hazardous	hazardous / minor
132	spark plug issues caused loss of power	maintenance	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
202	Pilot reported loss of power, NFF	No Fault Found	8020	N	hazardous	catastrophic / hazardous	hazardous / minor
241	Carburettor was not working properly due to a sticking float, there was also electrical shorting due to a breakdown in the ignition wiring and in addition overheating inside the cylinders. Metal shards were found in the engine oil, and there were signs of abrasion	maintenance	8020	Y	minor	catastrophic / hazardous	hazardous / minor
273	Cylinder blocking the exhaust valve and the valve push rod broke.	design	8020	N	minor	catastrophic / hazardous	hazardous / minor
344	Possible ignition issues, pilot SA	inadequate handling of engine failure	8020	N	catastrophic	minor / none	none
345	probable engine stall during reduction of power, fuel warning light inoperable	No Fault Found	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
352	Suspected ignition issues, power loss, delayed pilot reaction	inadequate handling of engine failure	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
368	Significant engine vibration and loss of power; No more information available	No Fault Found	8020	N	minor	catastrophic / hazardous	hazardous / minor
371	Possible unidentified transient defect in the fuel or ignition systems may have prevented the engine from producing adequate power. Possible flight technique issues (tail wind, rotor droop, vortex ring state)	inadequate handling of engine failure	8020	N	hazardous	hazardous / none	minor / none
374	Failure of one of the two drive belts transmitting power from the engine to the main transmission.	design	8010	Y	hazardous	catastrophic / hazardous	hazardous / minor
387	no direct engine malfunction, but exhaust pipe was detached from the turbocharger (due to fatigue), producing smoke and excessive heat	design	8020	N	minor	hazardous / none	minor / none
391	engine malfunction; possibly because the mixture control cable may have become disconnected from the mixture lever on the fuel injector servo.	design	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
529	Drive belt broke, wrong type of drive belt installed, not spotted during routine maintenance	maintenance	8020	N	minor	catastrophic / hazardous	hazardous / minor
596	intermittent loss of power during transition from hover to forward flight; the engine had exceeded its rated speed on the previous day; not reported to maintenance	flight preparation	8020	N	minor	catastrophic / minor	hazardous / minor
606	cylinder clearances adjusted incorrectly; cylinder exhaust valve was blocked in the closed position, loss of power	maintenance	8020	N	minor	catastrophic / hazardous	hazardous / minor
610	The camshaft had fractured; engine failure	design	8020	N	minor	catastrophic / hazardous	hazardous / minor
624	sudden power loss at low altitude, possibly fuel supply problem.	No Fault Found	8011 8020	N	minor	hazardous / minor	minor
674	driveshaft failure due to fatigue	design	8010	N	minor	catastrophic / hazardous	hazardous / minor
681	Engine failure during autorotation exercise. Applied wrong techniques during autorotation.	inadequate handling of engine failure	8020	N	minor	catastrophic / hazardous	minor
703	accidental engine shutdown by switch error	pilot induced	8020	Y	catastrophic	catastrophic / hazardous	hazardous / minor
717	Most likely belt tension problem, gradual power loss, delayed pilot response.	maintenance	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
751	driveshaft failure due to vibration cracks, causes by possible misalignment of the driveshaft	maintenance	8010	N	minor	catastrophic / hazardous	hazardous / minor
752	fuel supply problem, engine failure during low G manoeuvre (push-over) at 1500 ft, not allowed according flight manual. Successful restart.	pilot induced	8020	N	none	catastrophic / hazardous	hazardous / minor
781	engine component fail, possible maintenance flaw	maintenance	8020	N	minor	catastrophic / hazardous	hazardous / minor
797	carburettor icing	environment	8020	N	minor	catastrophic / hazardous	hazardous / minor
801	Fadec failure - power loss, maintenance status unknown	design	8010 8011	N	minor	catastrophic / hazardous	hazardous / minor
810	polluted fuel (polymer)	fuel pollution	8020	N	minor	catastrophic / minor	hazardous / minor
815	bearing failure drive belt pulley	design	8020	N	minor	catastrophic / hazardous	hazardous / minor

Table 9: PISTON List of events within SPS Level 1 = 800 (Part / system failure)

Next figure depicts the distribution of events over clusters, their severity and relative occurrence rates. The SPS Level 2: 8020 code (Part / system failure – Power plant) dominates this category as expected. Since this code occurs in all clusters and is attributed to events with a wide severity spread, it will be reviewed separately in order to draw up possible measures to mitigate the risk of identified hazards.

