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A DECISION-SUPPORT METHODOLOGY FOR PERFORMANCE-BASED ASSET MANAGEMENT

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(Received) **Q1**

A software-supported methodology for managing the performance of complex infrastructure systems is described. The infrastructure system is represented hierarchically, so that high level business decisions and more detailed operational decisions can be supported by the same methodology. Performance of each sub-system is captured by a set of Performance Indicators held in a database. Evidence of performance is assembled from all available sources, ranging from monitoring measurements and inspection records, design calculations and model studies to expert judgements, analogous cases and accounts of past failures. These Performance Indicators are projected through value functions reflecting organisational objectives and regulatory standards and are merged to generate a Figure of Merit for the system and each sub-system. Uncertainty in the available evidence is represented and propagated through the evidence hierarchy using Interval Probability Theory, providing a commentary on sources and implications of uncertainty in the decision. A case study of a hydro-electric reservoir system demonstrates how the approach can be used to provide a coherent overview of system performance and support asset management decision-making.

Keywords: Please supply **Q2**

1 INTRODUCTION

The aim of the research described in this paper has been to develop new decision support techniques to enable performance-based management of complex civil engineering infrastructure systems. The work has focussed upon a group of economically important and safety–critical infrastructure systems, including dams, flood and coast defences and engineered and natural slopes, which have following characteristics:

- The physical failure mechanisms are complex and site-specific. Available models of the failure mechanism have significant deficiencies.
- The structural behaviour is spatially and temporally varied. This is often associated with natural variability in loading regime (wind, wave, rainfall, seismic) and geotechnical conditions.

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- Monitoring information tends to be scarce and can be expensive to obtain.
- Because of both the scarcity of quantitative information and the complexity of the physical processes there has traditionally been a major element of expert judgement in condition monitoring.
- Condition assessments are characterized by uncertainty. Consequently monitoring and remediation resources can be mis-directed.

This paper begins by describing a study of current condition monitoring and asset management practice in the UK dam and flood defence sectors. This analysis has identified user needs for decision support. In Section 3, the key concepts that the decision-support methodology is based upon are introduced and explained. Issues of uncertainty handling are addressed specifically in Section 4. An example application to a hydro-electric reservoir system is described in Section 5. The paper closes with conclusions.

2 ANALYSIS OF THE PROBLEM DOMAIN

A descriptive study was conducted to identify generic problems, best practices and principal sources and types of uncertainty. A workshop with representatives from eight collaborating organizations from the public and private sectors provided an initial impression of the scope of asset management issues and challenges. Subsequent more detailed analysis involved, in an interactive mode, literature review, interviews with experts, site visits and case studies. This detailed phase of analysis of the problem domain focussed on one major private sector UK dam owner and the Environment Agency (EA), which has operational responsibility for flood defence in England and Wales.

The dams sector in the UK is subject to stricter statutory regulation than the flood defence sector, though there is overlap between the two, with some flood defence structures being subject to the regulations of the 1975 Reservoirs Act. In the UK there are roughly 2500 dams of a capacity exceeding 25,000 m^3, making them subject to the provisions of the Reservoirs Act. These dams are subject to statutory safety checks, which are based largely on the experience and engineering judgement of the Inspecting Engineer. The individual responsibility that the Act places on engineers involved in safety assessment is regarded as an enduring strength of the now aging legislation. However, despite the tradition of tight regulation, there is some concern that the prescriptive approach to safety in the dam sector may not have kept pace with developing approaches to risk and hazard management. So, for example, provisions for surveillance of dams are based on fixed intervals rather than on concepts of risk-based surveillance. For hazards that have in the UK only become a concern in relatively recent years, notably seismic hazard, there is a great deal of inconsistency of approach. Recent developments in hydrological analysis of spillway capacity and spillway functionality during earthquakes have also caused confusion (Hartford, 2000). There is an ongoing tendency to invest in dam improvements, but the evidence of beneficial impact of that investment on asset performance is inconclusive. Fundamental to the contemporary problems of dam safety assessment in the UK (as well as in many other countries) is the aging nature of the dam stock. Concomitant is the loss of expertise in dam design and loss of corporate memory of dam behaviour.

Whilst the regulatory framework for flood defence is different to the dams sector, issues of loss of corporate memory and lack of evidence to support asset management decisions were found to be common to both sectors. The present condition characterisation methodology used in England and Wales by the Environment Agency ranks a flood defence between 1 ("very good") and 5 ("very poor"). This score is based on visual inspection of the defence by comparison to standard photos, using linguistic descriptions of condition set out in the Condition Assessment Manual (Glennie *et al.*, 1991). At this basic level no precise measurements are made. Although grading defences on a scale of 1–5 is useful to an extent, it provides rather limited information about the defence's proneness to failure and its performance (Dawson and Hall, 2001). Although the grading is implicitly based on consideration of defence behaviour, it falls short of the explicit consideration of specific failure mechanisms in the US Army Corps of Engineers condition grading methodology for coastal, port and waterway structures (McKay *et al.*, 1999; McAllister and Ellingwood, 2001). In the UK more detailed assessments have only partially been implemented in England and Wales as recommended (NRA, 1993; MAFF, 1999). These assessments involve more detailed consideration of the defences' actual condition and may require more advanced surveying including levelling, underwater inspections and geotechnical testing.

There is some reluctance in both the dams and the flood defence sector to adopt reliability methods. Amongst the rather complex reasons for this reluctance (Blockley, 1999a) are the recognized limitations of existing models of failure mechanisms and scarcity of data.

Civil infrastructure asset management decisions are a multi-disciplinary endeavour involving a complex set of technical, economic and environmental issues (Hsieh and Liu, 1997; Chowdhury *et al.*, 2000; Hastak and Abu-Mallouh, 2001). Individuals are engaged in cycles of decision-making in their own domain, which contribute to key points of resource commitment in the collective process (Mintzberg *et al.*, 1976; Boland *et al.*, 1990). Yet, particularly in the public sector, it was unclear when and by whom these decisions were actually taken, being the result of negotiation processes that take place in parallel at several levels within the organization.

The processes of options analysis and evaluation can involve assembling and manipulating vast quantities of evidence. The evidence will appear in a range of formats, including dense numerical model results, textual evidence in technical reports, analogous cases, expert judgements, and perceptions and value judgements from the wider stakeholder group. In other words the evidence appears at very different levels of granularity and does not lend itself to being compressed into a single format. Whilst there may be a large volume of information relating to a decision, it is on the whole only of partial relevance, incomplete and sometimes conflicting.

A further characteristic of the domains being addressed is the growing awareness of the impacts of uncertainty and the need for improved decision-making. The quest for improved decision-making is being driven by intensifying organizational and cultural change. Decision-makers in both the public and private sectors are under great pressure to use resources efficiently. There are also increasing demands to identify and mitigate adverse impacts of asset management decisions. At the same time in-house expertise has been reduced due to down-sizing and out-sourcing of technical services. As a consequence, and also due to greatly improved communication and modelling technologies, decision-makers are facing intense information processing demands (Hall and Davis, 2001).

In the light of the analysis of current practice reported above, the following needs for decision support were identified:

- to assemble evidence about asset condition and performance from diverse sources and represent it in a common and coherent model;
- to externalize expert judgements;
- to provide a commentary on sources and implications of uncertainty in the evidence;
- to provide a platform for testing the implications of alternative asset management options (including data collection options);
- to facilitating dialogue between experts and other decision stakeholders.

3 KEY PRINCIPLES

The challenges outlined above have been addressed by the development of generic principles and a software tool that helps the non-expert user to implement those principles in a straightforward way. The following key principles are proposed:

1. The infrastructure system of interest is described *hierarchically.*
2. The hierarchy is constructed by considering the *processes* that the system enacts.
3. Performance of all systems and sub-systems is described by a *Figure of Merit*, which is a non-dimensional measure, on a 0 to 1 scale, of how the system is performing against objectives.
4. The Figure of Merit is calculated by assessing evidence of performance from either or both of two sources:
   - the Figures of Merit of sub-systems that are below the system of interest in the hierarchical system model, and
   - *Performance Indicators* that are associated with the system of interest.
5. Evidence of performance is assembled from all available sources, ranging from monitoring measurements and inspection records, design calculations and model studies to expert judgements, analogous cases and accounts of past failures. All of these types of evidence may be used as Performance Indicators.
6. Performance targets are expressed as *value functions*, which map from the (usually dimensional) scale of the particular Performance Indicator to a non-dimensional scale of performance relative to objectives.
7. Uncertainty in Performance Indicators, value functions and Figures of Merit is handled explicitly.
8. Asset managers may be interested in specific aspects of performance, for example cost, safety or environment, as well as the overall Figure of Merit, so it is possible to isolate system performance and Performance Indicators that relate to these aspects.

