Elicitation of Structured Engineering Judgement to Inform a Focussed FMEA

Lesley Walls[1], John Quigley[1] and Mick Balderstone[2]
Management Science, University of Strathclyde, Glasgow G1 1QE, Scotland
Smiths Industries, Cheltenham, UK

Abstract

The practical use of Failure Mode and Effects Analysis (FMEA) has been criticised because it is often implemented too late and in a manner that does not allow information to be fed-back to inform the product design. Lessons learnt from the use of elicitation methods to gather structured expert judgement about engineering concerns for a new product design has led to an enhancement of the approach for implementing design and process FMEA. We refer to this variant as a focussed FMEA since the goal is to enable relevant engineers to contribute to the analysis and to act upon the outcomes in such a way that all activities focus upon the design needs.

The paper begins with a review of the proposed process to identify and quantify engineering concerns. The pros and cons of using elicitation methods, originally designed to support construction of a Bayesian prior, to inform a focussed FMEA are analysed and a comparison of the proposed process in relation to the existing standards is made. An industrial example is presented to illustrate customisation of the process and discuss the impact on the design process.

Introduction

The research has been motivated by research within the UK aerospace industry where the practical use of FMEA has been criticised. This because it is considered to be implemented too late in the product development process and in a manner that does not allow information to be fed-back to inform the product design (Marshall and Newman, 1998). Therefore, while an exhaustive FMEA of a product design or process might be produced, the process is not regarded as efficient and the outcomes of analysis are not considered effective.

To address this problem, a consortium of aerospace companies[1] shared their experiences and produced a best practice guide. In parallel, the same companies were involved in specifying a Bayesian model to support estimation of reliability during design. This Bayesian model required inputs about the prior number of engineering concerns with a new design and the times at which these concerns are likely to be realised in use. The latter data is usually instantiated using relevant in-service or test data, while the former is captured through the elicitation of structured engineering judgement in order to gather insight into the state of engineering knowledge (Hodge et al, 2001). During the evaluation of Bayesian modelling with the industrial consortium, the synergies between elements of statistical modelling and FMEA have been developed into a process for eliciting beliefs about engineering concerns that has been referred to as a focussed FMEA in its implementation.

[1] REMM (Reliability Enhancement Methodology and Modelling), a DTI-industry funded project

This paper aims to describe the proposed process for eliciting beliefs about engineering concerns for a new design and explains how the approach taken has been informed by the scientific principles for survey sampling. An industrial example is presented to illustrate how the approach has been applied in practice and to analyse its impact on the previous best practice for FMEA in that company. In addition to FMEA, the approach is related to other methods and models aimed at analysing and documenting weaknesses in the design and operation of equipment. For example, HAZOP, root cause analysis, fault tree analysis and risk registers. Hence a comparison between the process and related methods and models is made with a view to explaining how the data collected through elicitation can be used within other models.

Process for Eliciting Engineering Knowledge

This section describes the proposed process for elicitation with particular emphasis upon who is involved and how structured engineering judgement is captured since these relate to the critical activities in survey design and method (Cochran, 1963). One of the goals of statistical science is to develop sound data collection strategies and there are recognised principles to which methods must adhere if they are to be deemed valid. For example, Cooke (1991) states that the principles of structured expert judgement are: reproducibility, accountability, neutrality, fairness and empirical control. We believe these are necessary, but not sufficient, conditions as they are more relevant to the 'how' aspects of data collection. When collecting data from experts, just like any other survey, it is fundamental to ensure that the people selected are representative of the population relevant to the problem. Achieving representation requires the population of interest to be defined. If not feasible to conduct a census of population, to design a strategy for selecting a representative cross-section and hence minimise biases that might arise from a haphazard approach. This is consistent with our view that all data collection strategies should be evaluated in terms of their opportunity for bias. Such an audit will flag weaknesses in the data so that improvements can be made to the design, or, if not feasible, the limitations of the data are acknowledged during subsequent analysis.

The proposed elicitation process aims to provide relevant data about engineering concerns to support decisions during product development in order to mitigate or manage failures. These can include design, test, manufacture, operational and maintenance decisions. Figure 1 shows a summary of the process. For further details about the theoretical basis of the process and assessment of its ability to manage biases see Walls and Quigley (2004). In the remainder of this section we describe the main elements of the process.