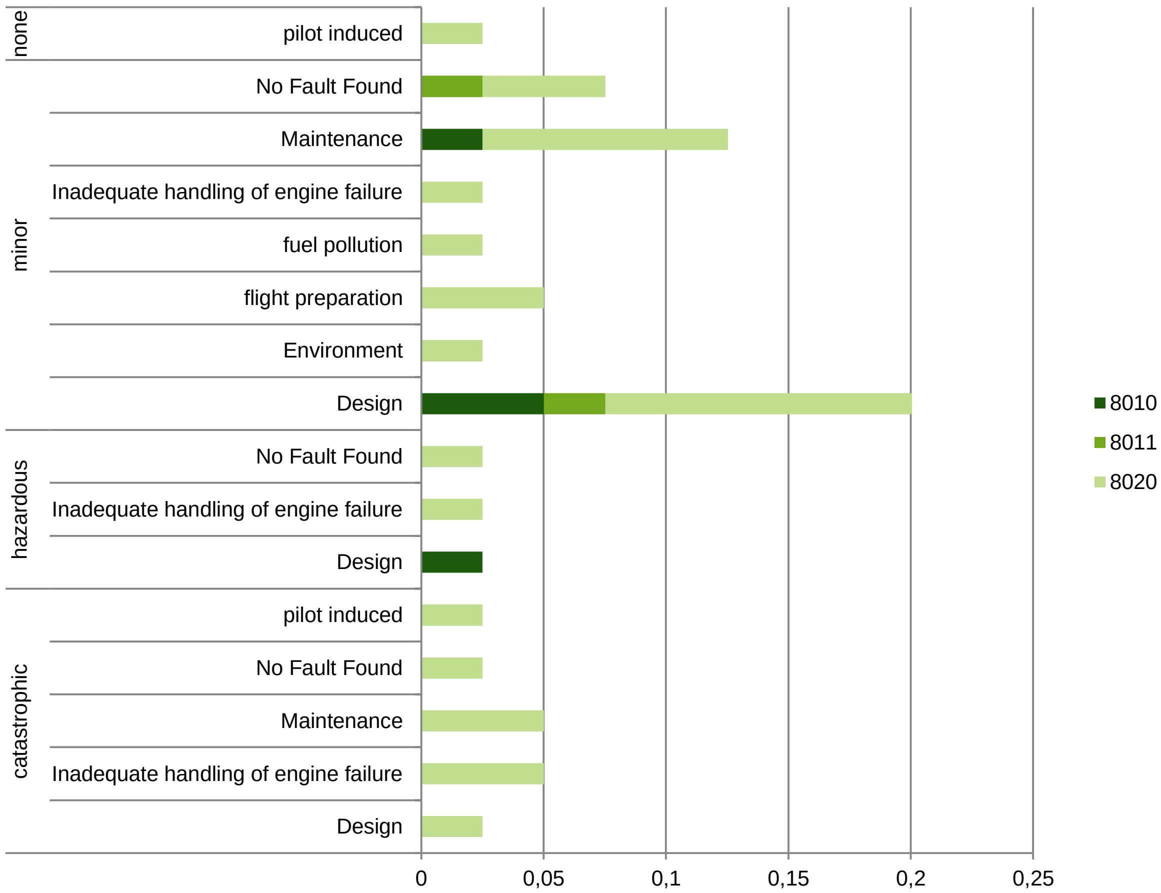

Figure 10: PISTON Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the “Part / system failure” category

5.2 Turbine single-engine helicopters

In this section the accidents and incidents of the turbine-engined helicopters are analysed based on the most frequent SPS Level 1 categories.

5.2.1 SPS Level 1: 300 (Maintenance)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 300 category (Maintenance). The events in this category range from minor to catastrophic severity and can be mainly attributed to flight preparation and maintenance- and design flaws. Presence of these three clusters indicates that the events can be attributed to the fact that engine-related flaws have been missed by either maintenance personnel (maintenance / design cluster) or the pilot.

Furthermore it should be noted that event number 643 cannot be addressed according to this methodology, since this event's catastrophic consequences can be attributed to clear violations of maintenance procedures and pilot licensing. Therefore, this event is not strictly engine-related.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
12	Engine flame-out that was probably caused by the engine ingesting wet snow accumulated on the engine air intake surface. The fact that the engine warning system was turned off, effectively eliminating the automatic reignition system, was a contributing factor.	environment	3040	Y	hazardous	catastrophic / hazardous	hazardous / minor
186	breakage of a gear in the module connecting the drive shaft to the accessory box caused power failure. Early warnings missed by maintenance.	maintenance	3040 3010	Y	minor	catastrophic / hazardous	hazardous / minor
240	Engine shutdown has been due to a total breakdown of compressor which in turn is derived to a compressor blade failed due to fatigue. This is most likely initiated by corrosion in the compressor rotor material.	design	3010	N	minor	catastrophic / hazardous	hazardous / minor
569	Loss of fuel supply from the FCU. The drive to the FCU ceased as a result of the disintegration of the 41-tooth Bevel Gear in the accessory drive due to fatigue.	maintenance	3020	N	catastrophic	catastrophic / hazardous	hazardous / minor
635	The cause of the incident was due to the intake of fuel spilled by the mouth of the pipe to access the fuel tank, the inlet of the turbine engine.	flight preparation	3020	N	minor	catastrophic / hazardous	hazardous / minor
643	irregular poorly performed maintenance, pilot not licensed to fly at night, no mechanical failure	other	3010	Y	catastrophic	-	-
668	Fracture of a stage-two blade due to crack progression in fatigue.	design	3010 3020	N	minor	catastrophic / hazardous	hazardous / minor
679	Mechanical problem in the N1 accessory drive gearbox, bad maintenance, early signs not reported.	maintenance	3020 3010	N	minor	catastrophic / hazardous	hazardous / minor
798	Driveshaft adapter burst during flight as a result of a fatigue crack. Fatigue missed by maintenance, design of adapter is weak	maintenance	3020	N	minor	catastrophic / hazardous	hazardous / minor

Table 10: TURBINE List of events within SPS Level 1 = 300 (Maintenance)

Next figure shows that SPS Level 2 code 3010 (MX Procedures/Management) has been assigned to events ranging from minor to catastrophic severity. It occurs in each cluster and therefore the events with this code will be reviewed in detail in order to provide measures to mitigate the associated risks.

