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Risk-based emergency decision support

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Abstract

In the present paper we discuss how to assist critical decisions taken under complex, contingent circumstances, with a high degree of uncertainty and short time frames. In such sharp-end decision regimes, standard rule-based decision support systems do not capture the complexity of the situation. At the same time, traditional risk analysis is of little use due to variability in the specific circumstances. How then, can an organisation provide assistance to, e.g. pilots in dealing with such emergencies?

A method called 'contingent risk and decision analysis' is presented, to provide decision support for decisions under variable circumstances and short available time scales. The method consists of nine steps of definition, modelling, analysis and criteria definition to be performed 'off-line' by analysts, and procedure generation to transform the analysis result into an operational decision aid. Examples of pilots' decisions in response to sudden vibration in offshore helicopter transport method are used to illustrate the approach.

Keywords: Emergency decisions; Procedures; Aviation; Risk analysis; Decision analysis

1. Introduction

Potentially catastrophic situations often require expedient decision making by the involved actors, based on limited or incomplete information. The decision must take account of the uncertainty about the cause, as well as the uncertainty associated with the outcome of potential decision alternatives, given the possible causes. This is a complex decision situation. Coupled with a decision context which is characterised by tight time constraints and limited analytical capacity, it is not clear how such situations shall be dealt with. The decision setting carries all the traits of crisis/emergency handling discussed by Kørte et al. [15]. A related issue is which responsibilities can be placed on the involved actors, both in the actual situation, but also the organisational responsibility to predefine decision criteria, procedures, checks and train for appropriate decisions. The problems have been highlighted by Rasmussen [20]. In traditional risk analyses, decisions are taken at present—now—and no uncertainty about the present circumstances exists. Variable future circumstances have to be presented by best estimates or by their distributions. The approach does not provide much help for future decision makers. This is of relevance, for example for the occurrence of severe vibration on offshore transport helicopters. This can occur in calm summer conditions or it can occur during winter storms. The commanding pilot has to choose among several decision alternatives, all of which involve significant risk.

Two events occurred in 1996 and 1995, both in the North Sea and both initiated by sudden, severe vibration. This is a condition which can be caused by a long range of causes, some of which are benign in the short term, and do not require immediate stabilisation, whereas others are extremely hazardous and could develop into an accident in a very short time period. The situations require a decision to be made in a short time scale, typically less than 5 min. The decision makers—in this case the aircraft commander-attempted to perform some analysis on the cause and origin of the vibration, based on their judgement of the frequency and the strength of the vibration. Based on these assessments of the probable cause and their degree of uncertainty, decisions were made. In one case the decision was made to perform an emergency water landing or 'ditching', with subsequent evacuation and rescue by rescue service helicopters. The operation took place in February with low water temperature, see AAIB/N [24].

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In the other case, during operation in harsh September weather, following the sudden occurrence of severe vibration, the decision was made to return and fly back to shore, approximately one hour, and land there, see UK AAIB [23]. In the first case, the accident investigation found a benign fault, which did not represent a safety hazard and would have allowed safe return to base. In the second case the investigation revealed a structural fault that had developed to a stage, when it was only a matter of chance that no disintegration of the tail rotor had occurred. This would, very likely, have led to a catastrophic accident. Both crews misjudged the cause and the associated hazard. With the benefit of hindsight, both decisions were criticised by some colleagues.

The authority and responsibility for all decision making during the duration of a flight lies with the aircraft commander. But at the same time the organisation in which the operation takes place takes responsibility by providing a framework of aids and guidelines to the pilot. If such sharing of responsibility is to have a meaning, the framework must address decisions that can be expected at some stage. The format should be designed to enable him to make responsible decisions in accordance with society's and the company's policy. The way such guidance and constraints for decisions are formally expressed is through the issuance of a Flight manual and emergency check lists. In these cases, the Flight manual did not give any decision aid for the cases in question. Emergency check lists, designed to advise on decisions in potentially hazardous situations, did not provide any assistance, apart from the emergency landing drill, once the decision to perform an emergency landing has been taken. Degani and Wiener [8] address the issue that little regulatory or advisory material exists with regard to the content and format for check lists. The problem of making decisions in situations of vibration has been identified, but no supplementary material has been provided to assist the decision. The situation leaves open the question of how the organisation accounts for its responsibility in such situations. The decision is still left unsupported with the pilots. We believe that this is not satisfactory, seen both from the future passengers point of view, as well as pilots and, ultimately, the organisation and its stakeholders.

We believe that this lack of decision support can, in part, be traced back to an inherently deterministic approach to operational decisions, which is incapable of dealing with situations of uncertainty where outcomes are contingent on situation specific variables. The mentioned manuals are principally rule based. Many of the rules have been devised after a careful analysis of the design, potential responses to alternative actions and judgement of the outcomes. This can be performed in an analytical setting. Rules of the if–then type can be assigned once the best decision alternative for a certain scenario has been identified. This is possible under relatively static conditions, i.e. that a certain response to a given input provides an outcome with limited variability. Uncertainty in this type of regime is more or less negligible. Investigating the situations described above, we find they are characterised by a significant number of variables and uncertainty of both the underlying cause and the outcome of alternative actions. The problem encountered in the examples given is that the conditions under which the decision has to be taken, e.g. the character of the vibration, the weather conditions, the availability of rescue capacity, etc. is unknown when the decision rules are to be designed. Accordingly, the result of the alternative decisions is highly uncertain. These situations do not lend themselves to traditional rules. Without assistance, a knowledge-based approach to process information and choose action alternatives is required, based on functional analysis of the system performance, cf. Rasmussen [19]. This is incompatible with the situation's constraints as illustrated in Klein's [13] discussions of the criteria for sound decision making as outlined by Janis and Mann [10]. The cases we investigated strongly indicate that the decisions are made by simplified heuristic reasoning, as well as personal preferences and rules. The criteria for exhaustive, 'rational' decision analysis are not met, and cannot be met.