Facilitator

We propose that a relevant person should take responsibility for facilitating the process. The facilitator should possess a thorough knowledge of the process and an engineering understanding of the designs being evaluated. This is because the facilitator needs to, for example, interact with the design engineers and managers; manage the process of eliciting judgement from relevant engineers about the reliability of the new design; analyse and report the findings to the design team and the customer. Ultimately the facilitator is responsible for ensuring the data integrity, analysis and the interpretation of the results within the context of the reliability requirements for the design under consideration. This facilitator may be a reliability engineer or analyst or engineer within the design team with responsibility for reliability performance. If necessary, there may be two facilitators, the lead with knowledge of the process and the second with knowledge of the design.

Plan

During planning, there are dual aims: to formulate the strategy for selecting representative people to provide knowledge about the design (i.e. who); to decide upon the best means of gathering data for the given context (i.e. how).

To meet the first aim, the population of interest should be defined in terms of the domains of knowledge required; for example, functionality, parts, technology, manufacture, use and maintenance of the design. The importance of each domain should be assessed, but the default is to assume each domain is equally important. All potential engineers and their domain of expertise should be identified so that the size of each strata within the population, and a list of all people within each, are established. From this target population, engineers should be selected as experts. The size of the population and the cost (in terms of, for example, accessibility, availability) will inform whether all or some engineers are selected. If the latter, then it needs to be decided whether this is proportional to the relative size of the domain. As a minimum, at least one engineer from each should be selected to ensure representative coverage of knowledge domains about the design. It is acceptable, and even preferred; to select engineers with overlapping knowledge as this provides better coverage of interfaces between domains. However failing to select engineers from a domain should be avoided. The facilitator needs to be able to justify that the experts selected meet agreed criteria in terms of the experience and expertise.

To meet the second aim, the form of the data collection methods to elicit data should be decided. For the original goal of eliciting probability information to construct a Bayesian prior it was recommended that engineers be interviewed in person. This was because the process was novel and hence a semi-structured discussion was regarded as being a more comfortable environment within which to share distinctive knowledge. Such opportunities to tease out data would not be available with alternative methods such a self completed paper or electronic questionnaires.

Since the goal is to obtain holistic knowledge about the design, it is appropriate to hold group sessions, where different perspectives can be shared and explored. However, it should be decided whether such group sessions are scheduled at the start or end of the elicitation process. For example, it can be argued (Hodge et al, 2001) that individual interviews are most appropriate to tease out the views of each engineer since they encourage openness and then group sessions are used to verify and combine views across the team. On the other hand, if there is more than one engineer per domain, it may be appropriate to set up small groups which each comprise a cross-section of experts, taking care to allocate line managers into different groups from the engineers reporting to them. Otherwise patterns of behaviour will be induced leading to bias in the form of lack of contributions or tendency to conform to expectations of performance. If individual interviews are held, it is recommended that about an hour is allocated to each engineer. Time should be allowed for preparation and collation of judgement and completion of records.

It is recommended that interviews be held with those engineers with high-level domains of knowledge (e.g. systems engineer, lead engineer) first. These engineers possess over-arching knowledge of the design and so can help the facilitator understand the broad nature of design features and hence high-level or integration concerns. This provides a sound basis for interviewing experts with more specialised knowledge and hence who may have more detailed concerns about specific aspects of design. For example, the designers (e.g. electronic, mechanical, software) should be interviewed followed by those with specialist knowledge (e.g. thermal, vibration, manufacture, components).

An interview pack should be prepared. For example, this may contain: photos, drawings, diagrams of the item to be assessed; tools to support concern mapping; list of fault classes, including descriptions; scales to be used to assess probability, severity as required. This is important means of motivating and focusing discussion.

