

the task distribution function of the system has only a Small effect.

- A Major reduction (factor 10) is expected in the probability of S35 base event “Flight crew does not execute terrain avoidance manoeuvre successfully” (in case of a terrain avoidance alert). It is expected that the third pilot system takes control of the aircraft if the pilots don’t react properly to the terrain avoidance alert and gets the aircraft away from the terrain.

A main result in the assessment is that all base event probabilities were assessed to remain the same or to be reduced due to the novel concept. Although potential safety negative effects were noted for several situations in the COP sessions, the overall safety effect was never judged negatively for the concept.

Overall, the concept was assessed to lead to a reduction in base event probabilities for 46 of the 236 base events that were in the scope of the study, i.e. for 19% of these base events. With respect to the mechanisms by which the third pilot adaptive automation system supports flight safety, in almost all of these 46 base events the system can detect the safety critical situation considered (43 base events) and it can support the

pilots in recovery actions (43 base events). In about half of the 46 base events, the system can support the pilots in avoiding an error (22 base events) that can lead to the safety critical situation.

C. Risk impact quantification

The fatal accident risk effects are shown in Table 3 for each of the scenarios that are in the scope of the assessment. It follows from this overview that there are 8 scenarios that profit from the third pilot adaptive automation concept, with a reduction of the probability of a fatal accident in the range from 41% to 93% per scenario with respect to the baseline condition. These reductions correspond with reductions of 2% to 13% with respect to the total fatal accident risk. Overall the fatal accident probability is reduced by 43% from 4.0E-7 per flight to 2.2E-7 per flight, where we made the conservative assumption that the 13 other scenarios (which were not assessed) do not contribute to any risk reduction. Comparing the fatal accident probability of the 16 scenarios that were assessed, shows that the summed fatal accident risk of this set of scenarios decreases from 3.6E-7 to 1.9E-7, being a reduction of 48%.

TABLE 3. FATAL ACCIDENT FREQUENCIES OF SCENARIOS IN THE BASELINE CONDITION AND IN THE NOVEL THIRD PILOT ADAPTIVE AUTOMATION CONCEPT.

Code	Scenario description	Fatal accident frequency (per flight)					
		Baseline		Novel concept		Change (%)	
		Freq.	Perc.	Freq.	Perc.	Scen.	Total
S18	Engine(s) failure in flight	7.1E-08	18.0%	2.1E-08	9.2%	-71%	-12.8%
S19	Unstable approach	4.1E-08	10.2%	2.9E-09	1.3%	-93%	-9.5%
S35	TAWS alert	3.2E-08	8.2%	3.2E-09	1.4%	-90%	-7.4%
S32	Runway incursion	2.8E-08	7.0%	2.8E-08	12.3%	0%	0%
S26	Aircraft handling by flight crew inappropriate during landing roll	2.6E-08	6.5%	2.6E-08	11.4%	0%	0%
S27	Aircraft directional control related system failure during landing roll	2.4E-08	6.1%	2.4E-08	10.8%	0%	0%
S31	Aircraft are positioned on collision course in flight	2.4E-08	6.0%	8.0E-09	3.6%	-66%	-3.9%
S16	Airspeed, altitude or attitude display failure	2.3E-08	5.8%	7.5E-09	3.4%	-67%	-3.9%
S13	Flight control system failure	1.8E-08	4.4%	1.0E-08	4.7%	-41%	-1.8%
S06	Aircraft takes off with contaminated wing	1.5E-08	3.8%	1.5E-08	6.6%	0%	0%
S10	Pitch control problem during take-off	1.2E-08	3.0%	1.2E-08	5.3%	0%	0%
S09	Single engine failure during take-off	9.8E-09	2.5%	9.8E-09	4.4%	0%	0%
S25	Aircraft handling by flight crew inappropriate during flare	9.8E-09	2.5%	9.8E-09	4.4%	0%	0%
S14	Flight crew member incapacitation	9.6E-09	2.4%	9.6E-10	0.4%	-90%	-2.2%
S12	Flight crew member spatially disoriented	8.0E-09	2.0%	6.4E-10	0.3%	-92%	-1.9%
S03	Aircraft directional control by flight crew inappropriate during take-off	7.8E-09	2.0%	7.8E-09	3.5%	0%	0%
	13 other scenarios (not assessed)	3.8E-08	9.6%	3.8E-08	17.0%	0%	0%
	Total	4.0E-07	100%	2.2E-07	100%		-43%

