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THE MEASUREMENT OF SAFETY EFFECTIVENESS IN ATM

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Research has identified six enhancement measures that may be applied to Safety Management Systems (SMS) in Air Traffic Management. The current system of measuring SMS maturity requires further extension to provide the means to assess both the individual and collective effects of the enhancement measures. This allows Air Navigation Service Providers, in seeking to increase overall SMS effectiveness, to make informed judgements regarding the value of implementing the measures in their individual operational contexts. The use of Bayesian analysis, and specifically Bayesian Networks, provides a mathematical modelling approach which meets these needs.

Keywords: ATM, Safety, SMS, Maturity Measurement, Bayesian Networks

1. Introduction

In Air Traffic Management (ATM), Safety Management Systems (SMS) are the principal vehicle for implementing safety policies, practices and procedures in accordance with internationally agreed Standards [1]. In a constantly changing operating environment, it is essential to maintain SMS effectiveness as a means to maintain and enhance levels of ATM safety. It is also an international requirement that each *'ATM Service Provider shall monitor and assess the effectiveness of its SMS processes to enable continuous improvement of the overall performance of the SMS'* [2].

With this overall objective, research (by the author) into the future development directions of SMS has identified a range of new safety approaches and methods designed to ensure that safety performance keeps pace with increasing industry challenges and pressures and thus avoids a progressive decline in aviation safety.

Six development paths for enhancing the effectiveness of SMS have been identified:

- Three in the category of '**Opportunities'** where proactive measures may be self-initiated as part of SMS management and development: -
    - ***Enhanced SMS Management and Operation*** - proposing safety improvements to be gained within the internal mechanisms of an SMS. It addresses the need for SMS to operate as an integrated system rather than a

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collection of un-related safety functions, and also proposes organisational and managerial improvements relating to SMS;
  - ***New Safety Thinking*** – recommending means by which new safety concepts currently under application in a wide range of safety industries may be applied to ATM safety. This includes investigating whether the scope of SMS can be extended to make the coverage of the system more comprehensive, and therefore more effective.
  - ***SMS Knowledge Transfer*** – reviews the scope for importing lessons from other industry sectors - both other aviation sectors and non-aviation industries - and provides specific measures deriving from the rail industry relating to risk assessment decision-making processes.
- Three in the category of **'Threats'** where protective measures are required in order to respond to factors, external to the scope of operation of the SMS, which have the potential to degrade ATM safety levels: –
  - ***Institutional Change*** – recommends measures to counter the effects of political changes which have the potential to lead to non- or partial implementation of agreed regional and global standards, or planned divergence from those standards, and their potential negative effect on both safety and economic performance.
  - ***Cybersecurity*** – derives and presents enhancements required to equip SMS in ATM with protection against security risks, focussing on the fast-rising threat in cyber-security. This includes consideration of the integration of Security Management Systems with SMS into a single protection system.
  - ***Unmanned Aviation*** – focusses on the effects on ATM Safety of the arrival of unmanned aircraft systems (UAS), including their integration into current operations in non-segregated airspace. A range of SMS enhancement measures are presented, including those supporting provision of UAS Traffic Management (UTM) services.

For each development path, enhancement measures are proposed which, if implemented, are designed to contribute to an overall increase in levels of SMS effectiveness over the next decade, thereby enhancing overall SMS performance and countering the effects of increased pressures and threats in the ATM system over that time.

However, progressive development of SMS in this way raises a further question which needs to be addressed: -

….If these enhancement measures are applied, what will be the methodology for measuring the resulting improvement in SMS effectiveness in ATM?

The answer necessitates the use of quantitative measurement of SMS maturity and performance to establish how effective these new enhancements are. This paper therefore presents the development of a methodology with this capability.