Briefing

It is important to brief experts about the process and how the information they provide will be used prior to an elicitation, particularly the first exercise. This briefing aims to inform and condition the engineers so that honest and full accounts of potential concerns. It provides an opportunity to reinforce that the data collected reflects their beliefs and the probabilities represents their state of knowledge, and is not a judgement on the state of their knowledge. It is important to ensure that experts do not perceive the elicitation of concerns as a judgement of their own performance. This is one of the reasons why we use the term ‘engineering concern’ since it allows the engineers to define what they perceive to be the root cause of a problem and be constructive in suggesting ways in which it might be addressed. The negative connotations of using fault or failure that may be associated with a blame culture should be avoided as the emphasis moves from the person to the system design.

Interviews

Each stage in the interview requires subtly different facilitation. However throughout, the facilitator should be vigilant in identifying any biases exhibited by the engineers. For example, engineers who are consistently optimistic/pessimistic, engineers who anchor chances of failure on historical data rather than understanding of engineering elements, engineers who are unwilling to share information. Such biases can be detected by observing, for example, body language, behaviour and wording of responses. If bias is suspected then the facilitator has two choices: either try to explore the source of bias through discussion and try and overcome; or to disqualify the engineer as an expert if it is thought that the judgement being provided is not constructive.

As is usual good practice, the facilitator should open the interview by summarising the process and its purpose, and asking the engineer if he has any questions to relax the interviewee and interviewer before the formal process begins.