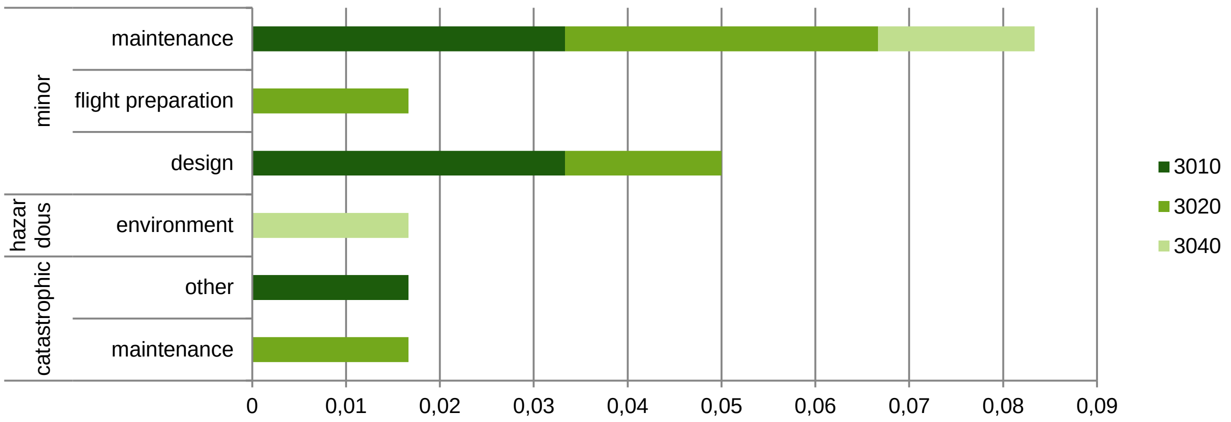

Figure 11: TURBINE Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the "Maintenance" category

5.2.2 SPS Level 1: 500 (Pilot judgment & actions)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 500 category (Pilot judgment & actions). The events in this category have occurred in both hostile and non-hostile environment and range from minor to catastrophic. As expected several pilot induced accidents can be found in this category, but the majority primary/initial causes can be attributed to maintenance, design and environmental factors.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
92	Failure of centrifugal compressor due to fatigue cracks on the blade	design	5011	Y	catastrophic	catastrophic / hazardous	hazardous / minor
93	Engine bearing failure, autorotation inadequately managed	design	5040	N	catastrophic	catastrophic / hazardous	hazardous / minor
282	Operation at performance limit under difficult environmental conditions caused loss of control, engine failure is secondary	pilot induced	5060	Y	hazardous	catastrophic / hazardous	hazardous / minor
365	Power fluctuations in flight, loss of power, NFF	no fault found	5020	N	hazardous	catastrophic / none	minor / none
643	Irregular poorly performed maintenance, pilot not licensed to fly at night, no mechanical failure	other	5030	Y	catastrophic	-	-
679	Mechanical problem in the N1 accessory drive gearbox, bad maintenance, early signs not reported.	maintenance	5030	N	minor	catastrophic / hazardous	hazardous / minor
748	Compressor blade failure due to sucking in ice/snow	environment	5030 5010 5040	N	catastrophic	catastrophic / hazardous	hazardous / minor
753	Insufficient fuel, loss of power	flight preparation	5060	Y	minor	catastrophic / hazardous	hazardous / minor
798	Driveshaft adapter burst during flight as a result of a fatigue crack; fatigue missed by maintenance, design of adapter is weak	maintenance	5030 5010	N	minor	catastrophic / hazardous	hazardous / minor

Table 11: TURBINE List of events within SPS Level 1 = 500 (Pilot judgment & actions)

Similar to distribution of SPS Level 2 codes for piston-engined helicopters, as depicted in next figure, turbine-engined events cannot be attributed to a single SPS code. Therefore, SPS 500 category will be addressed as a whole in the risk mitigations chapter.

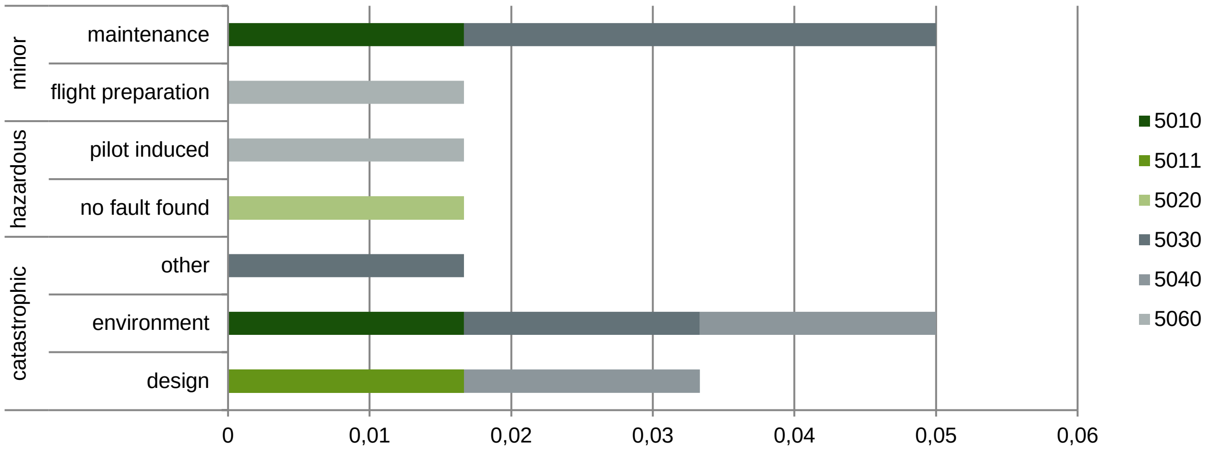

Figure 12: TURBINE Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the "Pilot actions & judgment" category