It follows from Table 3 that in the third pilot adaptive automation concept the scenarios that would contribute mostly to the overall fatal accident risk are different from those in the baseline. It is assessed that the fatal accident probability is strongly reduced for the top-3 of the baseline, especially the remaining contributions to the overall risk for S19 “Unstable approach” and S35 “TAWS alert” are expected to be very low. The new top-3 of scenarios in the novel concept consists of scenarios that are expected not to be influenced: S32 “Runway incursion”, S26 “Aircraft handling by flight crew inappropriate during landing roll” and S27 “Aircraft directional control related system failure during landing roll”.

V. DISCUSSION

In this paper we presented a straightforward approach for safety impact quantification of innovative aviation concepts in early stage development. Such an approach supports decision-making for early stage selection of safety-effective concepts. Next we discuss some main aspects and limitations of the approach and its results to the case study.

The basis of the approach is the total aviation system risk model, which is a combination of event sequence diagrams and fault trees for a range of safety-critical aviation scenarios. Event sequence diagrams and fault trees are well known and broadly used methods in safety assessment studies, which can be depicted and understood quite easily. On this basis, the total aviation system risk model provides a broad, structured and straightforward categorization of aviation accidents and their main causes, and an overview of the frequency by which they occur. This a valuable asset to assess potential safety improvements in early stage concept development.

On the basis of this risk model, the safety impact quantification approach provides a high-level, broad and rough overview of the accident risk reduction that may be obtained by the novel concept. Sources of uncertainty in the risk quantification include the following.

- There exists uncertainty in the total aviation system risk model. It is an extensive model, which consists of 29 scenarios with 425 base events and 51 accident end states. The quantification of the ASCOS-CATS model was achieved using data on 502 accidents and expert judgement, and using insights from earlier quantification of the CATS model with a broader world-wide scope. Given the model size, the limited data set and the use of expert judgement, the quantification results include some levels of uncertainty, especially for events with little associated accident data.
- There exists uncertainty due to the model structure. A key limitation of fault trees and event sequence diagrams is that these do not well represent the interactions and dynamics of agents in a sociotechnical system. Therefore, the risk implications of dynamic relations between events and actions of human operators and technical system in an operational context cannot be studied and understood in detail by such risk modelling [11].

- There exists uncertainty in the assessment of the change factors of the base event probabilities. The assessment has primarily been based on the feedback obtained from commercial pilots and system designers in the COP sessions. Some uncertainty is due to differences in opinion between the participants of these sessions. Most importantly, it is intrinsically difficult to judge the effect of dynamic scenarios and the performance of humans and systems herein. This is strengthened by the judgement of the novel concept rather than a less abstract specific implementation of the concept.

The particular levels of uncertainty due to above aspects have not been assessed, neither during the development of the total aviation system risk model, nor during the assessment of the change factors. A particular level of uncertainty is inherent in any safety risk assessment and it is typically more prevalent for early stage concepts. As long as the presence of uncertainty is realized and the results are being interpreted as indicative, this is acceptable in the early development phase.

As part of the development process of specific technical implementations of a concept, more detailed safety assessment studies would be needed during its subsequent development phases. Such safety assessment should consider in detail the performance of new technical systems, their interactions with human operators, and the role in the overall sociotechnical system. The analysis should be done in the context of specific scenarios and it should consider a broad range of hazards which may disturb the technical systems, the performance of the human operators, and the context of the flight operations. The safety assessment method applied should be commensurate with the characteristics of the scenario studied. For instance, to assess in detail the safety implications of scenarios during which the timing of interacting actors is critical, a dynamic safety assessment method is advised, such as agent-based dynamic risk modelling [11, 12].