While development of a completely new system was considered, existing methodologies were also reviewed as potential platforms offering faster implementation and user acceptance, and revealed three possible measurement approaches: -

- The well-established Safety Maturity Framework (SMF) / Standard of Excellence (SoE) developed by EUROCONTROL and the Civil Air Navigation Services Organisation (CANSO) – discussed below [3][4];
- The system proposed by Yeun (Griffith University and Civil Aviation Safety Authority, Australia) in which the results of safety oversight activities are used as quantified indicators of implementation (and therefore effectiveness) [5];
- A trial system developed by The US Federal Aviation Administration / Embry-Riddle University, using Data Envelopment Analysis (DEA) techniques. Review showed that this was similar to, but not as wide ranging nor as comprehensive as, the EUROCONTROL/CANSO system [6].

Significantly, none of these systems currently offer the means to measure the effectiveness of SMS in an extended and enhanced form.

2. The Need for a new enhanced measurement methodology

Serious accidents in 2001 and 2002 led to the realisation that the maturity, and therefore the effectiveness, of SMS was not sufficiently known. As a result, the EUROCONTROL Organisation developed and implemented the SMF – a rigorous questionnaire-based system framed on the SMS structure internationally agreed within the International Civil Aviation Organisation (ICAO).

In 2013, this system was further refined in conjunction with CANSO to provide a well-accepted measurement platform - the Standard of Excellence (SoE) in SMS - applied Europe-wide and also to a number of major Air Navigation Service Providers (ANSPs) in other regions of the world – ref. Figure 1 below: -

Fig. 1 – Current CANSO/EUROCONTROL SMS Arrangements (source CANSO/EUROCONTROL)

The SoE framework identifies 17 constituent parts of the SMS and defines an assessment system for each, thus leading to integration into an overall maturity rating. However, when assessing the impact of the SMS enhancement areas described above, the SMF/SoE approach provides a good foundation but needs significant extension to provide a methodology which can: -

- Serve as the extended basis for effectiveness measurement,
- Enable the assessment of performance of the SMS with the proposed enhancement measures applied – as compared with SMS performance without enhancements - and
- Identify the relative benefit of each enhancement to be identified, thus maximising the value and priority of the work involved in applying each enhancement measure.

Figure 2 below illustrates the overall context of the required methodology: -

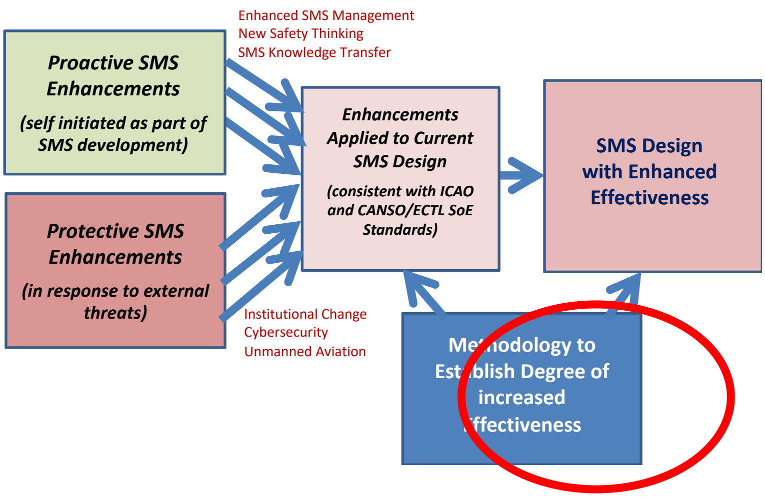

Fig. 2 – Context of the Required Measurement Methodology

A mathematical model is therefore required that could be adapted by operators to capture the key measurement criteria involved in assessing maturity. To derive the above capabilities in a manner offering an acceptable level of adaptability, it has been found optimal for the model to be based on the use of Bayesian Analysis principles and methods.

3. Use of Bayesian Analysis

Bayesian Analysis is a statistical approach which, *inter alia*, offers a quantifiable way of assessing the influence of new information – in this case, the effects of applied SMS enhancements - on current measured levels of SMS maturity.

Bayesian methods are named after Thomas Bayes (1701–1761). Bayes' Theorem is probabilistic in its basis, and has the capability to show how new information can be used to make better decisions under conditions of uncertainty.