5.2.3 SPS Level 1: 700 (Pilot situation awareness)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 700 category (Pilot situation awareness). The events in this category have occurred in both hostile and non-hostile environment. The majority of these events are of high severity and can be attributed to several clusters: Design, No Fault Found and Environment. It should be noted that this SPS level 1 category is not as dominant as amongst piston-engined occurrences.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
12	Engine flame-out that was probably caused by the engine ingesting wet snow accumulated on the engine air intake surface. The fact that the engine warning system was turned off, effectively eliminating the automatic reignition system, was a contributing factor.	environment	7010 7020	Y	Hazardous	catastrophic / hazardous	hazardous / minor
92	failure of centrifugal compressor due to fatigue cracks on the blade	design	7030	Y	Catastrophic	catastrophic / hazardous	hazardous / minor
365	power fluctuations in flight, loss of power, NFF	No Fault Found	7030	N	Hazardous	catastrophic / none	minor / none
569	Loss of fuel supply from the FCU. The drive to the FCU ceased as a result of the disintegration of the 41-tooth Bevel Gear in the accessory drive due to fatigue.	design	7020	N	Catastrophic	catastrophic / hazardous	hazardous / minor
577	engine stoppage during a flight, NFF	No Fault Found	7020	N	Catastrophic	catastrophic / hazardous	hazardous / minor
643	irregular poorly performed maintenance, pilot not licensed to fly at night, no mechanical failure	other	7010	Y	Catastrophic	-	-
679	mechanical problem in the N1 accessory drive gearbox, bad maintenance, early signs not reported.	maintenance	7020	N	Minor	catastrophic / hazardous	hazardous / minor
748	compressor blade failure due to sucking in ice/snow	environment	7010	N	Catastrophic	catastrophic / hazardous	hazardous / minor
798	Driveshaft adapter burst during flight as a result of a fatigue crack. Fatigue missed by maintenance, design of adapter is weak	maintenance	7030	N	Minor	catastrophic / hazardous	hazardous / minor

Table 12: TURBINE List of events within SPS Level 1 = 700 (Pilot situation awareness)

Next figure shows that the 7020 SPS Level 2 code (External Environment Awareness) occurs most frequently amongst accidents and incidents in this category. Due to the nature of these events, dominance of the 7020 assignment is not entirely surprising. This code will be addressed in the mitigation measures chapter.

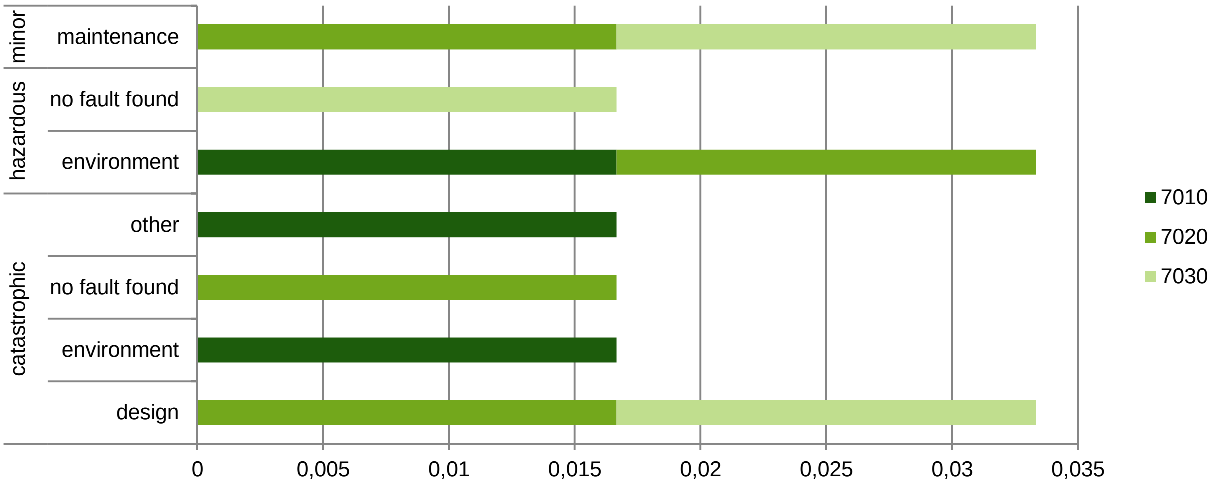

Figure 13: TURBINE Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the "Pilot situation awareness" category

5.2.4 SPS Level 1: 800 (Part / system failure)

Next table provides a list of accidents and serious incidents within the SPS Level 1: 800 category (Part / system failure). The events in this category have occurred in both hostile and non-hostile environment. The majority of these events are of high severity and can be attributed to design and maintenance clusters. The findings in the turbine-engined category are similar to those of piston-engined.