The assessment of change in accident risk due to a novel concept used the assessment of multiplicative change factors by expert judgement in combination with the total aviation system risk model as a main method. The values and terminology of the change factors were based on earlier work on bias and uncertainty assessment in risk modelling [6]. In the current application for the assessment of change in base event probabilities using expert feedback (in the COP workshops), it was found that the system designers and pilots well understood the use of the change factors. The range and granularity of the change factors were mostly appropriate for this study, but it was noticed that the term Negligible (factor 1.1) was never used and that some pilots referred to an above Major (factor 20) effect for some base events. The lack of the use of the term Negligible may be due to the rather high conceptual level of the operation assessed, which made it difficult to distinguish with respect to Neutral and Small effects. In future assessments, a term for an above Major effect may be explicitly included, as it better reflects the option that the likelihood of particular events is very strongly suppressed.

Scoping was used to select the most risk-relevant scenarios and impressionable events. Such scoping was needed to downsize the number of base events to an amount that could be handled well in the sessions with experts. The selection of the most risk-relevant scenarios reduced the number of base events from 425 to 236, and the subsequent selection of impressionable base events further reduced the set to 83 base events. This set could be well handled in the sessions with experts.

The results attained for the third pilot adaptive automation concept indicate that it may facilitate a reduction in the probability of fatal accidents by 43% from $4.0E-7$ to $2.2E-7$ fatal accidents per flight. In addition to the overall impact on the fatal accident probability, the assessment also provided results for the contributions of scenarios. The largest reductions with respect to the total fatal accident risk were assessed for scenarios S18 “Engine(s) failure in flight”, S19 “Unstable approach”, and S35 “TAWS alert”. Complete development and operational introduction of the third pilot adaptive automation system for these scenarios thus is expected to have the largest impact on aviation safety.

High impact is expected in situations where the third pilot system takes control of the aircraft. Examples are events where pilots do not respond well to alerts to avoid collisions with terrain or other aircraft, and an event where pilots do not initiate a missed approach although they have been warned about an unstable approach condition. In such situations, the automation may need to take control of the aircraft without the consent of the pilots, since the required actions are time-critical and the pilots did not respond by themselves in first instance. Clearly, such taking over by automation is sensitive from different perspectives. (1) It implies a shift in responsibility from the pilots to the automation. (2) Such shift in responsibility means that the liability of aircraft and avionics manufacturers has to be studied carefully. (3) Such shift in responsibility would need to be accepted by the pilot, the aviation community and the travelling public. (4) The situations in which control would be taken over by the automation need to be defined and studied in large detail using appropriate methods for studying all kinds of combinations of events and the dynamics of the scenarios. Such detailed and well-validated understanding is a necessary condition for items 1 – 3 related to the shift in responsibility to be accepted. Only if all these sensitive aspects have been handled well, the large reductions in fatal accident risks associated with these situations may be achieved.

A further reduction of the fatal accident risk (e.g. towards the safety goal specified in [1]) can most effectively be attained by additional innovative approaches that can reduce the fatal accident probabilities of scenarios that are not influenced by the described third pilot adaptive automation concept. These

scenarios most importantly consider landing and take-off operations, as well as runway incursion scenarios. For an advanced concept to be effective in these kinds of scenarios it should have the information and means to react and possibly take control very rapidly.

Overall, the safety impact quantification approach is a straightforward way to obtain quantitative insight in the safety implications of early stage aviation concepts. In later development phases, other dedicated methods are needed for more detailed safety assessment of the sociotechnical system. The new third pilot adaptive automation concept allows for improved partnership between pilots and automation, which is expected to significantly improve the safety of flight, especially in abnormal situations and crisis management.

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