The main elements of the proposed modelling approach are illustrated in Figure 1. The photograph on the bottom left hand side of the diagram represents the “real” system of interest, in this example a reservoir system. Abstracted from this are measurements of performance (where the term “measurement” is used in its most general sense, as discussed above) and a hierarchical system model. The Performance Indicators are associated with one or more relevant sub-systems in the hierarchical model. Value functions are based on organisational values and objectives, codes of practice and company and regulator standards. Performance Indicators are projected through value functions and weighted to generate a Figure of Merit for each sub-system. A revised set of weightings is used to generate Figures of Merit for specific aspects of system behaviour.

The conceptual and theoretical structure of the proposed approach is now addressed in detail.

3.1 Process

A process is a purposeful activity, in the sense that it enacts a transformation in a controlled manner. Process is a fundamental construct in the analysis of purposeful systems like civil engineering infrastructure systems. The transformation is enacted by some sub-system within the overall system under consideration. There is therefore a link between the process that delivers a desired response and the sub-system that enacts the process. The sub-system may be “hardware”, “software” or “bioware” (Wymore, 1993). The concept of process

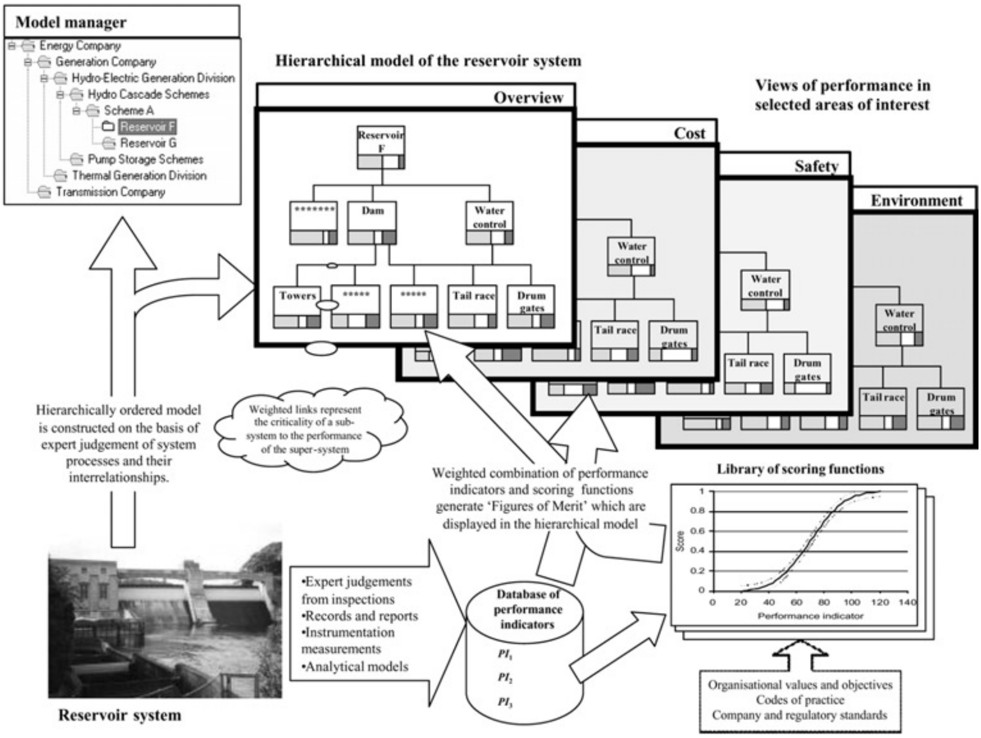

FIGURE 1 Schematic of the model.

therefore combines in generic terms "hard" and "soft" aspects of general systems, helping to overcome the traditional and rather unproductive distinction (Blockley, 1999b). A process perspective emphasizes dynamic nature of infrastructure systems, focussing on how they deliver performance.

There are very many ways of representing a process, some of which are commonplace and others less so. Examples are a simple input–output-transformation model, a flow chart, a PERT chart and a critical path network. These are essentially models describing the relationships between events, usually through time. In complex dynamic situations, process modelling becomes practically impossible without computer support, and a number of tools are now available, such as IPSE 2.5 and its successor Processwise (Snowdon, 1990; Warboys and Snowdon, 1998), IDEF-0 (Colquhoun *et al.*, 1993), RAD (Ould, 1995) and ARIS (Scheer, 1998). In the current research the aim has not been to develop workflow description of the process, but rather an overview of the system at a range of levels of resolution. A hierarchical process-oriented view of infrastructure systems has therefore been adopted.

3.2 Hierarchical Representation of Processes

The system of interest is represented by a hierarchical model of nodes and links. Higher levels represent more abstract descriptions of the system, whilst lower levels will be more closely related to elements of the physical system. The extent and structure of the network is at the discretion of the user, but can be extended up to the highest-level processes within the organisation and down to whatever level of detail is appropriate. The aim is to structure the problem in a way that forms the basis for logical thinking, rational debate and new insights into the decision problem. The notion of hierarchical description of systems is fundamental to systems thinking (Haimes, 1977; Haimes and Jaing, 2001; Checkland, 1981) and well established in practice for infrastructure management (see for example Ezell *et al.*, 2000a; Ezell *et al.*, 2000b; Hastak and Abu-Mallouh, 2001).

Constructing a hierarchical process model usually begins with identification of the high level processes that reflect organisational objectives. These processes are then decomposed into the sub-processes that are required to enact the high level processes. Note that the model is not merely an inventory of the physical elements of the system. Nor is it necessary to replicate the organisational structure. It can include human sub-systems, and should be structured to represent the processes that the sub-systems enact, rather than necessarily representing their physical proximity or connectedness.

As the example Figure 1 illustrates, the hierarchy is a directed acyclic graph rather than being a strict tree structure *i.e.* each sub-system can be connected to more than one super-system. The only constraint on model structure is that it has to be hierarchically layered.

There will inevitably be an element of judgement in the development of model structure, since the criteria for model decomposition are open to different interpretations. However, experience with this approach to hierarchical process modelling (Davis and Hall, 1998) has demonstrated that by using a combination of group sessions and guidance from the process modelling expert it is possible to develop reasonably stable model structures.

3.3 Performance

Performance can be thought of as those aspects of system behaviour that are relevant to meeting objectives. A system may enact several processes, and there will be several perspectives on any given process. However, only the behaviours and perspectives that are relevant to objectives embody the performance of the system (Fig. 2).

Traditionally, performance has been treated in rather crude terms in engineering systems. At the most basic level, performance has been constrained to describing the system as either "failed" or "not failed". This is extended to consider perhaps two performance criteria, serviceability and ultimate limit states. More recently, the move towards performance-based engineering is leading to multi-attribute descriptions of performance under a whole range of loading conditions (SEAOC, 1995; Hirano *et al.*, 2000; Crandall and Freeborne, 2001; Sato and Ogi, 2001). This more general notion of performance has been adopted.

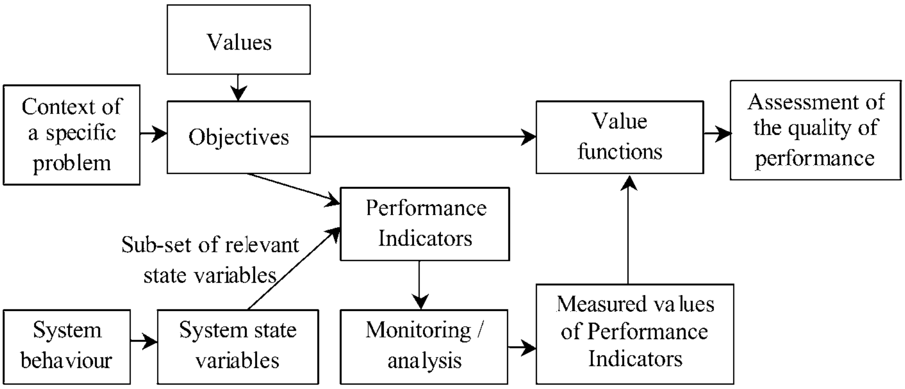

FIGURE 2 Derivation of Performance Indicators.