Rules to address these situations would have to be different for each situation; they would have to be 'contingent' on the specific scenario. de Brito [7] emphasizes the difficulty in prescribing instructions 'due to the multiplicity of situations'. This would require an unmanageable list of different rules. On the other hand, a rule-type format provides a most comprehensible format for decision aid for the pilot-in-command in situations with tight constraints on time and processing capacity. The context does not allow for processing of data and uncertainty. The present lack of adequate rules in the decision aids for helicopter pilots has to be attributed in part to this dilemma. The problems encountered in this type of crisis decision making and the requirement for analysis prior to the emergency require new considerations of risk and decision analysis. Using an approach that applies risk and decision analysis conditional on a set of factors describing the possible decision scenarios, we can model future decision situations and establish criteria for decisions in an analytical/design setting. Once the model has been established, by calculating the consequences and risk for alternative decisions under varying scenarios we can establish a catalogue of risk indices for alternative decisions under different scenarios. A discussion of the principles of this approach can be found in Aven and Kørte [1]. Combined with meta-rules on how to apply the risk indices, guidelines can be derived on how to act in such situations.

The rules for conduct must take consideration of the risk specific for the known factors of the situation, the 'contingencies'. This approach can be seen as an attempt at organisations way of expressing its values and preferences, as well as discharging its responsibility to provide their operators/pilots with guidance in decision situations with significant potential for accident and material consequences.[1]

2. Approach—methodology

The purpose of the present approach is to provide potential decision makers with information to support a best possible decision in situations with short times for a decision of complexity and with significant risk.

The initiation of the decision situation occurs through some form of indication, i.e. some form of phenomenological change that is associated with a possible abnormal state of the system. This state could be a potential cause of failure or not. Depending on the failure cause the effect could be catastrophic or it could be benign. In short, an indication exists and the decision maker is uncertain of the associated cause and the effect of the cause. The decision maker has more than one alternative paths of action (the very nature of a decision situation). The outcome of each decision is dependent on the—unknown—cause and a number of situational constraints. We can say that the decision is contingent on the situation. These situational constraints can vary largely and cannot be determined beforehand. They will be known to the decision maker at the time of the decision. However, the interaction and the effect of a combination of such constraints on the outcome of the decision alternatives can be complex and difficult to judge ad-hoc at the time of the decision. The outcome, and the verdict whether it is good or bad, depends on the judgement of what is of importance for several stakeholders. Again, it seems obvious that such value judgements are not readily made by a decision maker in such a constrained situation. It adds to the complexity of the decision.

This paper makes no pretension to analyse or understand the mental mechanisms of unaided, 'intuitive' decision making in such situations. It is aimed to structure and simplify the decision situation for the decision maker. The generic description of the elements of the decision situation outlined above can be seen as the background for the approach.

The approach considered here can be detailed in the following steps:

1. *Identification of hazard indications*. We need to start by identifying the anticipated indication or indications $\mathbf{i} = \{i_1, i_2, \ldots\}$, of a hazardous state. For example: i_1 could be observation of smoke, i_2 could be smell and i_3 could be observation of flames. Together they would allow inferences about the nature of the underlying hazard, e.g. a fire.

[1] Note that the intention of this paper must not in any way be interpreted as an attempt of critique of the decisions taken by involved pilots in the presented cases. On contrary, it may be regarded as an expression of sympathy for the ability and the acceptance of responsibility to make life critical decisions under, sometimes, extreme conditions without reliance on the assistance of others.

In the simplest form there is only one type of indication and it takes one of two values; 'normal' and 'abnormal'.

2. *Define decision alternatives*. There must exist a set of decision alternatives, $\mathbf{d}$ with more than one alternative, i.e. $\mathbf{d} = \{d_1, d_2, \ldots, d_m\}$.

3. *Consequence definition*. We must then identify what is at stake, i.e. what things of value that are threatened by the potential hazard. We will call them the consequences $\mathbf{C} = \{C_1, C_2, \ldots, C_n\}$. The set of consequences considered is obviously an important premise for an organisations value judgement.

4. *Decision influence model*. A model of the structure of the decision situation must be established that captures the elements and the relations involved in the decision in a qualitative manner. In addition to the variables mentioned, there are the contingent variables χ, quantities that will be known at the time of the decision and that affect the outcome, there are uncertain hazardous states, $\mathbf{X}$, such as the origin of the vibration, the nature of the fire. In addition, there are uncertain hazardous events, $\mathbf{E}$, which depend on uncertain quantities and contingencies. We need a way of connecting these variables to the consequences $\mathbf{C}$.

We need to build a model connecting situational and environmental variables to uncertain hazardous events $\mathbf{E}$ and consequences $\mathbf{C}$. The general structure of the decision can be modelled effectively using an influence model format as shown in Fig. 1.

In accordance with general conventions on decision influence diagrams, see e.g. Clemen [5], decisions are drawn as rectangles, consequences as rounded rectangles and knowledge variables as ellipses/circles. Arrows indicate influences, either deterministic or probabilistic. This means that the probability of one variable is conditioned on the outcome of the variables lying prior to ('pointing at') it in the influence chain. The emergency is indicated by the observance of $\mathbf{i}$, knowledge indicating that a hazardous state X is present with some degree of certainty. At the time we have to make the decision we know $\mathbf{i}$. The value of $\mathbf{X}$ is not known to us with certainty; it is uncertain and has to be judged on the basis of $\mathbf{i}$. Dependent on the value of the uncertain $\mathbf{X}$, events $\mathbf{E}$ will occur. In addition to the uncertain hazard state $\mathbf{X}$, the chain of events depends on the specific environment and situation. These are described by variables

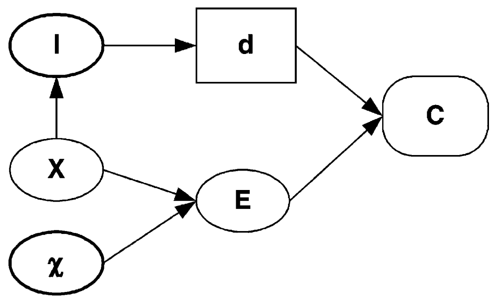

Fig. 1. Influence model connecting decisions, contingencies, indications, uncertain variables and events with consequences.