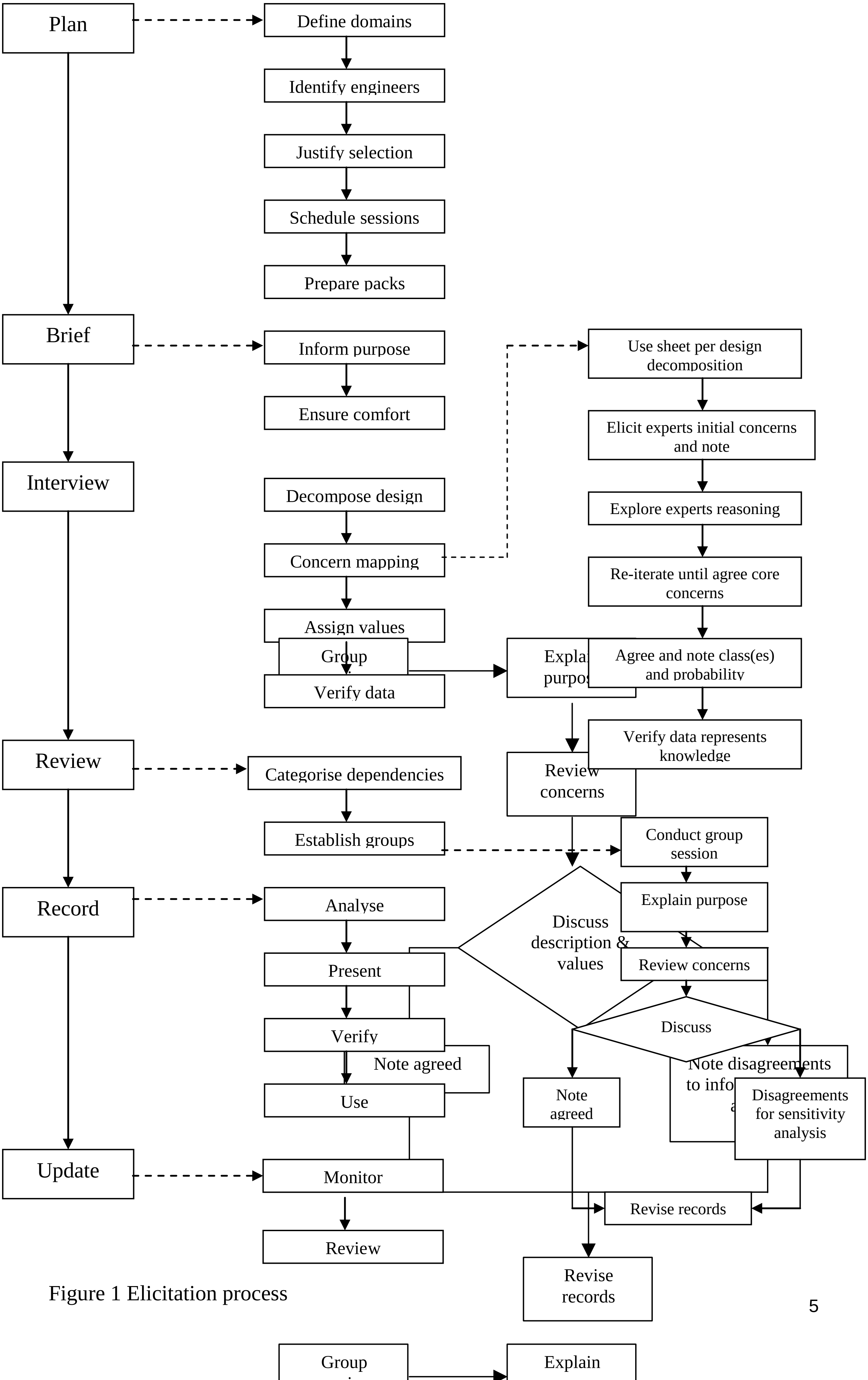

Figure 1 Elicitation process

The facilitator should post a worksheet onto wall, white board or use mapping software. This will be used to record issues and trace lines of reasoning from initial concerns through to causes, modes and consequences. Keeping the data visible to all is important since it ensures transparency, helps verification and allows dependencies between issues to be identified and explored. Figure 2 shows a template for a concern map. This version was used to support identification of potential faults within pre-defined root cause classes, hence the linkages between agreed engineering concerns to classes. Variations of this type of map can be generated depending on the needs of subsequent modelling of the data.

To structure the process, the design should be decomposed in an appropriate manner. For example, for variant designs it can be useful to review by proposed change, while for novel designs by functionality or part. The facilitator should be aware and ask the engineer about other aspects of the design that may affect reliability, in particular, pre-existing design weaknesses.

The facilitator should tackle each identified element of the decomposition in turn to identify all associated concerns. The reasons for raising the concerns should be noted and the impact explored. In our example, this path of reasoning is captured in the sub-concerns portion of the map. From this the facilitator and the engineer should agree the description of the concern to be formally noted. The rules for this allocation depend upon the model used to analyse the data. For example, for use with our Bayesian model it must be judged whether or not the concern is an accurate representation of an aspect of engineering that could lead directly to failure. In the case where the concern data contributes to a focussed FMEA, then the concern may represent a weakness against which someone can be own and hence take action to address since it is regarded as controllable and implicitly the probability of leading to failure is (close to) 1.

Collecting probability information is important since it allows us to represent an engineer's state of knowledge about the concern. Hence we propose asking the engineer to state his belief with respect to the chance a concern might result in a fault in use, assuming no corrective action is taken. The latter condition allows a translation from the design to use without making any assumptions about the efficacy of subsequent analysis or test. Probability templates or scales aligned with company practice can be used. For example, we have often used probability lines where the engineer marks a point on the scale with 'x' that best represents his understanding of the chance each concern will be realised as a fault in use given no change to the design. The engineer may also mark a range on the scale to indicate his uncertainty in the judgement. Many engineers naturally express their beliefs in terms of lower and upper surprise limits. If record sheets are used, a separate probability scale should be used for each concern to reduce the possibility of the engineer anchoring on the initial value. The probability can be marked on the appropriate concern map. Although not required for Bayesian modelling, other quantitative data about the severity of consequences can be elicited during the interview. For example, for each concern, the severity of the concern should be assessed using an appropriate severity classification scale and noted on the worksheet.

The mapping process should be repeated for all elements noting that any reason can be mapped to any number of concerns and concerns may relate to more than one change, function or part. Once all elements of the decomposition have been exhausted, the facilitator should ask the engineer to identify any other concerns that they have not yet identified. It is desirable to conduct a consistency check of the engineer's responses and reasons for any differences should be explored. This can be built into the design by, for example, framing the questions about the in different ways. This has been achieved in small elicitations where engineers have been asked questions prior and at interviews in different ways so that cross-checks of their states of knowledge in terms of probabilities can be performed. However this is more difficult for large complex designs or for purely qualitative descriptions only. In such cases, the facilitator may need to rely upon continual review of the consistency of the expert's reasoning. To conclude the interview, an expert should be asked to review and verify that the probabilities recorded as a correct representation of their beliefs.