3.4 Performance Indicators

Evidence about performance of a system or sub-system is provided by a set of *Performance Indicators*. As illustrated in Figure 2, the Performance Indicators represent a sub-set of the system state variables that are relevant to the system objectives. Objectives are themselves derived from organisational and stakeholder values.

High level Performance Indicators may, for example, be the probability of catastrophic failure, the probability of interrupted service to customers or the Net Present Value of an asset. Lower level indicators may, for example, include rates of structural decay and maintenance costs. Evidence of performance is assembled from all available sources, ranging from monitoring measurements and inspection records, design calculations and model studies to expert judgements, analogous cases and accounts of past failures. In the systems being studied, monitoring information tends to be scarce and can be expensive to obtain, so no evidence is excluded by pre-specifying a particular (for example probabilistic) format. Performance Indicators may be derived from monitoring activities or from model predictions of future behaviour, expressed for example as probabilities of failure or fragility curves. The measured value of a Performance Indicator may be a numerical value, but could also be a linguistic statement (*e.g.* "poor" or "very good").

Many measurements of system state variables will require further interpretation in order to be meaningful Performance Indicators. Thus a record of flood defence overtopping does not necessarily represent unsatisfactory performance – in order to make a meaningful statement about performance it has to be compared with the incident loading conditions. It will often therefore be necessary to apply some model to a measurement of system state, or combine it with other measurements, before it can be used as a Performance Indicator.

Many performance-indicators are time varying, in which case it may be the rate of change or higher derivatives that are most informative indicators of performance. By storing time series of Performance Indicators these derivatives can be extracted. Moreover, the original data can be examined and scrutinised for expert interpretation if necessary.

3.5 Valuing Performance: Value Functions and Multi-attribute Weighting

A given sub-system will usually have a range of Performance Indicators associated with it, which may be measured against different dimensions. Therefore in order to generate an overall estimate of the performance of a given sub-system it is necessary to:

1. compare each of the Performance Indicators with targets that represent acceptable performance, or, in general, functions that value performance;
2. weigh the relative importance of the various Performance Indicators;
3. map all of the Performance Indicators onto a common (non-dimensional) scale.

The first two tasks are achieved by mapping the Performance Indicator through a value function that represents how the user rates different levels of performance and maps the Performance Indicator onto a non-dimensional scale. The third task is achieved by applying a weighting to each of the Performance Indicators.

The approach to valuing performance is based on conventional multi-attribute value theory (French, 1988). A given sub-system will usually have a range of Performance Indicators associated with it, which may be measured against different dimensions. These Performance Indicators can be thought of as providing evidence about different attributes of the sub-system. A vector $\mathbf{a}$ of attributes is written $\mathbf{a} = (a_1, a_2, \ldots, a_q)$. The space of $\mathbf{a}$ is $A = A_1 \times A_2 \times \cdots \times A_q$ where A_1 is the set of possible levels of achievement for the first Performance Indicator, A_2 is the set of possible levels of achievement for the second

Performance Indicator, and so on. The symbol $\gtrsim$ denotes weak ordering of preferences *i.e.* $(a_1, a_2, \ldots, a_q) \gtrsim (b_1, b_2, \ldots, b_q)$ indicates that the performance levels $(a_1, a_2, \ldots, a_q)$ are considered by a decision-maker to be at least as good as $(b_1, b_2, \ldots, b_q)$. An ordinal value function v is a function that agrees with these preferences *i.e.*

$$(a_1, a_2, \ldots, a_q) \gtrsim (b_1, b_2, \ldots, b_q) \Leftrightarrow v(a_1, a_2, \ldots, a_q) \gtrsim v(b_1, b_2, \ldots, b_q) \tag{1}$$

There exists a linear value function

$$v(\mathbf{a}) = w_1 a_1 + w_2 a_2 + \cdots + w_q a_q \tag{2}$$

where $w_1, w_2, \ldots, w_q$ are weights, agreeing with $\gtrsim$ on A if and only if the following two conditions apply:

(i) There are constant relative trade-offs between every pair of attributes, *i.e.* for every pair (a_i, a_j) of attributes there is a constant ratio ρ_{ij}:1 such that

$$(a_1, a_2, \ldots, a_i, \ldots, a_j, \ldots, a_q) \sim (a_1, a_2, \ldots, a_i + \rho_{ij} k, \ldots, a_j - k, \ldots, a_q)$$

for any k, positive or negative, where $\sim$ denotes indifference.

(ii) Preferences are monotonic *i.e.* for any $\mathbf{b}$ and any $\lambda > 0$, $\mathbf{b} + \lambda \mathbf{a} > \mathbf{b}$, and $\mathbf{a} > \mathbf{0}$, where $\mathbf{0} = (0, 0, \ldots, 0)$.

The approach adopted here involves first mapping each Performance Indicator a_i through a value function $v_i(a_i)$ and then applying a linear weighted combination:

$$v(\mathbf{a}) = w_1 \cdot v_1(a_1) + w_2 \cdot v_2(a_2) + \cdots + w_q \cdot v_q(a_q) \tag{3}$$

and for convenience normalise so that

$$\sum_{i=1}^{q} w_q = 1 \tag{4}$$

$v(\mathbf{a})$ is referred to as the Figure of Merit for the system or sub-system in question (Wymore, 1993). In Eq. (3) it is therefore assumed that the conditions (i) and (ii) above apply to the transformed quantities $v_1(a_1)$, $v_2(a_2), \ldots, v_q(a_q)$. The justification is that whilst conditions (i) and (ii) may under some circumstances be inappropriate for the original attribute measurements (for example when a decision-maker is indifferent to the value of a particular attribute unless it exceeds some critical value), conditions (i) and (ii) are not unreasonable, once the values have been transformed by a function v_i that reflects the relative importance of different values of a_i. This is reasonable, provided appropriate values of w_i are used and unless q is large in which case the effect of any individual a_i may be rather small.

Figure 3 illustrates the general shapes of value functions $v_i(a_i)$ that have been adopted. Codes of practice or regulatory thresholds are equivalent to a stepped value function (Fig. 3a) – performance one side of the threshold is "acceptable" and given a score of 1, whilst performance on the other side is "unacceptable" and given a score of 0. Under some circumstances it will be desirable to "smooth" the stepped value function, which is the S-shape function (Fig. 3c). Economic benefits will conventionally be represented by a linear (Fig. 3a) or decreasing marginal value (concave) function (Fig. 3b).