χ, known to the decision maker when the emergency occurs, i.e. certain at the time of decision. The consequences **C** are dependent on the outcome of the uncertain events **E**. In order to discriminate variables that are certain at the time of decision and variables and events that are uncertain, the following notation is chosen here: Uncertain variables are shown as ellipses of thin lines, variables known at the time of decision, i.e. observations of the anomalies, **i** and the contingent variables, χ are shown as ellipses of thick line. For a more detailed account on construction of influence diagrams, see e.g. (Clemen [5], Howard and Matheson [9]). Here, the influence diagram is not used to calculate results, but solely to structure the decision problem.

5. *Identification of contingent variables—definition of scenarios*. In reality, no situation is identical to another. To produce advice for situations we need to define them, we need to build scenarios. The scenarios are defined by a set of contingent variables, i.e. variables that will be known at the time of the decision. Among the influencing variables in the model, we identify those variables that will be known, certain at the time of a decision—the contingencies χ. The number of scenarios is determined by the number of contingent variables and the number of values each of these variables can take. For each of the known, conditioning variables χ_i, we need to define a set of categories we want to analyse. Although, in reality, each variable may take an indefinite number of real values, the approach requires that a limited set of states—categories—is defined for each variable. The number of categories that we assign must be limited to make the modelling manageable.

6. *Contingent model definition—assessment of probabilities*. We reduce the model to dealing with contingent decisions, i.e. a model for analysis of consequences and risk conditional on the known variables χ. Decision trees are used to model the consequences and risk of the decisions. In developing the model, the set of events **E** needs to be specified. As the outcome of the events is uncertain, we need to assess the probabilities, conditional on the contingencies. To complete the model, assessments of the consequences, conditional on the contingencies and the branch events is required.

7. *Contingent risk analysis and cataloguing*. For each scenario, i.e. each relevant combination of conditioning variables, we perform a risk analyses for each considered decision alternative. The results are then generated as a catalogue of risk expressions or indices, conditional on the contingencies. Presented in a proper format, a decision maker can now, for a certain set of circumstances/contingencies, find the calculated consequences and risk.

8. *Decision criteria definition*. We need to define certain meta-rules and criteria for decisions. Meta-rules could be trade-off rules among different consequence variables, statements regarding risk-aversion, e.g. more than proportional weighting of high fatality consequences, use of expected values vs. assessment of distributions, etc. It is to a large degree by the definition of the criteria and meta-rules, that an organisation states its preferences and values.

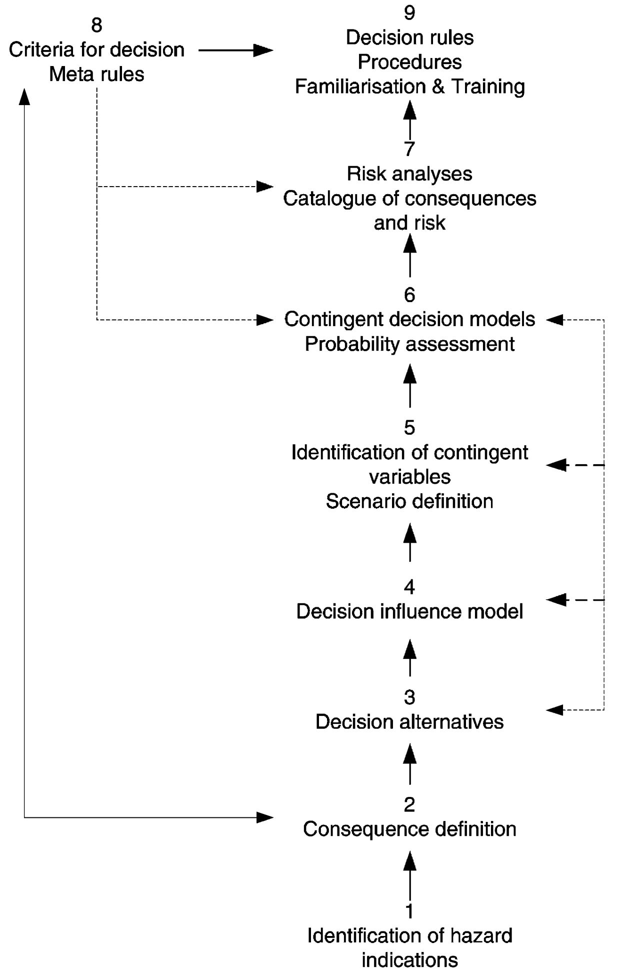

Fig. 2. Process of contingent risk and decision analysis. Iterative loops indicated by dotted connections.

9. *Procedure generation and training*. Based on the contingent risk catalogue, meta-rules and decision criteria, procedures and decision rules could now be generated. The process will often not be linear, but require iterations among several of the mentioned steps. The flow and the iterative loops are presented in Fig. 2.

3. The worked case—sudden vibration during flight

The case here is a result of studies of helicopter accidents and incidents involving the occurrence of severe vibrations during flight. A number of hazardous conditions are accompanied by the production of vibration. It is known, though, that vibration can also be the result of benign conditions. The vibration as perceived by the crew does in itself not provide sufficient information about the underlying cause, and therefore the associated hazard.

1. *Hazard indication*. The attention to a hazard is in this case raised by the occurrence of vibration, $i = 1$.

The investigation of actual incidents of vibration shows that it is difficult for helicopter pilots to judge the nature of the failure that has led to the vibration. Even discrimination between vibrations stemming from main and tail rotor failures is frequently judged wrong. For the present analysis tail rotor failure and main rotor failure are treated as an uncertainty.

2. *Decision alternatives*. The decision alternatives considered here are: d_1, to perform a controlled emergency landing on the sea (termed 'ditching') or d_2, to divert to the nearest landing site on land or d_3, to fly to the nearest platform (or other floating device with landing deck).

3. *Consequences*. The potential consequences of the potential hazardous condition, which are considered here are C_s, loss of the lives of the crew members and the passengers and C_m, material losses due to damages or loss of the helicopter and rescue/salvage costs.