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
13	The bearing of the Gas Producer Fuel Control Unit failed due to insufficient lubrication	design	8011	Y	hazardous	catastrophic / hazardous	hazardous / minor
92	failure of centrifugal compressor due to fatigue cracks on the blade	design	8020	Y	catastrophic	catastrophic / hazardous	hazardous / minor
93	Engine bearing failure, autorotation inadequately managed	design	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
186	Breakage of a gear in the module connecting the drive shaft to the accessory box caused power failure. Early warnings missed by maintenance	maintenance	8020	Y	minor	catastrophic / hazardous	hazardous / minor
240	Engine shutdown has been due to a total breakdown of compressor which in turn is derived to a compressor blade failed to due to fatigue. This is most likely initiated by corrosion in the compressor rotor material	design	8020	N	minor	catastrophic / hazardous	hazardous / minor
276	Loss of power due to leak in air control line between the fuel control unit and was leaking accumulator	design	8011	N	minor	catastrophic / minor	hazardous / none
282	operation at performance limit under difficult environmental conditions caused loss of control, engine failure is secondary	pilot induced	8020	Y	hazardous	catastrophic / hazardous	hazardous / minor
286	failure of clutch unit due to stress/fatigue, loss of power	design	8010	Y	catastrophic	catastrophic / hazardous	hazardous / minor
491	cable break in fuel warning system, loss of power due to low fuel	maintenance	8011	N	minor	catastrophic / hazardous	hazardous / minor

Event			SPS	Hostile env. (Y/N)	Severity		
					Actual	Estimated	
ALG seq.	Description	Cluster	Level 2			Hostile	Non-hostile
500	engine failure, NFF	No Fault Found	8020	Y	catastrophic	catastrophic / hazardous	hazardous / minor
569	Loss of fuel supply from the FCU. The drive to the FCU ceased as a result of the disintegration of the 41-tooth Bevel Gear in the accessory drive due to fatigue..	design	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
577	engine stoppage during a flight, NFF	No Fault Found	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
625	required engine power could not be obtained as a result of pollution in the fuel control unit	Fuel pollution	8020 8011	N	minor	catastrophic / hazardous	hazardous / minor
643	irregular poorly performed maintenance, pilot not licensed to fly at night, no mechanical failure	other	8011 8020	Y	catastrophic	0	0
645	The engine to main gearbox drive train was interrupted. Examination of the engine drive shaft revealed a broken KaFlex coupling at the engine to lower pulley drive shaft	design	8020	N	hazardous	catastrophic / hazardous	hazardous / minor
668	Fracture of a stage-two blade due to crack progression in fatigue	design	8020	N	minor	catastrophic / hazardous	hazardous / minor
679	Mechanical problem in the N1 accessory drive gearbox, bad maintenance, early signs not reported	maintenance	8020	N	minor	catastrophic / hazardous	hazardous / minor
736	NFF, possible fuel contamination	inadequate handling of engine failure	8020	Y	catastrophic	catastrophic / hazardous	hazardous / minor
748	compressor blade failure due to sucking in ice/snow	environment	8020	N	catastrophic	catastrophic / hazardous	hazardous / minor
798	Driveshaft adapter burst during flight as a result of a fatigue crack. Fatigue missed by maintenance, design of adapter is weak	maintenance	8020	N	minor	catastrophic / hazardous	hazardous / minor

Table 13: TURBINE List of events within SPS Level 1 = 800 (Part / system failure)

Next figure clearly shows that the 8020 SPS Level 2 (Part / system failure – Power plant) code occurs most frequently amongst turbine-engined helicopter events. This result was expected, since only engine-related events are part of this analysis. The 8020 code will be addressed separately in order to provide potential mitigation measures.

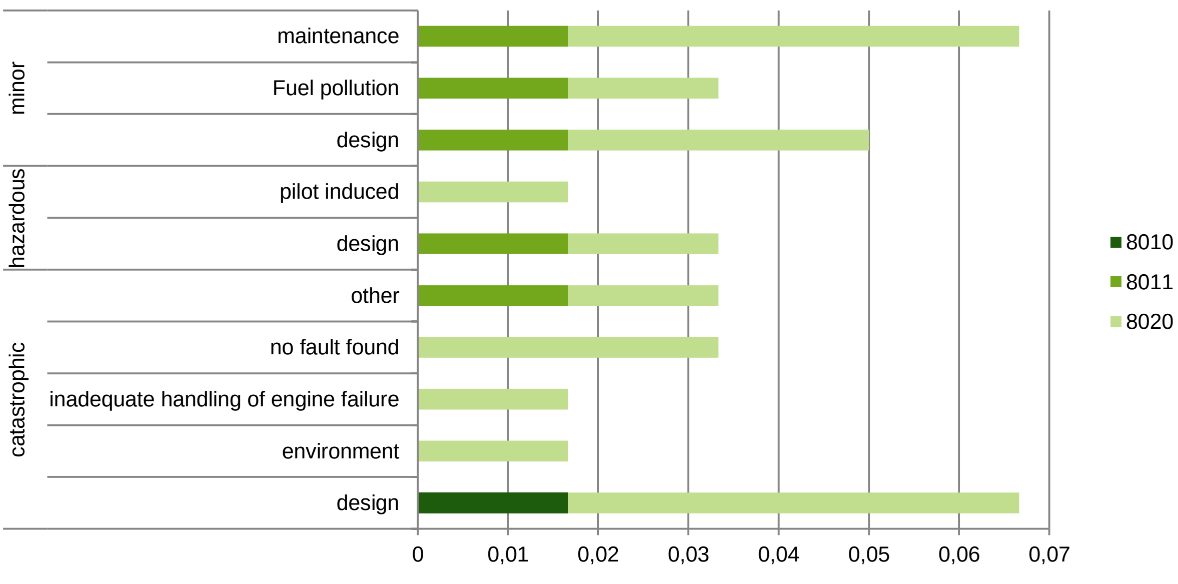

Figure 14: TURBINE Relative occurrence rates per 100.000 FH of SPS Level 2 codes within the “Part / system failure” category