The value function has to be chosen by the user in the light of organisational objectives, codes of practice, regulatory standards etc. This is not a straightforward task, though there is

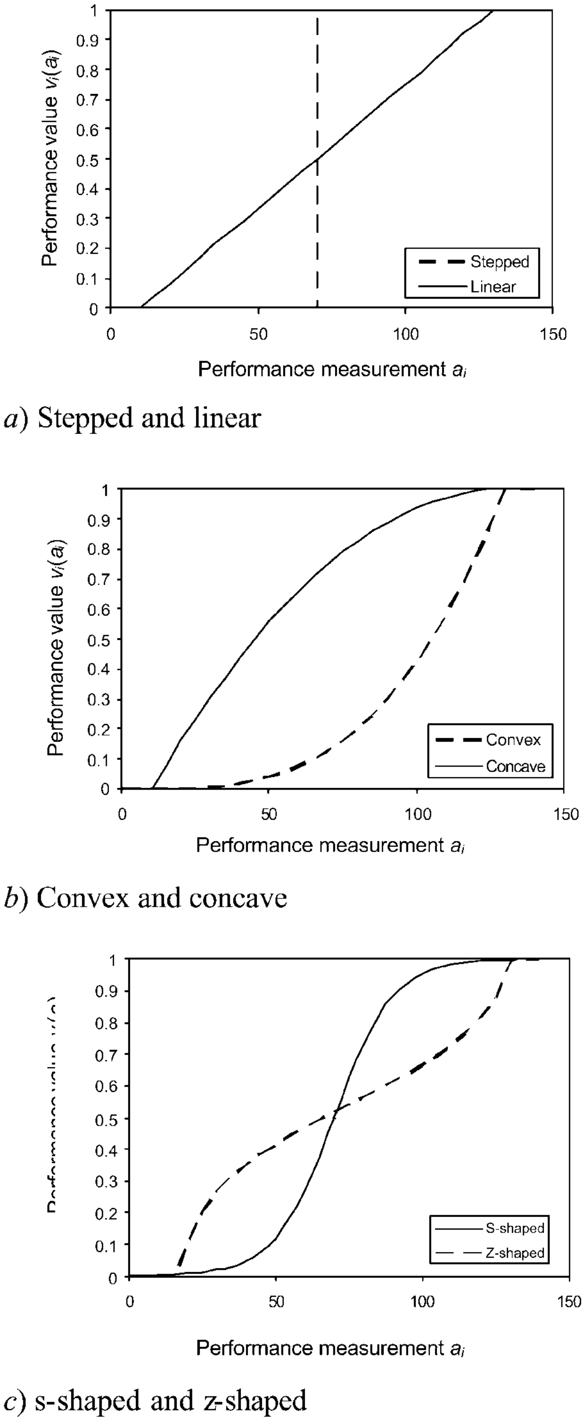

FIGURE 3 Shapes of value function curves.

an extensive literature on elicitation of value functions (Raiffa, 1968; Keeney and Raiffa, 1976; De Neufville, 1990). The process of eliciting preferences and scrutinising them to rational construction in the form of value functions $v_i(a_i)$ and a set of weights w_i can yield important and sometimes unexpected insights, as the case study described in the following section illustrates.

3.6 Propagating Evidence Through the Hierarchy

Besides the evidence from the Performance Indicators associated with a given system, the performance of its sub-systems also provides evidence of performance. In other words, as well as being *measured locally* evidence about performance is *propagated* through the hierarchy. The amount of evidence provided by sub-systems depends on the criticality of those sub-systems to the performance of the system. The lowest-level sub-systems in the hierarchy will just have measured evidence of performance, but all other systems will have propagated evidence and will usually also have locally measured evidence. Propagation of evidence is achieved using the uncertain inference mechanism of Interval Probability Theory (Hall *et al.*, 1998) and is discussed in Section 4 below.

3.7 Specific Aspects of System Attributes

The Figure of Merit provides a summary of system performance against a range of objectives. Asset managers may be interested in seeing how the system is performing against specific objectives, for example, cost, safety or environment. This is achieved by applying a different weighting to each Performance Indicator according to the aspect of system performance under consideration. So, for example, the number of days lost due to accidents on a given system can apply to the safety aspect, but perhaps also to cost and operations. By weighting the Performance Indicators in this way it is possible to generate multiple views of the system for a range of different aspects, as illustrated by the multiple sheets on the upper right hand side of the diagram in Figure 1.

The Figure of Merit $v_S(\mathbf{a})$ which describes the performance of a sub-system with respect to aspect S, is given by

$$v_S(\mathbf{a}) = w_{1,S} \cdot v_1(a_1) + w_{2,S} \cdot v_2(a_2) + \cdots + w_{q,S} \cdot v_q(a_q) \tag{5}$$

where $w_{i,S}$ is the specific weight set relating to aspect S. If a given Performance Indicator is irrelevant to aspect S, then its weight is set to zero. Under some circumstances it may be appropriate to also specify a value function $v_{i,S}(a_i)$, specific to the aspect under consideration, though the default condition is that the general function $v_i(a_i)$ is adopted.

4 HANDLING UNCERTAINTY

Performance Indicators and Figures of Merit will inevitably have uncertainty associated with them. The uncertainty will be both due to variability in measurements and predictions and due to epistemic uncertainties in their dependability.

The Figure of Merit can be interpreted as a measure of belief in the hypothesis that the given system or sub-system is performing satisfactorily. In other words it can be interpreted as a subjective probability $P(H)$ of the truth of the proposition H, where H is “the system is performing well”. A probability interval is used to represent the uncertainty in this belief measure. This approach to uncertainty handling is founded in the mathematical theory of evidence (Shafer, 1976; Klir and Folger, 1988). The aim is to provide a useful support to reasoning with uncertainty in the complex socio-technical situations with vague and often incomplete evidence, areas where Bayesian theories of probability have been most challenged (Henkind and Harrison, 1988; Shafer and Pearl, 1990; Krause and Clark, 1993). In the current research the aim was to use a relatively straightforward approach to evidential reasoning, called Interval Probability Theory (IPT) (Cui and Blockley, 1990; Hall *et al.*, 1998), which retains the desirable properties that have made evidence theory more attractive than conventional Bayesian approaches:

1. IPT represents in a fairly straightforward manner aspects of ambiguity, conflict, randomness and incompleteness in evidence. Aspects of fuzziness can also be conveniently captured through the adoption of hierarchical knowledge structures.
2. The axioms of IPT provide a balance between, on the one hand, not being so weak as to provide inferences that are of limited practical use, yet on the other hand not artificially constraining the problem implying less uncertainty than is in fact the case.
3. IPT conveniently represents dependency relationships between evidence. Dependency is an important issue in complex evidential situations.
4. IPT can also capture a range of inferential relationships between levels in the evidence hierarchy.

IPT is closely related to probability theory, but, in common with belief and plausibility measures (Shafer, 1976), necessity and possibility measures (Zadeh, 1978) and mass assignments (Baldwin *et al.*, 1995), it is not necessary to exclusively allocate probability to a conjecture or its negation. Thus if E is a proposition about the satisfactory performance of a system,

$$P(E) \in [S_n(E), S_p(E)] \tag{6}$$

where $S_n(E)$ is the lower bound, and $S_p(E)$ is the upper bound of the probability $P(E)$. The negation is

$$P(\bar{E}) \in [1 - S_p(E), 1 - S_n(E)]. \tag{7}$$

If, as here, an interval probability is interpreted as a measure of belief, then $S_n(E)$ represents the extent to which it is certainly believed that E is true or dependable, $1 - S_p(E) = S_n(\bar{E})$ represents the extent to which it is certainly believed that E is false or not dependable, and the value $S_p(E) - S_n(E)$ represents the extent of uncertainty of belief in the truth or dependability of E. Three extreme cases illustrate the meaning of this interval measure of belief:

$P(E) \in [0, 0]$ represents a belief that E is certainly false or not dependable,
$P(E) \in [1, 1]$ represents a belief that E is certainly true or dependable, and
$P(E) \in [0, 1]$ represents a belief that the status of E is unknown.

A simple graphical representation has been adopted to display this interval-valued Figure of Merit (Fig. 1). Each sub-system has a coloured bar (an "Italian flag") associated with it, which is a graphical representation of the interval-valued Figure of Merit (Blockley and Godfrey, 2000). The green proportion represents the evidence for satisfactory performance, the red proportion represents the evidence against satisfactory performance and the white proportion represents the uncertainty. The Italian flags provide an immediate overview of system performance, enabling the user to identify areas of poor performance and their implications.

A special case of uncertainty is when Performance Indicators are recorded as linguistic values, for example on a five-word scale from “very poor” to “very good”. If information on confidence in the linguistic judgement is also obtained, again on a five-word scale, then it is possible to use these two pieces of information to generate in interval measure, again on a [0, 1] scale (Fig. 4). So, for example a judgement of “good” performance made with “medium” confidence yields an interval probability of [0.62, 0.87].