4. *The decision model*. For each decision alternative, the variables influencing the outcome are numerous. The main factors affecting the outcome of a controlled emergency landing are the sea state, wind state, sea temperature and time until rescue. The outcome of a decision pursue a landing at a land site or a platform helideck is affected by the time to reach the landing site, the time for the fault to develop to complete failure, the location/origin of the fault/failure and the resulting effect on the helicopter. The outcome of a decision to land is further affected by the already mentioned factors.

For the decision to ditch or, in the event of an unanticipated emergency or crash landing following the decision to pursue a landing, the threat to survival arises mainly from the possible submersion into water with hypothermia, drowning or shock/heart failure as a result. For additional information on survivability see, e.g. (Brooks, et al. [3], Joint Aviation Authority [11]). The risk of occurrence of these is largely dependent on a number of events. The successful performance of an emergency landing, the successful transfer to the life rafts and, in case of capsizing of the helicopter during landing, the successful escape from the helicopter. These are uncertain events, conditional on the wind and sea state, the sea temperature. The ability to successfully perform an emergency landing depends on the weather, in particular the sea state. A successful transfer to the life rafts is, likewise dependent on wind and sea state. In the event of immersion into the sea, the survival will depend heavily on the sea temperature. Also the ability to escape from a submerged helicopter will depend on the sea temperature, due to the effect of cold water shock and the increased likelihood of immersion of water into the immersion suit. Additional information on evacuation of helicopters, cold water effects and survivability aspects can be found in Brooks and Tipton [4], CAA-UK [6]. Given the outcome of these events, the further survival is dependent on, again, the sea temperature and state as well as wind, and the time to rescue, the last of which depends on the distance to the nearest rescue helicopter base or other rescue vessel.

To simplify the model, we have defined a new variable which combines the sea and wind state. These are strongly correlated, although not perfectly. The reasoning for this will become clearer under point 7 of the process, scenario definition. The weather categories are chosen in accordance with PBS Development Task-Force [17].

The model for the relations among variables, decisions and consequences/outcomes was developed in a process with involvement of experts in different fields of expertise, such as pilots, helicopter dynamics/vibrations experts other areas of helicopter operation and emergency performance. An effective tool for illustration of the interactions is by an influence diagram, in this case as per Fig. 3.

5. *Identification of the contingencies—definition of scenarios*

Variables that are known (more or less) at the time of the decision are the and sea state, the sea temperature and the distance to the nearest take-off site for a rescue helicopter. For reasons of simplification and due to a strong correlation, we have combined the wind and sea state in the above model into one variable, the 'weather state', χ_W. Further, rather than referring to the sea temperature, which is the ultimate influence, we introduce the proxy-variable 'season', χ_S. The time before a rescue vessel/helicopter can be expected is more or less known and will be identified by χ_R.

The number of scenarios is defined by the number of values that these contingencies can take. We let χ_W take values in {calm, moderate, severe, extreme}, in accordance with PBS Development Task-Force [17] and referred standards. We let χ_S take values in {Winter, Intermediate seasons, Summer}. For χ_R, we defined a state space {long, medium, short}.

6. *Contingent model definition—probability assessments*. We can now build quantitative models for the decisions, which are conditioned on certain values of the contingencies and only take account to the events, unknown at the time of decision. The quantitative models require detailing best achieved by decision trees.

Let us take the decision to perform a controlled emergency landing. Conditional probability assessments are required for the uncertain events. The events are the outcome of 'ditching', E_D (successful landing or capsizing of the helicopter), the safe transfer to life raft in the event of a successful ditching, E_T, and the successful evacuation of submerged helicopter in the event of capsizing after ditching, E_E. The events are here defined such that they normally can take one of two values, 'yes' or 'no'. The model is greatly simplified by conditioning on the state of the contingent variables, i.e. the variables that are known at the time of the decision, rather than including these variables in the model. The decision to perform a controlled emergency conditional on given values χ_S, χ_W, χ_R can now be represented by a decision tree, see Fig. 4. To be able to

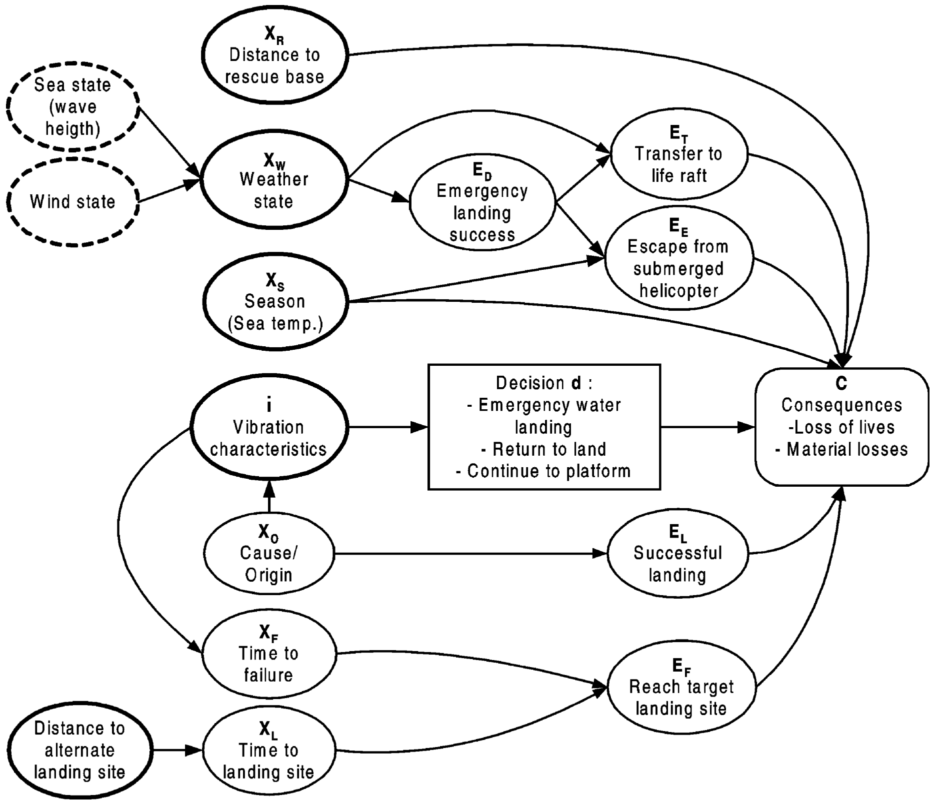

Fig. 3. Decision influence diagram—pilots decision upon observation of sudden vibration. Thin lined ellipses: uncertainties, fat lined ellipses: contingencies, rectangles: decisions, rounded rectangle: consequences.