Of specific relevance, the use of Bayes' Theorem permits current assessments – viewed as ***prior*** probabilities – to be revised in the light of new data or evidence to become new, updated ***posterior*** measurements, as shown in Figure 3 below: -

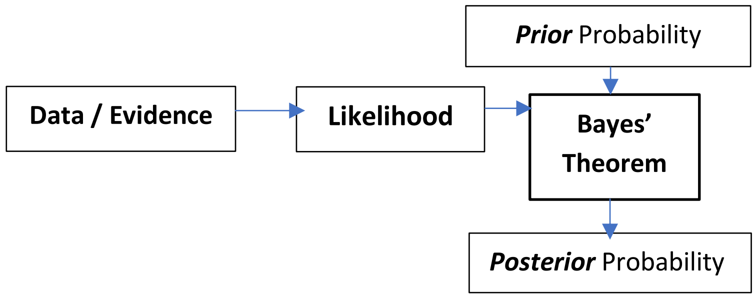

Fig. 3 – Conceptual Flow of the Operation of Bayes' Theorem (source Kurt)

4. Bayes' Theorem

The above schematic shows, in conceptual terms, what is happening during the application of Bayes' Theorem [7]. The Theorem addresses the conditional probabilities of two (or more) events A and B which may, or may not, be causally independent. If they are independent, the product rule of probability theory applies and the joint probability of both events occurring (i.e. being true) may therefore be expressed as: -

$$p\,(A,B) = p\,(A) \times p\,(B) \qquad (1)$$

whereas if A and B are mutually dependent, their joint probability may be expressed as: -

$$p\,(A,B) = p\,(A) \times p\,(B|A) = p\,(B) \times p\,(A|B) \qquad (2)$$

where p (B|A) means the probability of B occurring on condition that A has already occurred, or p (B given A).

Where the information needed to calculate the required probability values is not all available, Bayes' Theorem provides a means to calculate unknown or missing variables. In its most basic form, the Theorem states that: -

$$p\,(A|B) = p\,(A) \times p\,(B|A) \,/\, p\,(B) \qquad (3)$$

Thus, for example, if the probabilities of B and 'B given A' are known, but the probability of 'A given B' is not, Bayes' Theorem can provide the means to calculate the missing variable.

If applied to the updating of known, existing measurements in the light of new data, the posterior probability may be represented as a 'hypothesis given the new evidence (i.e. new data)'. In this context, Bayes' Theorem may be presented as: -

p (hypothesis | data) = p (data | hypothesis) x p (hypothesis) / p (data) (4)

It is important to recognise that: -

- The term 'hypothesis' is understood to mean 'the hypothesis is true' [8], and that
- The evidence can either support the hypothesis (be 'probative') or counter the hypothesis (be 'not probative') [9] .

To translate equations (3) and (4) into terms specific to the task of assessing the effectiveness effect of the proposed SMS enhancements, Bayes' Theorem may be expressed as:

$$p(M^e \mid D) = p(D \mid M^e) \times p(M^e) \; / \; p(D) \qquad (5)$$

where: M^e is the enhanced maturity score, and

D is the new measurement data.

While a comprehensive explanation of Bayesian analysis is beyond the scope of this paper, it is useful to understand its methods, including the use of Bayesian Networks.

5. Bayesian Networks

In a Bayesian Network (BN), each measurement variable may be represented by a node within an inter-connected network of causal relationships. The nodes of the BN are connected together in a manner which reflects both their influence within the network and their inter-dependence.

Each node can represent a series of probabilistic states for the variable in question, depending on their initial 'prior' values - as established by evidence or estimation – and the influence of any external inputs. A convenient way of explaining the operation and value of BN's is by means of a simple example.

The context for the example below is the flow of arriving aircraft at a busy airport. At the busiest airports, the arrival spacing is such that any interruption affecting a landing aircraft will cause the following aircraft to execute a "go-around" – aborting its landing and making a further circuit before performing another approach. The probability of a go-around is of critical interest to both the airport operator and the ANSP as it is one measure of the efficiency of operations, and therefore the financial success, of the airport.