Review

After interviews the facilitator should review data collected to ensure records are complete and note issues arising, for example, problems with expert bias. If individual interviews are held, all concerns should be reviewed to assess which are unique to an individual engineer and which are common to two or more engineers. Common concerns are likely to arise due to overlapping domains of knowledge and be identified and managed so that they are not double counted in analysis. The facilitator will want to distinguish between concerns that are identical between engineers and those that are related but not necessarily referring to the same root cause. At a group session the treatment of concerns should be verified, or corrected, as appropriate, and the common concerns can be explored in more detail so that probabilities values, or ranges, are agreed and different scenarios for modelling identified.

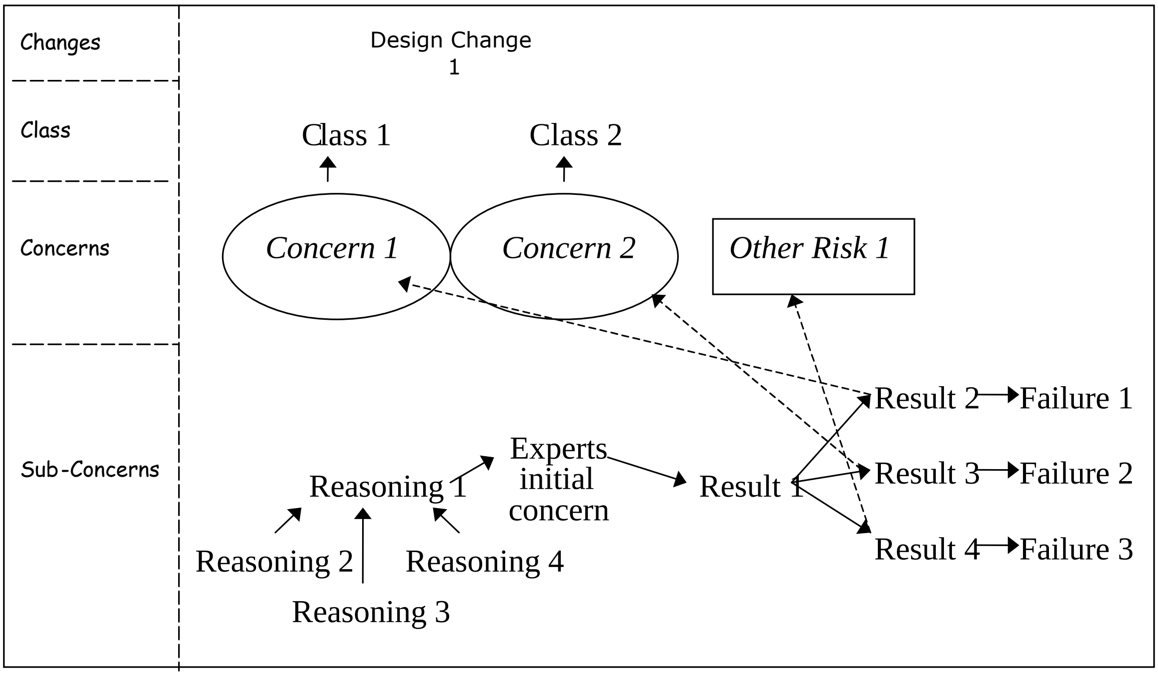

Figure 2. Example concern map

Record

The output can be a record of concerns where an example form is shown in Table 1.

Concern description	Fault Class	Concern Number	Number of occurrences	Probability	Comments
e.g. Textual description	C	4.2,	1	0.90	Text
e.g. Textual description	B	3.3	1	0.80	Text
e.g. Textual description	A	1.1, 2.5, 5.1	3	0.45, 0.70, 0.5	Text

Table 1. Concern record

Update

To be useful, the information about concerns should be revised as development progresses allowing feedback from analysis and test to both measure the degree of calibration of engineering knowledge and facilitate learning. There should be minimal set-up costs for the re-elicitation, since the same people should take part and the methods of data collection need only be adapted to update maps, either by revising probabilities of established concerns or by expanding upon concerns which were previously expressed at a higher level. It is expected that the number of issues raised will increase in detail as the design evolves from concept to detailed. Thus the elicitation will enable engineers to articulate the root causes of concerns at a level of detail appropriate to the stage of development.