quantify the expected fatalities under the circumstances, we need to state probabilities for the branches of the decision tree, e.g. $P(E_D =$ 'Yes'). To be more precise, the probability chosen is conditional on the decision and the contingencies, i.e. $P(E_D =$ 'Yes'$|d = d_1$, $\chi_S =$ 'winter', $\chi_W =$ 'severe', $\chi_R =$ 'medium'). The branches further to the right are conditional on the outcome of the previous events in addition to the contingent variables, e.g. $P(E_T =$ 'No'$|E_D =$ 'Yes', $d = d_1$, $\chi_S =$ 'winter', $\chi_W =$ 'severe', $\chi_R =$ 'medium'$) = 0.15$.

The consequence of each branch, i.e. the number of fatalities, had to be assessed, conditional on the event outcomes along the decision tree branch and the contingencies. The number of fatalities, given that the helicopter has capsized and that evacuation has not been evacuated successful, for winter sea temperatures, severe weather conditions and a medium length of rescue time was predicted to be 14.

The decision tree is used to calculate the statistical expected value for fatalities, given the conditions and the decision to ditch, here 1.94. For details on construction and calculation of decision trees see Raiffa [18]. The statistical expected number of fatalities is used as a risk index to compare the risk associated with alternative decisions under varying conditions. The use of expected values is not the only way of judging risk. For further discussion, we refer to paragraph 8.

Once the decision for a controlled emergency landing has been taken, any uncertainty regarding the cause of the vibration—the fault—or the effect of a potentially developed failure is irrelevant, as this no longer affects the outcome. For the alternative decisions, 'Divert to landing site' or 'Attempt landing on platform heli-deck', the decision tree is complicated by the additional uncertainty regarding the nature of the fault, the development to a failure and the effect of a failure on the helicopter.

Assessing the remaining event uncertainties

A fault that will undergo gradual deterioration, will allow a new decision to ditch at a later point in time. Some failures, though, materialise instantaneously after a period

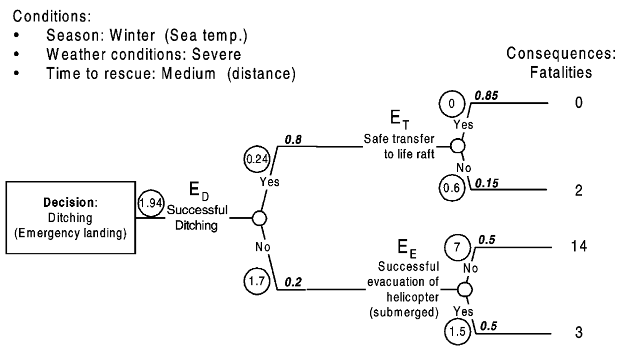

Fig. 4. Decision tree—ditching/emergency landing; branch probabilities in bold italics; branch expected values in circled numbers.

of vibration. The aircraft commander therefore has to make such judgement from the observation of the vibration characteristics and the knowledge of available landing prospects. The outcome of the decision to fly to a landing site depends on the ability to arrive at and successfully land at the targeted site. In the model this is represented by the events (and the associated probabilities) of reaching the targeted landing site, E_F, the event of a successful landing at the site, E_L and, in the event that the fault condition develops to an acute failure, the event that the helicopter can undergo en emergency landing, E_C.

Assessing the probability of successfully reaching an alternative landing site $P(E_F)$ is not a trivial task and it needs to be done in the very limited time scope available. One approach used here is detailed in Appendix. If the landing site can be reached successfully, there is a risk of not being able to perform a successful landing. This uncertainty can be expressed as $P(E_L)$. This uncertainty is, in addition to the contingent weather conditions, very much dependent on the origin of the fault/failure, here the tail rotor or the main rotor, which is unknown. The uncertainty about the origin of the vibration/failure is expressed as $P(E_O)$. Investigations into a number of incidents and accidents involving vibrations indicated that the pilots' assessments of the origin of the vibrations were very unreliable. For the purpose of the analyses here, the probabilities for this uncertainty were set, based on historical rates of tail rotor failures and main rotor failures, respectively, as well as one manufacturer's safety assessment, which concludes with a higher overall probability of tail rotor failure compared to main rotor failures.

If the failure materialises before reaching the landing site, i.e. $E_F =$ 'no', we can define two outcomes: $E_C =$ 'no', meaning that the failure is such that no emergency landing can be initiated—a catastrophic outcome is inevitable—or, $E_C =$ 'yes', the condition is critical but an emergency landing can be attempted. The conditional probabilities for these event outcomes need to be assessed. The consequences—number of fatalities, given the conditions and the sequences of events as defined by the decision tree model—can now be assessed. For the present exercise this required input by expertise from helicopter operations and training, evacuation training and research, and vibration and dynamics specialists. The details of structuring the inputs and the conditioning are outside the scope of this paper.

For the decision 'continue flight to platform for landing', an example is given under the same conditions as for the above ditching example is given in Fig. 5. We find the number of statistically expected fatalities—the risk index—for this decision to be 5.5.

The model structure for the decision to return to land for landing is identical to the one shown. The event probabilities change and the predicted available time ratio for reaching the landing site would change though and, accordingly the result.

7. *Contingent risk analyses and cataloguing of results*. With the model structure defined and the conditional probabilities assessed, the modelling and calculation of the contingent decisions could now commence for all defined scenarios, i.e. all combinations of contingencies. In our application the prediction of the ratio of means of time to failure, to time to landing site is treated as a contingency.

In principle we now model the consequences and risk of all three possible decisions under all possible circumstances. These circumstances or contingencies will be known at the time of decision and by making the assessment results available for the decision maker, his judgement and decision can now be based on the result of a structured approach.

The results can be compiled as expected consequence numbers for alternative situations in a catalogue; for an example, see Table 1.