The reasons for a Go-Around can include adverse weather and either an accident to, or late vacation of the runway by, the preceding aircraft. The example network below (Figure 4) is a representation of the context in BN form. It may be seen that the probability of a go-around is influenced by the factors mentioned above. However, the factors are also inter-connected probabilistically as shown. To explain the nodes and their inter-relationships further: -

- Adverse Weather can lead to late vacation by the aircraft from the runway, perhaps due to reduced braking effectiveness. It can also be the cause of an aircraft accident, or simply render the runway temporarily unusable.
- Aircraft operating problems can give rise to an accident on the runway in all weathers – including undercarriage failure and heavy landing causing tyre burst.
- Late runway vacation can also be caused (in all weathers) by adverse pilot operation – perhaps inattention or unfamiliarity with the airport.

A key attribute of the use of BN's in this example§ is that the numerical basis for calculating the probability of a go-around is measurable. The statistical information relating to the influencing factors - weather, accident rates, late clearances – are all measured and recorded within relevant meteorological, operational and occurrence reporting systems.

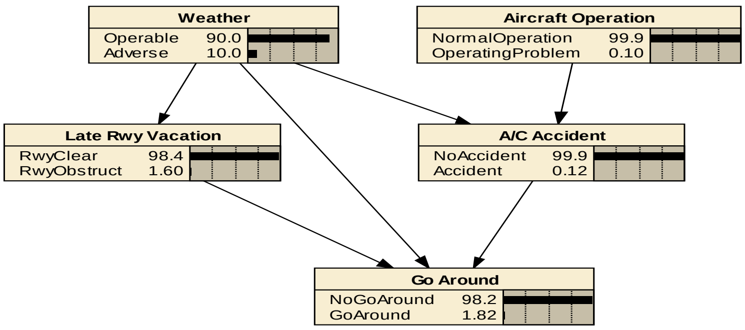

Fig. 4 – 'Go-Around' Example Represented in Bayesian Network Form

In Bayesian Networks, the probabilities of the influencing factors are set by means of Node Probability Tables (NPT's) for each node of the network. Thus, in the above example, the NPT for the node 'Aircraft Accident', which has two influencing inputs, sets out the relative degrees of influence (in terms of their prior probabilities in percentage terms) for all probabilistic states of those inputs, as follows: -

Node probability Table for the Node 'Aircraft Accident'

Weather	Aircraft Operation	No Accident (%)	Accident (%)
Operable	Normal Operation	99.9	0.1
Operable	Operating Problem	99.7	0.3
Adverse	Normal Operation	99.7	0.3
Adverse	Operating Problem	99.5	0.5

It is stressed that the values assigned for this and all other nodes in this network are presented here simply for illustration purposes. Real values can vary from location to location and from ANSP to ANSP, but can be introduced based on collected statistics, as mentioned above. Nevertheless, it is possible to deduce the interrelationships of influencing factors and the magnitudes of their effects on the eventual outcome – namely, the probability of a 'Go-Around'.

It should also be noted that the operation of even a relatively straightforward network, such as in this example, requires a significant multiplicity of mathematical calculations. This can be made practically feasible by the use of software applications, of which a number are commercially available [10]. For the purposes presented in this paper, the application used is Netica [11].

6. Measurement of SMS Effectiveness

With reference to the SMS arrangements shown in Figure 1 above, the framework for the disposition and inter-relationship of SMS elements may therefore be mapped into Bayesian Network form, as shown in Figure 5 below. The key features to note from this figure are: -

- With two exceptions, the SMS elements are grouped into major components of the system, reflecting their role in achieving the overall objectives of the SMS. The exceptions are Safety Culture and Safety Risk Management, which are major components in their own right.
- The elements and major components are both included in the BN – both for clarity, and to ease the complexity of calculations at each node of the BN.
- Each SMS element leads to a Study Area (SA) within the SoE measurement system, thus yielding a measured score for each.
- To provide clear illustration, the numerical values for the SA's shown in Fig. 5 are authentic and correspond to real measurements submitted on behalf of a European State for 2018. They are reproduced here anonymised (but with the State's permission).
- In applying a Bayesian Network approach to maturity measurement, it is assumed that, for each node, two probabilistic states may suffice – True or False. Thus, in the case of an individual Study Area Maturity score of say 70%, the two probabilistic states may be defined as "Mature 70%, Not Mature 30% (or equivalent descriptions e.g. Effective and Not Effective). The sum of probabilities at any node must be 1 – i.e. 100%.