4.1 Dependency

Cui and Blockley (1990) developed previous work on interval representations by introducing the parameter ρ, which represents the degree of dependence between propositions E_1 and E_2:

$$\rho = \frac{P(E_1 \cap E_2)}{\min(P(E_1), P(E_2))}. \tag{8}$$

Thus $\rho = 1$ indicates that $E_1 \subset E_2$ or $E_2 \subset E_1$ (*i.e.* they are nested propositions), whilst if E_1 and E_2 are independent

$$\rho = \max(P(E_1), P(E_2)) \tag{9}$$

so that

$$P(E_1 \cap E_2) = P(E_1) \cdot P(E_2). \tag{10}$$

The minimum value of ρ is given by

$$\rho = \max\left[\frac{P(E_1) + P(E_2) - 1}{\min(P(E_1), P(E_2))}, 0\right] \tag{11}$$

where $\rho = 0$ indicates that E_1 and E_2 are disjoint.

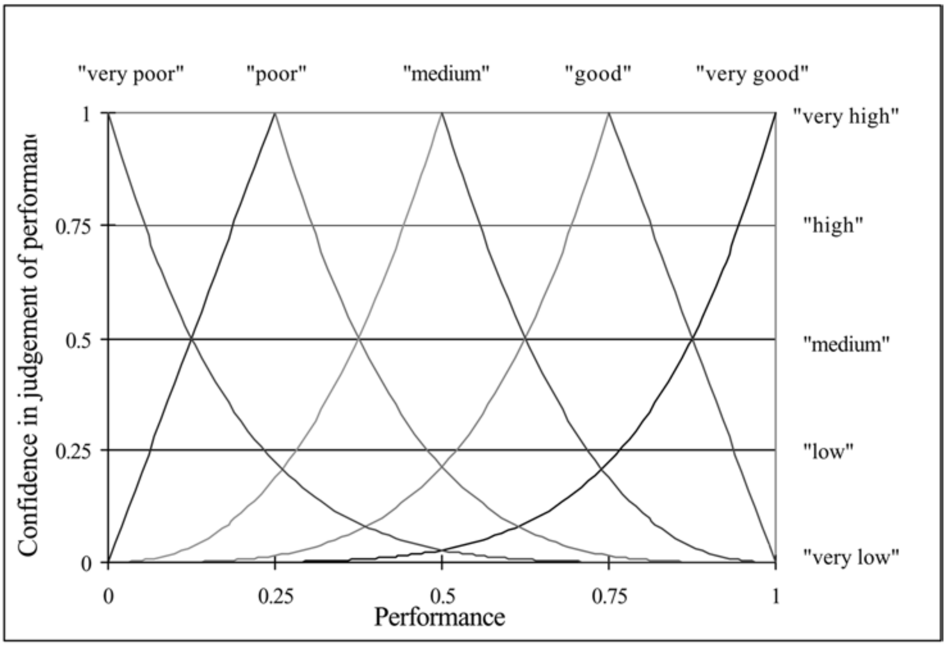

FIGURE 4 Mapping from linguistic descriptions of ‘performance’ and ‘confidence in judgement of performance’ to interval values of performance.

If ρ is defined as an interval $[\rho_l, \rho_u]$ then

$$S_n(E_1 \cap E_2) = \rho_l \cdot \min(S_n(E_1), S_n(E_2)) \tag{12}$$

$$S_p(E_1 \cap E_2) = \rho_u \cdot \min(S_p(E_1), S_p(E_2)) \tag{13}$$

$$S_n(E_1 \cup E_2) = S_n(E_1) + S_n(E_2) - \rho_l \cdot \min(S_n(E_1), S_n(E_2)) \tag{14}$$

$$S_p(E_1 \cup E_2) = S_p(E_1) + S_p(E_2) - \rho_u \cdot \min(S_p(E_1), S_p(E_2)). \tag{15}$$

The dependency parameter ρ is an additional item of information, which is elicited in order to address explicitly the dependency between propositions. It is a convenient means of exploring different dependence relationships when the exact nature of dependence is uncertain.

Dependency can be interpreted as being due to evidence originating from a common source or being influenced by common processes. So for example there would be a high dependency between the age of an asset and its condition recorded upon inspection. Both pieces of evidence could be used in an assessment of performance, but if they were combined without recognising the dependency then the overall evidence for satisfactory performance may be overestimated.

4.2 Logical Inference

The next step is to address the relationship between propositions $E_1, E_2, \ldots, E_n$ about performance of sub-systems $1, \ldots, n$ and some hypothesis, H, about the performance of their super-system. $E_1, E_2, \ldots, E_n$ partition the universe of discourse into k mutually exclusive and collectively exhaustive sub-sets, $\theta_1, \theta_2, \ldots, \theta_k$, where $k = 2^n$. A relatively straightforward solution to measuring the degree of support for H is based on the total probability theorem, which is in this context is usually thought of as Jeffrey's rule of conditioning (Jeffrey, 1983; Pearl, 1988; Schum, 1994). The total probability theorem is axiomatic in probability theory:

$$P(H) = \sum_{i=1}^{k} P(H|\theta_i)P(\theta_i). \tag{16}$$

Jeffrey's rule uses this structure as a method of estimating the degree of belief in a hypothesis, H, given inconclusive evidence about some propositions that influence H. Here $P(H|\theta_i)$ is the probability of H, as if θ_i were true. $P(\theta_i)$ represent uncertain belief in θ_i, given available information e. The situation, expressed in these terms, is represented by the Bayes conditionalization formula (Pearl, 1988)

$$P(H|e) = \sum_{i=1}^{k} P(H|\theta_i, e)P(\theta_i|e). \tag{17}$$

Application of Jeffrey's rule requires that the hypothetical probability $P(H|\theta_i)$ is conditionally independent of the information e that happens to be available at any given instance, *i.e.*

$$P(H|e) = \sum_{i=1}^{k} P(H|\theta_i)P(\theta_i|e) \tag{18}$$

The probabilities $P(\theta_i|e)$ ($i = 1$ to k) are derived, as outlined above, from (equivocal) judgements of belief in $E_1, E_2, \ldots, E_n$ on the basis of available evidence e and the dependencies between $E_1, E_2, \ldots, E_n$. The hypothetical probabilities $P(H|\theta_i)$ determine the relationship between the θ_is and H.

Consider the case in which $n = 1$, so the space of propositions is partitioned between two subsets E and $\bar{E}$, *i.e.* $\theta_1 = E$ and $\theta_2 = \bar{E}$, and

$$P(H) = P(H|E)P(E) + P(H|\bar{E})P(\bar{E}). \tag{19}$$

Dubois and Prade (1990) showed that when all the terms are expressed as intervals the bounds on $P(H)$ are

$$\left.\begin{array}{ll} S_n(H) = S_n(H|E)S_n(E) + S_n(H|\bar{E})(1 - S_n(E)); & S_n(H|E) \geq S_n(H|\bar{E}) \\ S_n(H) = S_n(H|E)S_p(E) + S_n(H|\bar{E})(1 - S_p(E)); & \text{otherwise} \end{array}\right\} \tag{20}$$

and

$$\left.\begin{array}{ll} S_p(H) = S_p(H|E)S_p(E) + S_p(H|\bar{E})(1 - S_p(E)); & S_p(H|E) \geq S_p(H|\bar{E}) \\ S_p(H) = S_p(H|E)S_n(E) + S_p(H|\bar{E})(1 - S_n(E)); & \text{otherwise} \end{array}\right\} \tag{21}$$

The conditional probability terms (corresponding to the $P(H|\theta_i)$ terms in Eq. (16)) are a feature of the structure of the inference problem. For example E may be a *necessary* condition for H, in which case

$$P(H|E) \leq 1 \qquad P(H|\bar{E}) = 0, \tag{22}$$

or E may be a *sufficient* condition for H, in which case

$$P(H|E) = 1 \qquad P(H|\bar{E}) \leq 1. \tag{23}$$

In the special case when E is a *necessary* and *sufficient* condition for H

$$P(H|E) = 1 \qquad P(H|\bar{E}) = 0. \tag{24}$$

A weaker and more general condition is when E is *relevant* or *partially sufficient* to H, in which case

$$0 < P(H|E) \leq 1 \qquad 0 \leq P(H|\bar{E}) \leq 1. \tag{25}$$

Hall *et al.*, (1998) provide a worked example of the inference calculation for $n = 2$ and explain how the bounds on $P(H)$ can be found in the general case.