As stated above, the number of decisions to be calculated is proportional to the number of scenarios defined and the number of relevant decision alternatives. In our case the number of scenarios is 108. The number of decisions to be calculated is 252 (the risk associated with ditching is independent of the probability of reaching an alternate landing site).

8. *Decision criteria, meta rules*. In the development of the risk indices above, we have assumed the use of expected fatalities as the sole basis for the decision to be made. This is not the only option as a decision basis, it is a choice. An alternative to using expected values could be to use the consequence distributions as a comparison and decision basis. In our case, for contingencies $\chi_S =$ winter, $\chi_W =$ severe, $\chi_R =$ long, and TTF:TTL $= 1$, we have consequence distributions as shown in Fig. 6.

Although the distributions provide more information, it may be difficult to interpret the implications. It may be impractical to assess 108 decision scenarios, and evaluate the consequence distributions under the alternative decisions, in our case three decisions.

If we limit the consequence dimensions to fatality risk, one way of providing additional information could be to state the probability of N_F greater than one, $P(N_F \geq 1)$, i.e. the risk of occurrence of fatalities. We could call this the fatality risk index (Table 2). In the example here, we would then have

From this additional information, we can see that although the number of *expected* fatalities is higher for the decision to return to a landing site compared to the decision to ditch, the risk of at least one fatality is equal for the two decisions. For both decisions not to ditch, the risk is mostly associated with higher numbers of fatalities. One could envision strategies that emphasised avoiding high fatality accidents.

Other ways of addressing non-linear risk preferences, e.g. a disproportional aversion towards the large consequences, could be introduced by a weighting function of the consequence classes/sizes or by defining non-linear utility functions. We believe, though, that it is not a prudent practice to introduce such weighting before the risk figures, based on the assessment of probabilities and consequences,

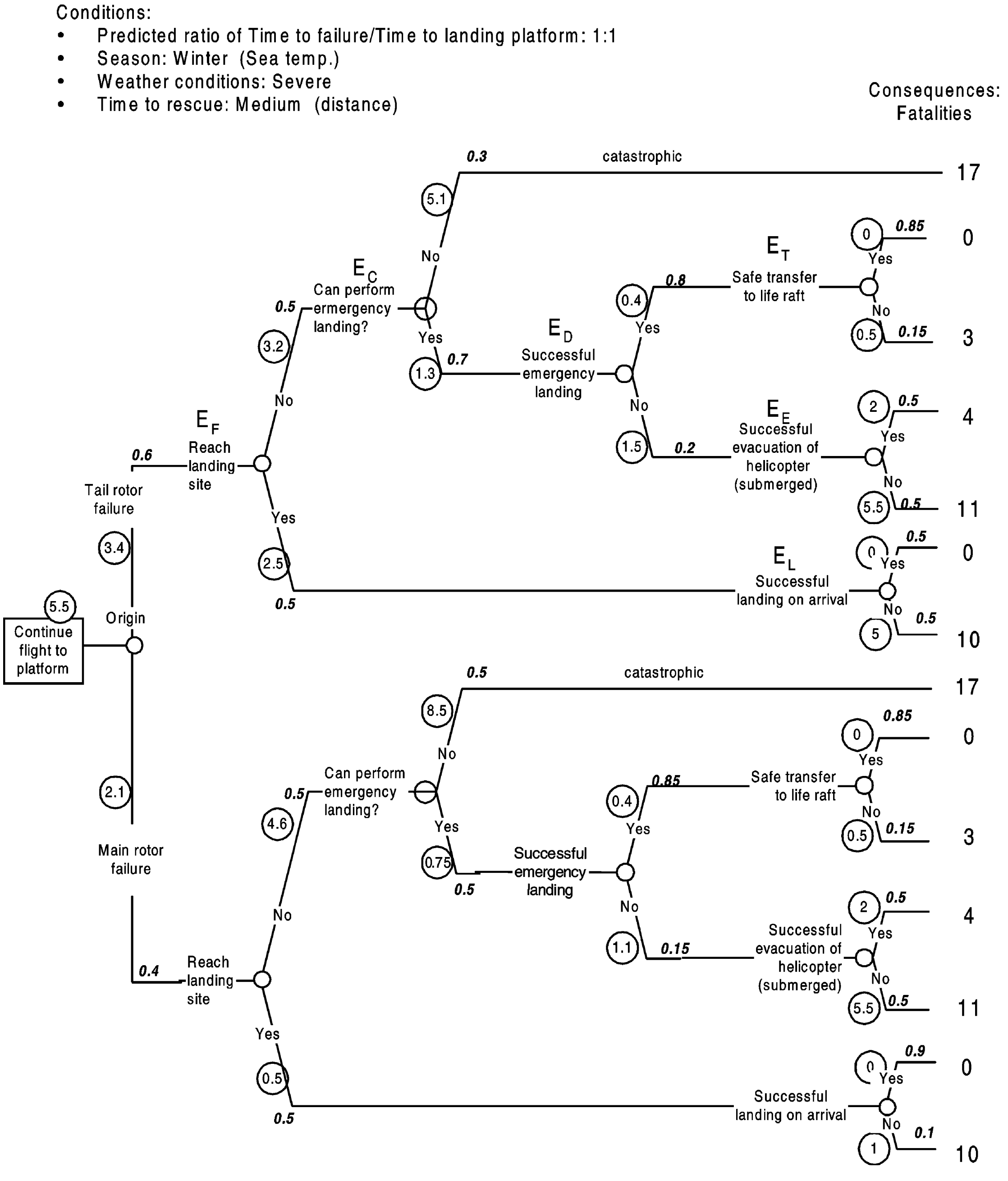

Fig. 5. Decision tree for decision ‘continue to platform landing site’.

have been calculated and presented. The approach above allows review by stakeholder groups with possibly different preferences.

9. *Multi-attribute considerations*. The decision involves other consequences than potential fatalities. An obvious consequence is material damage. Material damages can be treated in much the same way as above. The modeling of the material consequence risk can be much simplified as the consequences depend less on sea temperatures and other survivability factors associated with human lives.