6 Risk mitigation strategies

Mitigation measures have been established for the identified relevant risks. Mitigations will, when possible, be based on received information regarding technological and/or procedural improvements expected for the next decade.

Further principles applied for mitigation measures are:

- when possible low cost solution,
- supporting as much as possible the complete range of operations,
- uncomplicated, easy implementation, and
- expected effect (residual risk) of the mitigation measure must be significant compared to existing situation.

In general, risk analysis showed a similarity in areas of interest for both piston engine and turbine engine equipped helicopters. As a consequence, most of the mitigations are equally applicable for both types of helicopters.

6.1 Mitigations piston events

6.1.1 Piston 2090 Safety management – inadequate pilot experience

Within SPS 200 category of the piston events, compared to the turbine category, a relative high number of codes refer to the factor inexperience, student pilot. This could be explained by the fact that Flight Training Organisations (FTO) use less expensive helicopters to offer reasonable prices for their student pilots. Piston helicopters are generally cheaper.

Student pilots should be trained using uncomplicated helicopters with typical helicopter characteristics. This enables the student pilot understand helicopter behaviour quickly and reduces required system knowledge to analyse possible problems. It would require further detailed analysis of the current fleet to determine whether the FTO's use the best suitable machines for their training operation.

Lack of experience increases the workload for the student pilot, limiting the ability to analyse unexpected situations. Processed information, proper cueing and warning regarding the status of the helicopter can assist the student pilot in the process of analysis and taking the proper action. **EICAS systems** can provide more adequate voice warning and cueing to reduce the student pilot workload and increase the probability of proper response. The warning system can be further improved by adding **tactile warnings, such as a collective stick shaker**.

6.1.2 Piston 3010 Maintenance – maintenance management

Within the SPS 300 category, 9 out of 14 events had maintenance management as contributing factor. The reports revealed examples where deficiencies were missed by maintenance, possible improper maintenance, and deficiencies not reported to maintenance and the use of inappropriate parts. The available reports contained insufficient information to establish common causes for these mishaps.

Improvements in quality can generally be achieved by improvements in education, recurrent training, implementation of quality and safety management systems etc. As root causes for the observed mishaps could not be determined, the effectiveness of possible mitigations cannot be assessed. **Further investigation would be required to evaluate causes and determine proper mitigations**.

6.1.3 Piston 500 Pilot judgment and actions

Within the SPS 500 category, a significant number of events had level 2 codes 5010 (pilot's decision), 5040 (landing procedure) and 5060 (procedure implementation) assigned as contributing factors. These events also appear to be in the higher severity categories, although the general environment was indicated as non-hostile. As mentioned earlier, a significant number of events reported, occurred in a generally non-hostile environment, but the reports revealed that the local condition at the moment of the event could be considered hostile. Within this group, helicopters were operated in an altitude band between 50 and 500 ft AGL or operated to/from a confined area or in the vicinity of obstacles limiting their options.

Although helicopters generally have more options to conduct a safe (emergency) landing than an equivalent fixed wing aircraft in case of loss of power, helicopter pilots usually have less time due to a higher sink rate of the machine. Decent rates of helicopters during an established autorotation are approximately 2500 ft/min. This requires rapid analysis and decision-making. Another issue might be the stability of the helicopter. The flight characteristics of a helicopter can also differ for powered flight compared to a similar speed in non-powered flight (autorotation). The pilot needs to adapt to this different behaviour of his helicopter, which can cause control problems. From altitudes below 500 feet AGL it is not always possible to establish a stable autorotation; this increases the workload in the final stage of an autorotation. Important elements for successful entry of an autorotation are: rapid response (analysis and proper action), sufficient altitude to establish a stable autorotation and provide sufficient time for decision making.

A requirement for rapid and adequate response is a good situational awareness (SA). Although not supported by the assigned SPS 700 codes, there is reasonable doubt that the pilots in the evaluated events were well aware of the technical problem and their respective options in the event of a loss of power.

Awareness of the technical status of the helicopter could be increased by providing **good cueing and intuitive warning systems. EICAS systems** could support better SA and assist in proper decision-making as well as a reduction of response time. A simple but effective mitigation for unintended loss of altitude could be a **radar altimeter with adjustable altitude selector for (audio) warning**. More advanced systems like **EGPWS** would provide, besides altitude information, a complete view of the flight path of the helicopter in relation to the surrounding terrain. Therefore, the use of EGPWS could also provide increased local (geographic) situational awareness; for instance, predefined routes and altitudes based on usage of EGPWS could ensure minimum safe relative altitude and enhance the ability to reach safe forced landing areas.