In the context of performance modelling in systems necessity and sufficiency can be thought of as follows:

Sufficiency is a measure of the amount of influence a given sub-system has on the performance of its parent or super-system.

Necessity is a measure of the extent to which failure (non-performance) of a sub-system will cause failure (non-performance) of its parent super-system.

From these definitions it can be seen that necessity is related to failure or poor performance whereas sufficiency is related to the positive contribution that performance of a sub-system makes to a super-system.

4.3 Merging Measured and Propagated Evidence with IPT

For any sub-system, other than bottom level sub-systems, there may be evidence from two sources.

1. There is the Figure of Merit, derived by projecting the Performance Indicators through value functions (Eq. (1)) and then merging (Eq. (2)). This is the *measured* evidence of performance.

2. There is the interval probability derived from the Figures of Merit of the sub-systems and their relationship with the system in question [Eq. (16)]. This is the *propagated* evidence of performance.

These two sources of evidence can be thought of as providing two different “proof paths” concerning the hypothesis that the system in question is performing satisfactorily. These two different sources of evidence are treated as two different Performance Indicators as discussed above. If monotonicity and constant relatsive trade-off between these two attributes is assumed (and it is reasonable to do so), a linear weighted combination [Eq. (2)] can be used to combine them to obtain a merged Figure of Merit, which is displayed as the “Italian flag” in the system model.

5 APPLICATION

The method outlined above has to date been implemented in a case studies for a major hydro-power generator in the UK (Scottish and Southern Energy) and the UK government agencies responsible for flood defence (the Environment Agency) and highways (the Highways Agency). The Scottish and Southern Energy (SSE) study is described briefly here.

To assist application, the methodology has been implemented in a Windows-based software tool. The tool comprises of a hierarchical systems model linked to a database of performance indicators, with the following key elements:

1. A graphical tool for drawing hierarchical models.
2. A model manager, to navigate large models and switch between alternative views of special aspects of the system.
3. A database of performance indicators, which is intended to be compatible with an organisation’s database and intranet systems.
4. A library of parameterised value functions, which can be chosen, visualised and adapted by the user.
5. An inference engine for propagation of probability intervals.

5.1 Constructing the Model of the SSE System

The hierarchical model of the SSE system is shown in Figure 5. The high level systems within the hierarchy reflect the company structure and its sub-division into generation, transmission and distribution processes. The focus of the case study was on modelling the processes within the hydro generation department, and this aspect of the model was developed in more detail. In order to fit the model on a single page, only part of the hierarchy is illustrated, however, Figure 5 does show the full height of the hierarchy, from low-level sub-systems that form part of a specific reservoir to high level business processes. Note how each system and sub-system in the model has an “Italian flag” associated with it, which is the graphical representation of the interval-valued Figure of Merit.

The model was constructed iteratively, in discussion with staff at a number of levels in the hydro generation organisation. In the first instance the tendency was for staff to use the company structure as the basis for the model, and when the company structure reflected the processes it enacted this proved to be the most effective decomposition. In general the most robust and rational criterion for model decomposition was consideration of the processes that the system enacted. Each box in Figure 5 represents a complete process, as described in Section 3.1. So for example the “Drum gates” process is not merely the inanimate object,

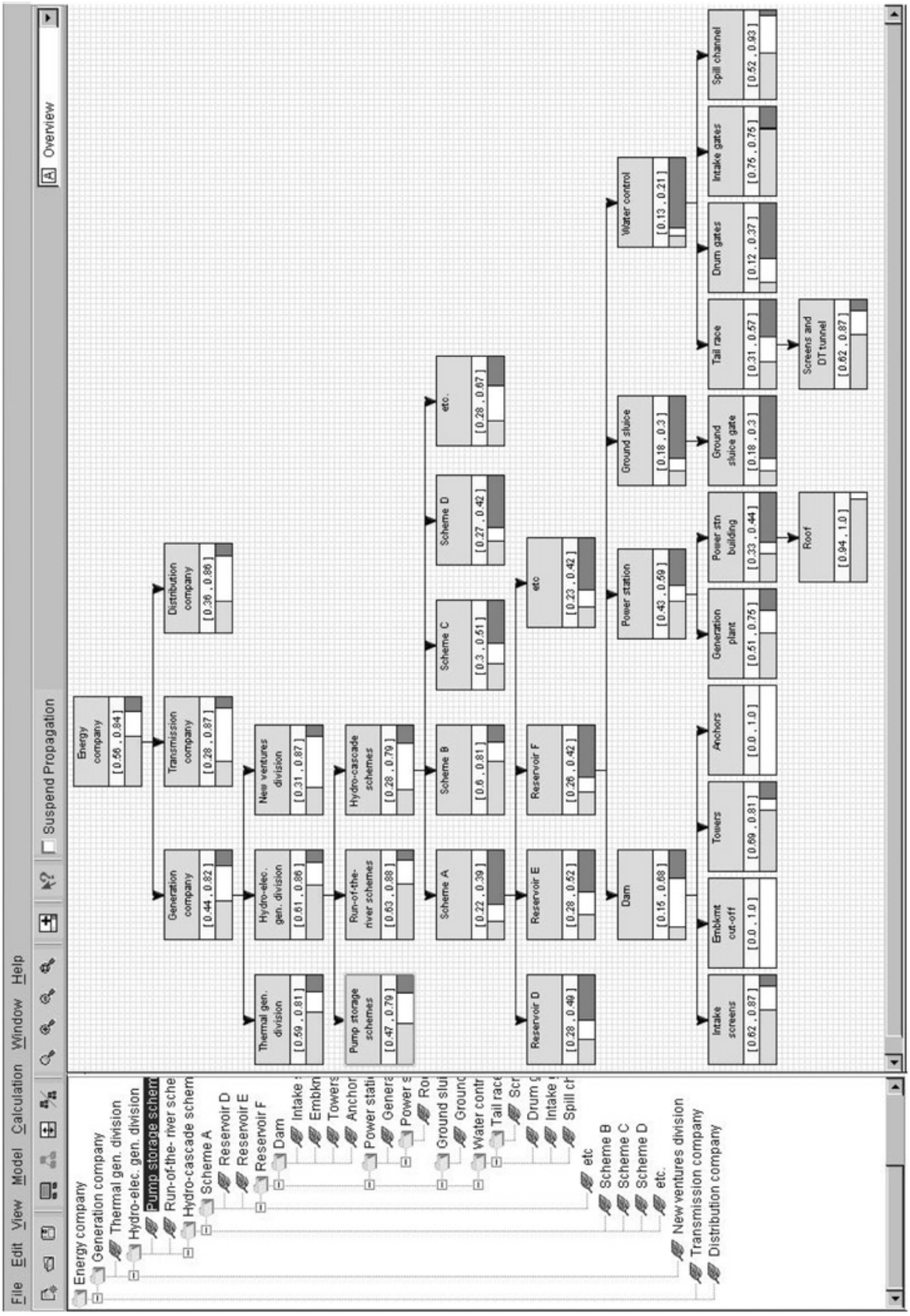

FIGURE 5 Hierarchical model of the SSE system.

but includes the associated control systems and most importantly the people who are responsible for operating, maintaining, inspecting and refurbishing the gate. Successful performance of many of the assets in the company relies upon the knowledge and experience of the people associated with them.

The lower levels in the process hierarchy were strongly influenced by an existing hierarchical structure used by the company in a risk assessment database, which is used to help demonstrate that the company is fulfilling its responsibilities for safety under the Reservoirs Act. However, processes such as "generation plant" that are not critical to reservoir safety so are not included in this database have also been included to the model because they are critical to system performance.

5.2 Obtaining Performance Indicators and Connecting Them with the System Model

In consultation with SSE engineers, a large number of existing Performance Indicators were identified. These Performance Indicators are used in the company for a range of purposes, for example financial management, monitoring safety and planning refurbishment. However, they had not previously been brought together into a single coherent model of the infrastructure system.