Industrial Application

The process has been applied to an electrical power management system and a data concentrator unit. The power management system has been designed for use on a military jet and is a development of systems previously designed and built for a military helicopter and a civil airliner. There is similarity in terms of function and the design of the structure and the boards.

Previously the company would have worked entirely to a set of prescriptive requirements from the customer. These development processes were the first to work within an enhancement framework, consequently there was a need to focus upon the use of elicitation to identify areas of concern from reliability and 'life' perspectives with data generated to contribute directly to the case presented to the customer. No quantitative reliability requirements were being supported, but the information from elicitation is being used to directly inform the reliability programme with analysis and testing activities put in place to establish whether a concern is real or not, with subsequent design changes being introduced to mitigate or eliminate real concerns.

The elicitation process used was aligned with elements of standard FMEA for process and design (Bowles, 1998) and hence has been referred to by the company as focussed FMEA. The front end comprised the major elements of the process used to elicit data, while the organisation of output was managed using FMEA record sheets.

The elicitation process shown in Figure 1 was customised and implemented by a company reliability analyst. The actual process implemented involved group elicitation sessions to identify engineering concerns and a subsequent group session to follow through the criticality analysis of the core concerns. Since the goal was to find out all major weaknesses, the decision was made to implement group sessions only. Individual interviews were omitted to shorten the process and to meet the distinctive aims. The group process involved several sets of experts, avoiding line managers within the same set, who were prompted using engineering drawings and models. Discussions were semi-structured and tabular records were compiled. Equally the need to quantitative data was limited to that required for FMECA and hence relied upon 5-point probability and severity classifications.

Evaluation

Evaluating the process, the company states that by focusing effort on those areas elicited as concerns gave rise to the following benefits. It allowed less effort to be expended in analysis and testing to 'prove or disprove' that the problems would be realised on an aircraft, although it has not been possible to quantify the reduction in effort. The process provided a more rounded understanding of the products to all engineers who participated. For example, the inclusion of manufacture and test engineers means that ownership of concerns was assumed and responsibilities for actions assigned early in design with designers, manufacturing, quality and test engineers sharing a common understanding of the core concerns. The company believes a better understanding means a more focused reliability programme is developed and solutions are more likely to be successful in eliminating or mitigating the problem. While the latter statement is logical, there is no evidence to support this claim at present since only feedback from test and use will indicate whether reliability has indeed been improved. However the use of the concerns to flag reliability drivers and hence motivate the reliability programme to explore the areas of uncertainty is positive. Overall, changes have been made to company procedures with flowcharts having been introduced for reliability tailored to the process. The guidance that accompanies the procedures run as animated files within the company intranet

However through this intervention, the company has identified issues relating to requirements that need to be explored with the customer if the proposed process is to be robust. In particular, there is a need for better reliability requirements capture with the customer needing to 'let go' and trust the supplier to work with a looser set of requirements. Our interpretation is that this comment arises due to tension between what the customer requires in terms of a reliability measure, which might be defined quite conventionally and rigidly, and the freedom they are giving the supplier to develop a reliability programme and case of evidence. Releasing the former will allow a better balance with the latter. However, at the same time, it means that there is a greater need to capture and structure what the customer actually requires so that the reliability analysis is focused on user needs.

Relationship to other Reliability and Risk Methods

Elements of the elicitation process share similarities with the approaches advocated for methods such as FMEA (Bowles, 1998), HAZOP (Kletz, 1999) and root cause analysis (Andersen and Fagerhaug, 2000). For example, all have the intent of bringing together relevant engineers to share knowledge through a structured process and to use the information generated to enhance system design and/or operation. Each represent a different perspective on the system: FMEA provides a basis for thinking through potential problems largely from a design or production process perspective; HAZOP considers the operational hazards during installation, production and de-commissioning of systems; root cause analysis tends to be a forensic investigation of an event that has, or could occur, back to its root cause. All demand that there should be multiple perspectives within the expertise of the people who take contribute to the analysis and all use methods to structure how the data collected is surfaced and organised that are appropriate to their primary goals. The elicitation process is most closely related to FMEA given its role in product development and its goal of informing decisions about the nature of analysis and test to be included in a reliability programme.