6.1.4 Piston 8020 Part / system failure – Power plant

The majority of events in the engine related category are related to failure of critical components of the power plant. The causes for the majority of the assessed events consisted of failure of components caused by wear (bearings, spark plugs), or fading adjustments (belt tension). Another frequently reported cause was fatigue. The nature of wear or fading adjustments is more gradual whereas fatigue cracks mostly cause a sudden disruption of power.

Abrupt failure, for example due to fatigue, will be hard to detect in an impending state, however wear and fading issues present themselves by gradual increase of vibration, 'roughness' of engine, minor fluctuations in power delivery, or gradual delay in response. The gradual nature of some of these impending failures, make it hard for humans to recognise these critical conditions, but these still are perfect measurable indicators of impending failure. **HUMS systems** can record and warn both technicians and aircrew of deteriorating condition of critical components. Proper implementation of HUMS in both maintenance practices and cockpit procedures could reduce the number of serious incidents and accidents significantly.

Loss of power in a helicopter requires rapid decisions and immediate action. Rotor systems of light helicopters tend to have little inertia and therefore loose rotational speed fast. Once below the critical rotor speed, control will be lost without possibility to restore it. **Hybrid techniques**, using electrical backup power to drive the rotor in case of loss of engine power, as demonstrated by EC, could provide valuable time for the pilot to maintain control of the helicopter and concentrate on safe landing options. This technique is still under development but sure it has great potential for enhancing safety of single engine helicopters in the near future.

6.2 Turbine hazards

6.2.1 Turbine 300 Maintenance

Similar to the piston engine findings, management factors were also reported within the turbine events. Beside SPS level 2 3010 (maintenance management), also 3020 (performance of maintenance duties) were reported in 5 events. Issues observed from the reports were mainly undetected deficiencies, bad quality of maintenance and reporting issues. The addressed issues were unique except for two suspected missed deficiencies. As stated above, the available reports contained insufficient information to establish common causes for these mishaps.

Identical to the piston findings, further investigation would be required to evaluate causes and determine proper mitigations.

6.2.2 Turbine 500 Pilot judgment and actions

Within the SPS 500 category, a significant number of events had SPS level 2 codes 5030 (flight profile) and 5040 (landing procedure) assigned as contributing factors. Within these two groups the 5040 category appeared to be assigned to events with a higher severity. All reported events occurred in a generally non-hostile environment, and similarly to the piston group, with one exception, the local condition at the moment of the event could be considered hostile. Within this group, helicopters were operated in an altitude band between 50 and 250 ft AGL, with one exception at 1500 ft AGL.

From the event descriptions it could be learned that, in most instances, the low altitude was intended as part of the mission (aerial work). Intentional prolonged operations with these single engine helicopters within the 'avoid' area of the H-V diagram will deny a safe escape in the event of a total power loss. Occurrence reports did not provide arguments or considerations for the choices to conduct these operations at low altitude regardless of the inherent dangers. A single report stated however that the operator held a 'low flight permit'.

Although it could not be verified whether flight rules had been ignored, adherence to the rules can relatively easily be monitored by using quick access recorders as required for **Flight Data Monitoring** purposes on large transport category aircraft. Operators could be encouraged or required to store these data.

When **hybrid techniques** will become available, they could enable the use of single engine helicopters within the 'avoid' area of the H-V diagram in the future.

6.2.3 Turbine 7020 Pilot SA – environment awareness

Within the category Pilot SA, environment awareness was assigned five times as a contributing factor, divided over four events. Three out of four led to catastrophic consequences. All events happened at low altitude, between 50 and 250 feet. The type of operation for most of these events was aerial work.

Although these flights were conducted at low altitude intentionally, the effect of loss of power was severe. The pilots did not have an effective response to these failures despite their intentional flight in unfavourable conditions. Either ignorance towards potential dangers or reduced awareness of limitations of their flight profile and surrounding environment, could have contributed to the outcome of these accidents. Similarly as discussed for piston engines, low-level environment requires quicker response from the pilot in the event of power loss and therefore a better awareness of the status of failures as well. A proper mitigation should provide increased awareness of both machine and surrounding environment.

Awareness of the technical status of the helicopter could be increased by providing good cueing and intuitive warning systems. **EICAS systems** could support better SA and assist in proper decision making as well as reduction of response time. A simple but effective mitigation for unintended loss of altitude could be a **radar altimeter** with adjustable altitude setting for (audio) warning. More advanced systems like **EGPWS** would provide, beside altitude information, a complete picture the flight path of the helicopter in relation to the surrounding terrain.

Besides technical aids to support awareness of actual situation, **additional training on Full Flight Simulators (FFS)** could increase pilot's awareness of his limited options for a favourable forced landing in case of low level operations and/or operation within vicinity of obstacles. There are different or unconventional methods of taking evasive action in risk situations that could be reinforced by FFS practises. For instance, training in autorotation is normally carried out within a speed bracket as prescribed by the OEM in the flight manual. Zero speed autorotation are not as safe as autorotation with (safe) forward speed, but could be a better option in certain conditions. These are never trained for in normal operation as damage or injuries are not unlikely. It could be compared to a landing on water with a passenger jet. These options have a low success rate, but could reduce the severity of consequences in certain conditions significantly. However, limited availability of simulators for this class of helicopters poses a disadvantage, since flight technical aspects cannot easily be trained. It should be noted that awareness training could be conducted on any type of FFS for the single-engine helicopter.