A "Key Indicator Report" produced for senior management on a monthly basis, reports on a relatively small number of indicators that give an overview of the performance of the hydro business (these are included in Tab. I). Many of these indicators represent aggregations of Performance Indicators derived originally from individual assets within the infrastructure system. The "Key Indicator Report" includes graphs of monthly performance relative to "budget" targets, which are a reflection of the value functions to be applied to each of these Performance Indicators. Not all the Performance Indicators being measured within the organisation contributed to the model. Some revealed no new information about the state of the system and proved to be redundant for this exercise – a useful insight in its own right.

Further important sources of performance data are the safety inspections conducted in order to comply with the Reservoirs Act, the results of which are held in a risk assessment database as mentioned above. SSE operates a system where inspected components are rated according to an expert estimate of their "probability of failure", "likelihood of detection" and "severity of consequence". In each case the component is rated on a scale of 1 to 5,

TABLE I Typical Performance Indicators Used by Scottish and Southern Energy.

Operational	*Safety*	*Environmental*	*Financial*
Availability	Lifting tackle enforcement orders	Local Authority improvement notices	Overheads
Outages	HSE* diving inspection improvements	Oil pollution enforcement orders	Direct costs
Failures to operate	HSE* improvement notices	Oil pollution reported incidents	Fixed contract income
Machine efficiency (output/water used)	Asbestos pollution events	ISO 14001 accreditation	Non-energy turnover
Output	Reservoir Act enforcement actions	Fish pass availability	Operational capital expenditure
Water storage	Lost time due to accidents		Overtime
Rainfall	Injury absence		Staff absence
Overtime			

*UK Health and Safety Executive.

the product of the three scores is referred to a the “Criticality index”. A similar approach has been proposed by the UK Construction Industry Research and Information Association (CIRIA) for general use in the UK reservoir sector (Hughes *et al.*, 2000). The CIRIA methodology involves a “likelihood of failure” score, a “confidence” score and a “consequence” score. These first two measures are equivalent to the linguistic performance and confidence scores discussed in Section 4 and illustrated in Figure 4. The SSE/CIRIA consequence score, which relates to the relationship between the inspected component and the failure of the system, can be used to estimate the necessity measure used in propagating evidence from subsystems to their super-system. The equivalence of terminology is illustrated in Table II. Thus, for example, an asset assessed as having a “probability of failure” score of 4 in the SSE system, is considered to have “poor” performance in the model. If the SSE database has a corresponding score of 3 for “likelihood of detection” the sub-system would be given an interval score of [0.62, 0.87] in the performance model, using the mapping functions shown in Figure 4.

5.3 Applying Value Functions and Weightings

The Performance Indicators relating directly to “reservoir F” are listed in Table III. The bounds on the accuracy of measurement are quoted along with the measured value, which, when projected through the interval value function generates the interval-valued, non-dimensional measure of performance. In Table IV the Performance Indicators from Table III have been combined using Eq. (2) to give a locally measured estimate of the system performance. Also listed in Table IV are the Figures of Merit of the four sub-systems and the results of the IPT calculations that give the propagated estimate of performance. The local measured performance and propagated performance have then been combined to give an overview Figure of Merit of [0.26, 0.42].

Apart from the performance overview, Table IV also illustrates how specific views of the model relating to “operations”, “financial”, “safety” and “environment” are generated by applying different weight sets. At the lower levels in the hierarchy, as used in this example, there are often only one or two pieces of evidence used in the calculation of performance of a process or component and these generally relate to the operational view. In such instances of sparse data it is not possible to generate different aspects of performance. Hence in the

TABLE II Equivalence Between SSE, CIRIA and Performance Model Terminology.

SSE	*CIRIA*	*Performance model*
	Terminology	
Probability of failure	Likelihood of failure of a particular element	Performance
Likelihood of detection	Confidence in the judgements of likelihood of failure	Confidence
Severity of consequence	Consequence – how directly is failure of the particular element related to failure of the dam (or a higher level process)?	Necessity for success of the super-system
	Range	
1 (=low) to 5 (=high)	1 (=low) to 5 (=high)	1 = very poor to 5 = very good
1 (=low) to 5 (=high)	1 (=low) to 5 (=high)	1 = very low to 5 = very high
1 (=low) to 5 (=high)	1 (=low) to 5 (=high)	Interval on [0, 1]

TABLE III Performance Indicators Relating to 'Reservoir F'.

Performance indicator	*Measured value*	*Shape of value function*	*Performance value*
Availability	79% (±2%)	Convex	[0.46, 0.65]
Lost time due to accidents	0 (precise)	Convex	[0.95, 1.00]
Efficiency (output/ water used)	90% (±2%)	Convex	[0.89, 1.00]
Output	4 GWhrs (±0.1 GWhr)	Convex	[0.27, 0.63]
Rainfall	99 mm (±10 mm)	S-shaped	[0.67, 0.84]
Overtime	267 hrs (±20 hrs)	Convex	[0.44, 0.77]
Failures to start	1 (precise)	Linear	[0.75, 0.95]
Fish count improvement on previous year	−4% (±2%)	S-shaped	[0.35, 0.62]

example shown in Table IV, the propagated Figures of Merit of "water control", "dam", "power station" and "ground sluice" process are the same for each of the operations, financial, safety and environment aspects. However at the next level up in the hierarchy there would be more evidence and the propagated Figures of Merit for each reservoir system would vary with each of the particular aspects.

5.4 Benefits of the Performance Model for SSE

5.4.1 Benefit 1: Learning About the System

The process of constructing a system model and populating it with Performance Indicators has proved to provide valuable insights about the system in question, even before the model is used for analysis or decision-support purposes. The process model provided a focus for high quality constructive debate and learning about the system in hand. By forcing experts to externalise their judgements it enabled an exchange of opinions and arguments, leading to a clearer understanding of the decision. Model building can become an effective tool for introducing participants in a system to one-another as well as allowing them to contribute to and question the system and the processes it enacts. Users have identified this catalytic effect as being one of the main benefits of the approach (Davis and Hall, 2003), which can on its own be expected to improve the immediate and long term performance of the system.

5.4.2 Benefit 2: Providing an Overview of the Performance of the Infrastructure System (Expressed as Figures of Merit) at a Range of Different Levels

The model illustrated in Figure 5 provides insights into the overall performance of the infrastructure system, down to individual asset systems and components. Note the impact of introducing evidence at different levels in the hierarchy. For example, even though the "roof" is performing well there is evidence of poor performance of the "power station building". In this case locally measured evidence is a dominant influence on the Figure of Merit. Note also that whilst at the detailed level many of the Performance Indicators come from the SSE safety inspection system, this information is being used here for broader purposes. Whereas the SSE inspection system focuses on failure, the model presented here allows performance to be assessed in a broad sense, where failure is one extreme of performance.

TABLE IV Calculation of Figure of Merit for 'Reservoir F'.

Performance indicators	*Performance value*	*Weights for overview and specific aspects of performance*				
		Overview	*Operations*	*Financial*	*Safety*	*Environment*
Availability	[0.46, 0.65]	0.18	0.19	0.13	0.00	0.00
Lost time due to accidents	[0.95, 1.0]	0.14	0.15	0.17	0.60	0.00
Efficiency (output/water used)	[0.89, 1.0]	0.14	0.15	0.00	0.00	0.14
Output	[0.27, 0.63]	0.12	0.13	0.25	0.00	0.00
Rainfall	[0.67, 0.84]	0.10	0.10	0.00	0.00	0.29
Overtime	[0.44, 0.77]	0.08	0.08	0.29	0.40	0.00
Failures to start	[0.75, 0.95]	0.14	0.17	0.17	0.00	0.00
Fish count improvement on previous year	[0.35, 0.62]	0.12	0.04	0.00	0.00	0.57
Measured performance		[0.61, 0.81]	[0.63, 0.83]	[0.54, 0.79]	[0.75, 0.91]	[0.52, 0.74]
Sub-processes						
Water control		[0.13, 0.21]	[0.13, 0.21]	[0.13, 0.21]	[0.13, 0.21]	[0.13, 0.21]
Dam		[0.15, 0.69]	[0.15, 0.69]	[0.15, 0.69]	[0.15, 0.69]	[0.15, 0.69]
Power station		[0.43, 0.59]	[0.43, 0.59]	[0.43, 0.59]	[0.43, 0.59]	[0.43, 0.59]
Ground sluice		[0.18, 0.3]	[0.18, 0.3]	[0.18, 0.3]	[0.18, 0.3]	[0.18, 0.3]
Propagated performance		[0.11, 0.25]	[0.11, 0.25]	[0.11, 0.25]	[0.11, 0.25]	[0.11, 0.25]
Weight (measured performance)		0.3	0.3	0.3	0.3	0.3
Weight (propagated performance)		0.7	0.7	0.7	0.7	0.7
Combined Figure of Merit		[0.26, 0.42]	[0.27, 0.42]	[0.24, 0.41]	[0.30, 0.45]	[0.23, 0.40]

5.4.3 Benefit 3: Providing an Indication of the Sources and Implications of Uncertainty

The interval representation of Figures of Merit provides, at a glance, an indication of the sources and implications of uncertainty. The graphical "Italian flag" is particularly powerful in this respect, with the white band representing the proportion of uncertainty.