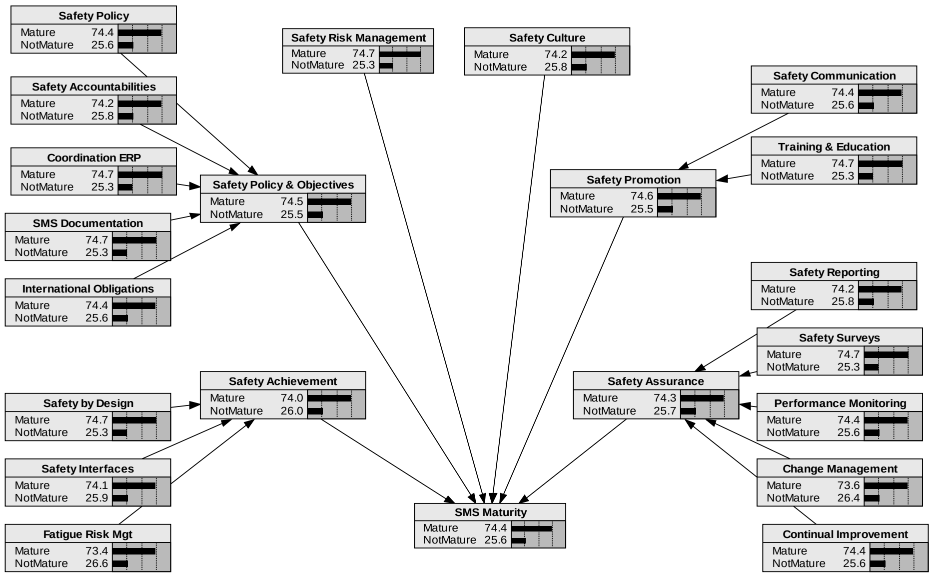

Fig. 5 – SMS Elements and Major Components in Bayesian Network Form

7. Measurement of SMS Enhancements

Bayesian analysis focusses on the ability to integrate new information into an already known situation. In this case, the application of SMS enhancements to existing and quantified levels of SMS maturity allows an assessment of the effects of those enhancements.

Figure 5 above presents, in Bayesian Network form, the results of assessments made currently using non-Bayesian methods. However, the use of a Bayesian approach is essential in providing a mathematical modelling system that is flexible and adaptable, and supported by bespoke software applications.

In order to integrate the enhancement areas into the SMS network, values must be derived for the effectiveness of each enhancement area, and also for the influence that the enhancement measures will have in each SMS element to which they are connected. These values can be derived by measurement, or estimated using brainstorming techniques, and are then introduced into the BN by entries in the relevant NPT's.