6.2.4 Turbine 8020 Part / system failure – Power plant

Almost 75% of the events in the SPS 800 category of the assessed engine related turbine events were caused by failures directly related to the power plant. Half of these events were caused by fatigue, other causes were found in maintenance, environment (snow/ice ingestion) and failure due to polluted fuel.

Similar to the piston category, fatigue cracks will be hard to detect in an impending state, but a lot of failures present themselves gradually by increased vibrations. These are measurable indicators of impending failure. **HUMS systems** can record and warn both technicians and crew of deteriorating conditions of critical components. Proper implementation of HUMS in both maintenance practices and cockpit procedures could reduce the number serious incidents and accidents significantly. Furthermore, HUMS real-time monitoring data of component wear can be used to adjust maintenance schedules in order to decrease the risk of component failure due to fatigue.

Again, **hybrid techniques**, using electrical backup power to drive the rotor in case of loss of engine power, could provide valuable time for the pilot to maintain control of the helicopter and concentrate on safe landing options. These techniques are still under development but have great potential for enhancing safety of single engine helicopters in the near future.

6.3 Remarks

From the reports it appeared that in some instances the pilots had received cues of impending failure prior to the actual event such as a different engine sound, rough running engine, delayed clutch engagement etc. These were either ignored or classified as unlikely to affect the operation. Changes in behaviour of engines, drive train or other critical components - as a slight vibrations or noise but within the limits of flight manuals -, could indicate an abnormal situation with an unknown status. Considering general flight conditions for helicopters, helicopters are mostly within one or a few minutes' flight time from a suitable landing area. Off shore or other hostile environments provide less opportunities to land, but on shore, there often are possibilities to land relatively safely. Precautionary landings are not popular within pilot community as they require a lot of subsequent administration and reporting. Another aspect is embedded in pilot culture: pilots rather solve a problem at home than land in a field. Moreover, company level issues regarding planning and costs of precautionary landings will not encourage conduct of a landing when it is not deemed absolutely necessary. It should be **encouraged that, in case of doubt regarding the status of the helicopter, that a precautionary landing is conducted**. Member state CAAs could facilitate this by decreasing the administrative burden for pilots and allowing them to land and have a quick check before continuing en-route. Companies should be encouraged to stimulate such decisions of their pilots. CAAs could encourage this by rewarding companies for every precautionary landing. For example safety credits could be assigned for these practices and published by the CAA on a list of safe operators. These could be used by companies to demonstrate their safety policy to the customers.

6.4 Bowtie model

The proposed mitigation measures for both piston- and turbine-engined helicopters are graphically summarised in a bowtie diagram depicted in next figure. Average actual severity of the occurred engine-related events grouped per SPS Level 2 is mitigated by proactive measures (on the left side of the figure) and reactive measures (on the right side of the figure). An expert helicopter pilot has estimated the effectiveness of the proposed mitigation measures. Residual severities of respective SPS groupings are provided on the right side of the figure.

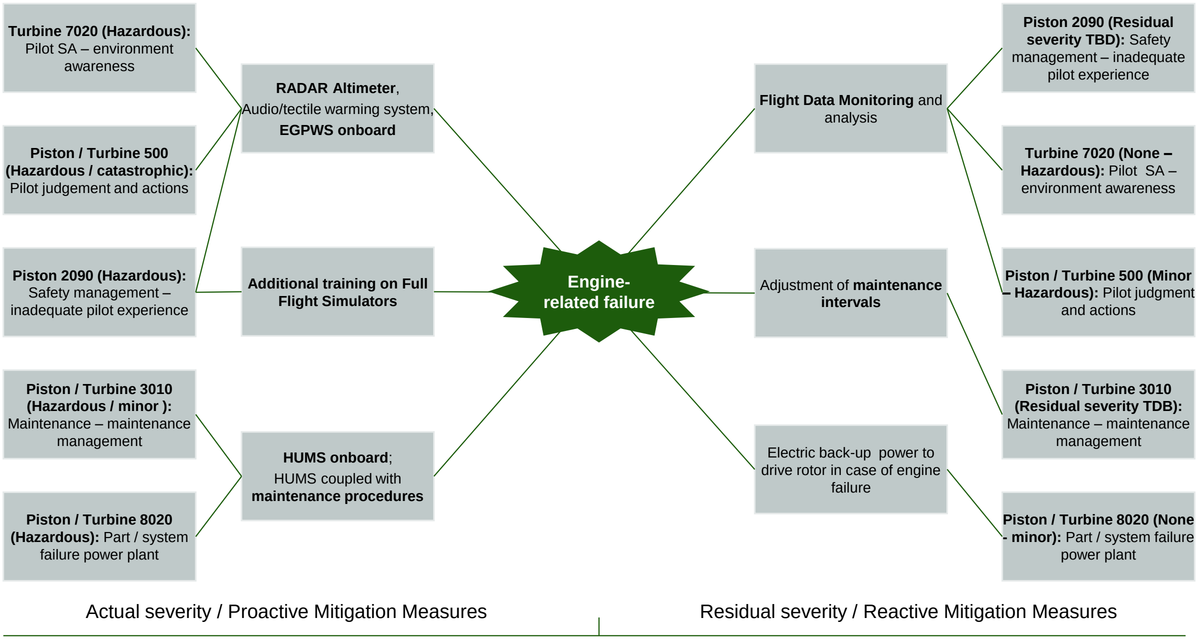

Figure 15: Bowtie diagram

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