A second consequence variable increases the complexity of the risk assessment in the decision situation. There are fundamentally two ways of including the second (or third, etc.) consequence variable in the decision. One alternative is to adopt a sequential consequence assessment approach. In the present case, the second approach was considered. This means that the aircraft commander would be advised to judge the fatality risk, based on expected values and high fatality risk. If an alternative exists, under the circumstances, which clearly represents the lowest fatality risk, this alternative is chosen. If the lowest risk is more or less equal for more than one alternative, then, the commander is advised to take into account the material damage risk. The rule—e.g. “If there is a clear best decision based on fatality risk, choose that decision; if not

Table 1
Risk indices conditional on environmental and situational conditions

Contingencies				Decision risk index		
Season	Weather	Rescue time	Ratio TTF:TTL	Decision		
				Ditching	Land on platform	Fly to land site
⋮	⋮	⋮	⋮	⋮	⋮	⋮
Winter	Severe	Long	2:3	3.3	7.6	7.4
Winter	Severe	Long	1:1	3.3	5.7	4.2
Winter	Severe	Long	2:1	3.3	3.7	0.8
Winter	Severe	Medium	2:3	1.9	7.2	7.1
Winter	Severe	Medium	1:1	1.9	5.5	4.0
Winter	Severe	Medium	2:1	1.9	3.7	0.8
⋮	⋮	⋮	⋮	⋮	⋮	⋮
Winter	Calm	Short	2:3	0.1	6.5	6.2
Winter	Calm	Short	1:1	0.1	4.8	3.5
Winter	Calm	Short	2:1	0.1	3.1	0.7
⋮	⋮	⋮	⋮	⋮	⋮	⋮
Summer	Extreme	Long	2:3	2.3	7.8	7.4
Summer	Extreme	Long	1:1	2.3	6.0	4.3
Summer	Extreme	Long	2:1	2.3	4.1	1.1
⋮	⋮	⋮	⋮	⋮	⋮	⋮

consider material risk”—becomes part of a statement of the organisation’s set of preferences/values.

The introduction of a second consequence variable complicates the formatting of the resulting risks and the communication/comprehensibility for the decision maker. The other alternative would be to define a common consequence dimension and aggregate the consequences and risks into one variable. This is typically done in cost/benefit assessments, see e.g. Sugden and Williams [21] or in subjective utility multi-attribute decision approaches, see Keeney and Raiffa [12] by trade-off of all attribute values into a common unit, e.g. monetary or an abstract ‘utility’.

Procedure generation and training

Based on the risk catalogue, the criteria and rules for using the risk indices, the generation of procedures is mostly a question of formatting and ergonomics. The stringent constraints of the decision situations require a careful combination of easy-to-use interface of the risk cataloguing and a prior training programme. The training programme must encompass both familiarisation with the concept of risk indices as well as communication of the preferences and values inherent in the criteria. The future decisions rely on the proper use of the risk indices, as well as the situational judgement of the pilots. Understanding of the underlying models will both facilitate appropriate use of the risk indices and enable final judgement before decisions are taken.

For pilots, who frequently train emergency situations under very realistic conditions in full-motion simulators, it is conceivable that the methodology could become part of the training schedule. The details of the man-machine interface are outside the scope of this paper. For a treatment of these aspects for a comparable situation, see Bove and Andersen [2].

4. Discussion

The decision/dilemma is not between a safe course of action and a risky course of action, i.e. a choice among values under uncertainty of outcomes. It is rather a choice among actions with outcomes that are extremely uncertain to the decision maker, due to the complexity of the situation and the lack of ability to assess the risk. By providing a risk catalogue, a simplified measure of the risk associated with the alternative decisions is presented to the decision maker. We do not see the risk indices as measures that can be used unconditionally to find an optimum decision. We see the indices as a basis for judgement; as an anchoring point for the decision, from which additional deliberation could lead to a choice.

The present approach is based on models of event sequences. Such models are an attempt to both capture and

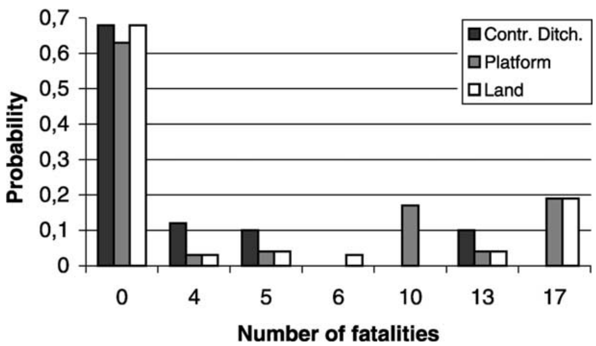

Fig. 6. Fatality risk distribution for alternative decisions.

Table 2
Fatality risk indices

Decision	Risk index EN_F	Fatality risk index $P(N_F \geq 1)$
Ditching	1.9	0.32
Platform landing	5.5	0.47
Landing site	4.2	0.32

simplify the complexity of real world behaviour. The models chosen in the presented case could be extended further or simplified. The calculated risk indices are results of simplifications inherent in the model. Future decision maker should be aware of this.

In the presented case we have assessed consequences as single values. Obviously, the consequences, conditional on one sequence of events are not deterministic. In principle one could specify a distribution, which would complicate the assessment and the calculation. We would view the given values of branch consequences as the most typical outcomes.

Judging from several reported cases of vibration with consequential failure or not, the uncertainty of the pilot about the nature of the failure and the time until a terminal failure occurs, is high. The method could be simplified by assuming a historical distribution of times to failure. This would require further study of historical data would limit the assessment load put on the pilots to the flying time to a landing site.

The risk catalogue, presented in a printed format can easily become a rather messy document. It would be a relatively simple affair to generate a look-up program that could retrieve situation specific figures. It is conceivable that such a program could be integrated with today's programmable pilot interfaces. For ideas on the interface, we refer to Bove and Andersen [2]. Another issue is the number of assessed scenarios. With an increasing number of contingencies, even for few categories of each contingency the combinations become many. In our case, $108 + 108 + 36 = 252$ scenarios were assessed. This presents a difficulty, not only for the assessment but also for the presentation of the results. Additional work should be spent in attempts, e.g. to identify how the scenarios could be clustered.