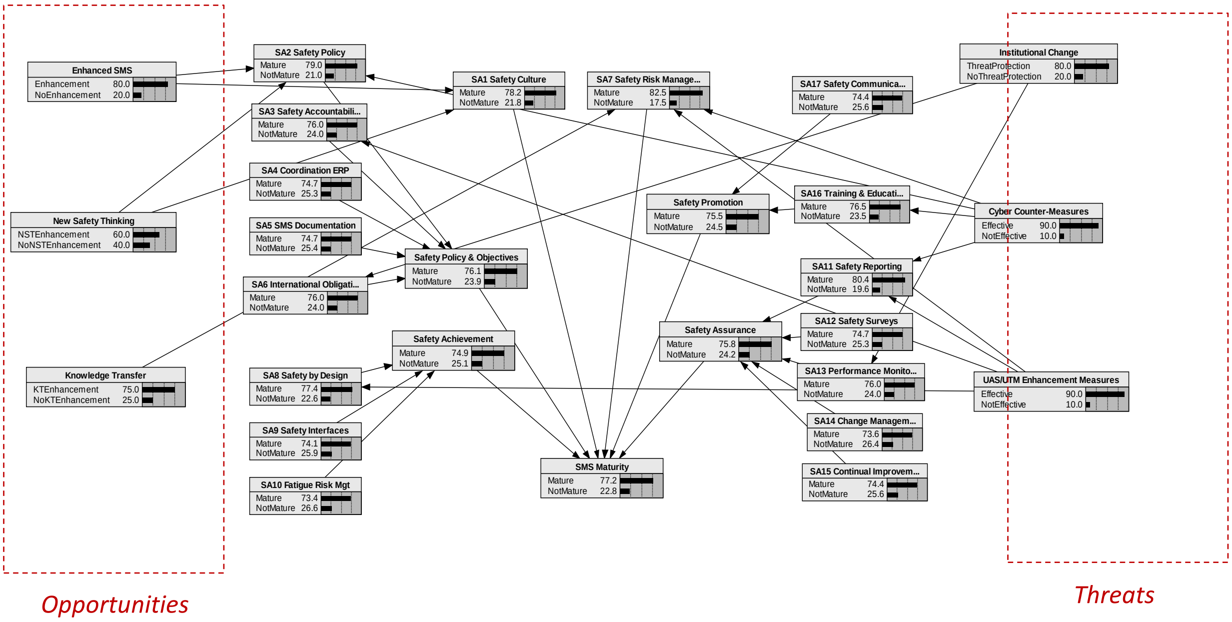

Fig. 6 – SMS Bayesian Network with Enhancement Areas Applied

Figure 6 above illustrates the BN for the SMS with Enhancement Areas applied. It is important to note that the Maturity values shown for SMS nodes are those real values used in Figure 5 as **updated** by the effect of the Enhancement Areas, for which estimated values have been used to illustrate the flexibility and adaptability of the mathematical model. These features may be illustrated by operating the BN in the following way: -

- Once the Bayesian Network has been 'activated' – i.e. the nodes are connected, and probability calculations are made in accordance with NPT values – the network can be adjusted in real time to investigate the overall effects of changes made. In particular, the probabilistic values in each of the Enhancement Nodes can therefore be individually adjusted dynamically.
- For individual assessment of the effect of each Enhancement Area, all six Enhancement Nodes can be adjusted so as to have zero effect on the network – i.e probabilistic state False (or 'Not Effective') set at 100%. In this situation, the scores for all Major Elements, and also for Overall Maturity, will revert to the values shown in the BN at Figure 5.
- From this condition, the Enhancement Nodes may be introduced ***one at a time in turn*** to their estimated or measured values. (Though these values are already

in the NPT's for the Major Element nodes, they do not have any effect on those nodes until the Enhancement Node values have a non-zero probabilistic value).

- In this way, the individual effect of each SMS Enhancement on the relevant Major Element(s), and on overall SMS Maturity, may be seen. As a further stage, the effects of **all** Enhancement Areas may be returned to their active states to show the collective effect on all Major Elements, and on Overall Maturity, when all enhancements are fully applied together.

8. Conclusions

A research project has examined means to enhance SMS in ATM and has identified six separate enhancement measures that may be applied. The current system of measuring SMS maturity, and therefore effectiveness, needs to be extended to include these additional areas of enhancement.

In particular, however, a system of measurement is also required which provides the capability of assessing the effects of each individual enhancement measure, so that ANSPs can make informed judgements of the value of implementing each measure in their particular operational context.

The examples shown in this paper are for illustration, but demonstrate that the use of Bayesian analysis, and specifically of Bayesian Networks, provides a mathematical modelling approach which successfully meets these needs.

Using adaptation of the model to local situations and contexts, ANSPs may therefore assess specific values for the degree of enhancement achieved by each enhancement measure individually, and by all enhancement measures collectively, in seeking to increase overall effectiveness of their SMS.

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