Comparison Between Methods

FMEA can be considered as a census of potential events within a product breakdown by part or functionality, or the process by which it is developed. This thoroughness, especially if delegated to one person, is time-consuming and risks becoming an accounting exercise. The elicitation process could be viewed as a rough-cut or focussed FMEA that allows mixes of product with process, including dependencies between them, and levels of detail so that prioritisation of issues is naturally taking place concurrently with data gathering rather than retrospectively after criticality analysis. However given elicitation is allowing the engineering experts to define their own sample path, there is a danger that important events could be overlooked. The approach to decompose the design and explore each element in turn provides one mechanism for partitioning the failure event space so that the opportunity for missing concerns is minimised. It is also important to monitor concerns through life so that the degree of calibration of the engineers' knowledge to the actual events is measured. This can provide feedback to experts to facilitate learning since it has to be acknowledged that, at best, will only be able to articulate what they know at any point in time and may underestimate the likelihood of any unexpected events.

In contrast to FMEA, HAZOP and root cause analysis we advocate an elicitation process that captures engineering concerns in natural language rather than using pre-defined key words. The advantages are that engineers express their knowledge in a language with which they are comfortable and hence reasoning processes are made explicit to the facilitator allowing uncertainties about concerns to be elicited. This overcomes the restrictions of having to select, for example, causes, modes, effects, and severities from pre-defined classes, which might aspire to avoiding ambiguity, but might in fact lead to anchoring of ideas. However, some classification taxonomy is required in order to make sense of elicited data otherwise it will be difficult to monitor and control concerns using some form of risk register through development.

Engineering concerns can also be used in different types of reliability modelling. For example, in Bayesian modelling, until recently there has been little attention given to the elicitation of meaningful priors. Instead convenient mathematical forms have been assumed and parameters abstract to the design team have been used. Hence elicitation of engineering concerns has allowed probability modelling conducted by reliability engineers to be integrated with the knowledge of the design team, with the latter providing the foundation of modelling. The challenges of classifying concerns leads us to reflect that they may be considered as natural base events within a fault tree albeit they have been derived in a bottom-up manner. Therefore engineering concerns could provide another source of data for validating elements of a fault tree model structure or assisting in defining the depth of the tree.

Conclusions

To conclude, there is little reported scientific analysis of the value of methods such as focussed FMEA. All evidence to date has been anecdotal and although attempts have been made to measure the real-time impact of the method in terms of, for example, comfort of those taking part, number and type of concerns raised relative to established methods and feedback information from test to establish efficacy of process in terms of concern coverage. However given the limited number of interventions, any evaluation data collected is limited in terms of the analysis it supports. Hence there is a need to further more controlled study as has been conducted in, for example, root cause analysis (Doggett, 2004). Although such studies must be carefully designed to allow fair comparisons and minimise learning through carry over effects.

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References

1. Bowles J. The New SAE FMECA Standards, *Proc. RAMS* pp 268-273 1998)
2. Cochran W.G. *Sampling Techniques*, Wiley (1963).
3. Cooke, R.M. *Experts in Uncertainty*, Wily (1991).
4. Dogget A. M. A Statistical Comparison of Three Root Cause Analysis Tools, *Journal of Industrial Technology*, **20**, pp 1-9 (2004)
5. Hodge R, Evans M, Marshall J., Quigley J. and Walls L. Eliciting Engineering Knowledge about Reliability During Design – Lessons Learnt from Implementation, *Qual. Reliab. Eng. Int.* **17**, pp 169-179 (2001).
6. Kletz T A, *HAZOP and HAZAN*, Taylor and Francis (1999)
7. Marshall J, Newman R, Reliability Enhancement Methodology and Modeling for electronic equipment – the REMM Project” *Proc. ERA Avionics*, 4.2.1-4.2.13. (2001)
8. Walls L. and Quigley J. *Structuring Engineering Knowledge to Inform Meaningful Prior Distributions for Modelling Reliability in Design – Principles and Practice,* University of Strathclyde Working Paper No. 2004/10 (2004).