An important aspect of any approach that is designed to support decision making in sharp end situations, which are strongly guided by heuristics of the actors, is that the reasoning behind the advice is understood by the actors, cf. Kuchar et al. [14].

At present the work presented is at a conceptual stage, to prove feasibility of the approach. The problem, when presented creates has created interest and the discussions around the models and the probability and consequence assessments generate insight and interest into different aspects of the problem. A full implementation of such risk based decision aids interfere with presently approved formats, philosophy and pilot interfaces. Further development is therefore dependent on additional acceptance and decisions.

5. Conclusions

Global risk analyses will often produce expected values of consequences, or risk distributions, unconditional of the situational context. In such analyses the human decisions of the kind discussed here would appear as figures of 'human reliability' in accordance with the approach of Swain and Guttman [22]. With no prior analysis or guidance to the decision makers, existing practices support this approach. The organisation in which the decision fundamentally takes place is not regarded; the pilot and the scene of actual situation are seen as the sole locus for the decision to be made. After the outcome—when all the facts are known—and when decisions turn out to have been inappropriate, the pilot can be viewed to be the source of 'human unreliability'. A present trend in the interpretation of accident causes puts less emphasis on human error with more weight put on systemic thinking where the human is an actor in a technical and organisational context. This raises the questions about what the organisational responsibility is and how it can be accounted for.

In the present approach we do not treat the human actions as stochastic variables. An underlying view is that the pilots action (or any other operators in comparable situations) must be seen as part of organisational conduct. In this perspective the answer to the question 'what did the organisation do to enable the best possible decision to be made'. The answer 'we trust the pilot's judgement' cannot be satisfactory. If the organisation's intention is to behave such that accident and fatality risk is minimised, then pilots must be given prerequisites to make decisions that support such a goal. It requires the organisation to anticipate the situation as far as possible and to be able to express what a good decision should be. This is the essence of risk and decision analysis. It requires that approaches are developed that allow interaction of operational knowledge and analytical skills prior to the actual decision. The approach developed here provides a framework for how this can be performed in practice, when the situation is dominated by constraints not know to the organisation in advance.

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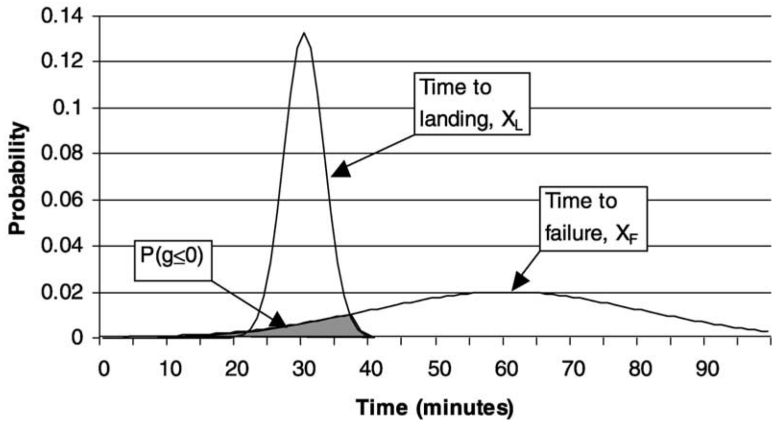

Fig. A1. First order reliability approach to assess probability of reaching a landing site.

greatly appreciated and have contributed to improve the paper.

Appendix A first order reliability approach to assess the probability of reaching a landing site

The probability of reaching the targeted landing site, $P(E_F = \text{'yes'})$, is dependent on the time before the fault materialises to a critical failure, X_F and the time to the landing site X_L. (Fig. A1) These are not known with certainty. When asked to assess this probability directly, we found that pilots were uncomfortable; especially if this uncertainty were to be assessed as part of the in situ decision process. The assessment requires taking Into account the distance to a potential landing site, the—often reduced—speed of the helicopter and the predicted length of time before a full failure materialises. With the significant uncertainty present, this is a complex task. We therefore chose a slightly different route.

If we define the severity of the situation in terms of the probability of reaching a landing firm site (as opposed to the sea surface). This depends on whether the time before a failure materialises is longer than the time to the targeted landing site. If we further assume that the time before the fault causing the vibration materialises into a failure prohibiting further flight, X_F, may be judged by the indications, but is uncertain. If we further assume that the time until a landing site can be reached under the circumstances is a variable, X_L with some uncertainty (the aircraft will normally fly at somewhat reduced power). Then we can define a limit state function $g(X_L, X_F) = X_F - X_L$, and the problem can be seen as a classic, stochastic load(X_L)/strength(X_F) problem, as illustrated in Fig. 5. Reaching the targeted landing site can now be expressed as a first order reliability problem, as the probability of failing to reach shore, $p_f = P(E_F = \text{'no'}) = P(g \leq 0)$. For details refer to textbooks on structural reliability, e.g. Melchers, [16].

We found this a fruitful approach, because it allowed assessing the failure developing time: "How long do I believe that this aircraft can continue to operate?", independent of the assessment of the time to reach a landing site. X_L can be established with relatively high precision. The time to failure, X_F is generally highly uncertain. A simplified approach was necessary to achieve some assessment and expression of the uncertainty involved.

If we represent the time to a landing site, X_L by a normal distribution with a mean μ_L and variance σ_L that is small but proportional to μ_L. If we further represent the time to failure, X_F by a normal distribution with a mean μ_F and variance σ_F that is large but proportional to μ_F.

Then, for constant ratios μ_L/σ_L and μ_F/σ_F it can be shown that the probability of success of reaching a landing site only depends on the ratio of the statistical means μ_F/μ_L.

Now, to assess the probability of success, the pilot would only have to establish his prediction of how much longer/shorter he assesses the aircraft to be operable, than the time to the targeted landing site. This could be 1:1, 2:1 or, in a severe situation e.g. a 2:3 ratio. We performed the calculations here with $\mu_L/\sigma_L = 10$ and $\mu_F/\sigma_F = 3$. For a ratio $\mu_F/\mu_L = 1:1$ we thus have $p_f = 0.5$, for 2:1, we have $p_f = 0.09$ and for 2:3, we have $p_f = 0.93$.

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