In this example it can be seen that performance of the dam anchors and cut off is completely uncertain. If this is considered unacceptable, a cost/benefit assessment can be made of the possible options for obtaining data to reduce the uncertainty. Performance of the ground sluice is highlighted as poor, which may lead to a decision to carry out refurbishment work, to achieve a reduction in the criticality index and hence an improvement in performance of the reservoir overall. For any decision, the model provides an audit trail back to original evidence since the model makes use of existing inspection data.

5.4.4 Benefit 4: Providing a Platform for Testing Potential Interventions in the System and the Impacts of Different Information Collection Strategies

The model provides a mechanism for testing options for intervention in the system, by altering the Performance Indicators to represent the values that would be observed in a given scenario. This will often be achieved using predictive models of how the system will behave in different scenarios of intervention. The results from predictive models, and the uncertainty associated with them, can be used as Performance Indicators.

A trial of the model has been carried out in a predictive mode based on two key areas of performance improvement that are currently receiving attention in SSE – turbine generator efficiency and flood gate performance (Smith, 2000; Sandilands and Noble, 1999).

During refurbishment of the Glenmoriston power station it was found that the original turbines had not been optimally matched to the site conditions due to a compromise to allow the same turbine to be installed in two nearby power stations (Smith, 2000). The new turbine installed during refurbishment was found by measurement of performance to have an overall efficiency of 91.5%, a 10% increase on the efficiency of the original turbine. A 10% increase in turbine efficiency was therefore tested as a change in the performance indictor.

SSE have recognised flood gates as having a significant risk associated with them and have initiated a programme of risk assessment and refurbishment (Sandilands and Noble, 1999). The risk assessment of flood gates is part of the overall inspection regime described earlier. A particular example of the data collected for a flood gate assessment is given in Table V. In this example the gate has been given scores of 4 for "probability of failure" and 3 for "likelihood of detection". Based on the criticality indices obtained from assessments of all the SSE gates, a gate refurbishment programme was devised (Sandilands and Noble, 1999). Other data from the risk assessment database show that a refurbished gate may achieve scores of 1–2 for "probability of failure" and "likelihood of detection".

Typical values of 10% increase in turbine efficiency and a reduction from 3–4 to 1–2 in criticality index factors for flood gates, as described above, have been used to predict post-refurbishment performance. These performance improvements and their effects on the interval values in the model of "reservoir F" are shown in Table VI. The trial of the model using these particular data shows that the overall performance of the reservoir system is influenced more significantly by a reduction in the criticality index of the drum gates than by a 10% increase in efficiency of the turbine. This type of comparison has the potential to provide useful insights into refurbishment decision-making. Whilst the example has been

TABLE V Data Collection Sheet Used in the Risk Assessment of a Flood Gate (After Sandilands and Noble, 1999).

Sheet No. 0_0

Scheme Awe 803
Location Barrage Ref. 7
Element Radial gate No. 1 Ref. 53
Component Brakes Ref. 5
Component function Provide automatic braking and holding of gate in set position
Failure mode Binding, slipping Ref.
Cause/trigger Corrosion, brake wear
Effect Gate will either seize in the raised position or drop shut, this will cause either prolonged water release or a surge effect if the gate drops
Knock-on effect likely Y
Multiple failure likely N
Parts affected Gate structure and deck
Overall consequences Surge of flows in the event of gate drop may affect attendants
Preventative actions Maintain brakes as manual
Contingency plans Manual override available
Time to develop (1 min) Probability of Prior Detection of Event M/H
Inspection (12 monthly) Probability of Detection of Failure M/H

Criticality assessment	4	×	1	×	3	=	12
	(Probability of failure)		(Severity of consequences)		(Likelihood of detection)		(Criticality)

FMECA comment The brakes do not at present receive the same attention as the rest of the system

documented with numerical values of Performance Indicators, in decision-making situations it is often more communicative to show alternative versions of the graphical model. In group decision-making situations the model can be actively used to test alternative changes and watch the impact propagate through the hierarchy.

TABLE VI Performance of 'Reservoir F' With Various Scenarios of Turbine Efficiency and Drum Gate Refurbishment.

	Scenario 1	*Scenario 2*	*Scenario 3*
Machine efficiency	80%	90%	80%
Gate criticality	4,3	4,3	1,2
		Figures of Merit	
Reservoir F	[0.26, 0.42]	[0.28, 0.43]	[0.30, 0.50]
Dam	[0.15, 0.69]	[0.15, 0.69]	[0.15, 0.69]
Power station	[0.43, 0.59]	[0.44, 0.60]	[0.43, 0.59]
Ground sluice	[0.18, 0.30]	[0.18, 0.30]	[0.18, 0.30]
Water control	[0.13, 0.21]	[0.13, 0.21]	[0.13, 0.21]
Intake screens	[0.62, 0.87]	[0.62, 0.87]	[0.62, 0.87]
Embankment cut-off	[0.00, 1.00]	[0.00, 1.00]	[0.00, 1.00]
Towers	[0.69, 0.81]	[0.69, 0.81]	[0.69, 0.81]
Anchors	[0.00, 1.00]	[0.00, 1.00]	[0.00, 1.00]
Generation plant	[0.51, 0.75]	[0.65, 0.85]	[0.51, 0.75]
PS building	[0.33, 0.44]	[0.33, 0.44]	[0.33, 0.44]
Ground sluice gates	[0.18, 0.30]	[0.18, 0.30]	[0.18, 0.30]
Tail race	[0.31, 0.57]	[0.31, 0.57]	[0.31, 0.57]
Drum gates	[0.12, 0.37]	[0.12, 0.37]	[0.94, 1.00]
Intake gates	[0.75, 0.75]	[0.75, 0.75]	[0.75, 0.75]
Spill channel	[0.52, 0.93]	[0.52, 0.93]	[0.52, 0.93]

Note: Sub-systems whose performance changes with scenarios are shaded.

6 CONCLUSIONS

Descriptive analysis of current asset management practice within the dam and flood defence sectors in the UK has demonstrated a need for improved ways of assembling and representing diverse evidence about system performance in order to improve decision-making. A decision support methodology has been introduced that aims to address this need by ordering the large number of processes and quantity of information that the decision-maker is expected to assimilate, providing an overview of the system and insights into those areas of the decision complex that are most influential.

The principles of hierarchical process modelling of infrastructure systems have been developed. System performance is established by assembling evidence from diverse sources and condensing it as a Figure of Merit for each sub-system in the model. Many organisations have large numbers of Performance Indicators, but have no straightforward mechanism for making use of them in decision-making. The proposed approach provides a direct link between Performance Indicators and overall system performance. The hierarchical model demonstrates how lower level systems influence higher level performance. More detailed interrogation of the model displays the individual items of information and judgement that the Figure of Merit is based upon.

The approach has the potential to improve communication, forming the basis for discussion and negotiation and enhancing transparency in decision-making. The model provides a guide to where attention and intervention in a system should be concentrated. It thereby provides a mechanism for prioritising asset management actions. Decisions can be readily justified because evidence upon which they are based is recorded in an auditable way. Finally, the approach provides a common platform for individuals engaged in different aspect of the system to work upon. Local technical decisions and higher level business decisions can be explored and justified using the same model, and the influence between these different types of decision-making can be illustrated.

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