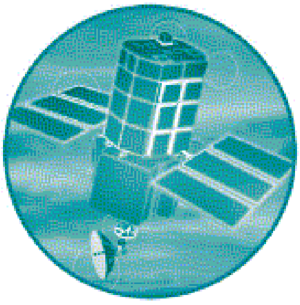
# DEFRA/Environment Agency
# Flood and Coastal Defence R&D Programme



## Condition monitoring and asset management of Flood and Coastal Defence systems

**R&D Technical Report W5A-042/TR**

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DEFRA
Department for
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R&D Technical Report W5A-042/TR

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**Statement of Use**
General information on schematisation of hierarchical flood management systems.
Specific uses in considering flood management systems (as opposed to individual assets) in the Performance Based Asset Management System (PAMS) - a major programme of work under the joint Defra / Environment Agency Flood and Coastal Defence R&D Programme to develop a decision support system for asset management.

**Key Words:**
Infrastructure, Systems, Uncertainty, Decision Support, Flood Defence, Characterisation

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## INTRODUCTION

The Condition Monitoring and Asset Management (CMAM) project addresses the science underlying the management and modelling of complex systems such as a coastal cell or reach of a river. It was motivated by the recognition that academic research on multi-attribute decision making, process modelling, condition characterisation, reliability analysis and uncertainty handling had failed to have a significant impact on a key group of economically important and safety-critical infrastructure systems. These include dams and hydropower systems, flood and coastal defences and related river and shoreline management, and engineered and natural slopes. To address this, the CMAM project brought together a group of seven industrial partners, including a major UK dam owner (Scottish and Southern Energy) and the Environment Agency (the authority responsible for the operation of flood defences in England and Wales). These organisations together with EPSRC (Engineering and Physical Science Research Council) supported two dedicated PhD studentships at University of Bristol and provided access to practical cases within their own organisations.

This represented a significant commitment on the part of the organisations, because whilst the underpinning theoretical approaches were of a sound academic pedigree, they had not previously been brought together in the proposed manner, nor had they been demonstrated in the participating organisations. Moreover, the remit of the research was challengingly (and potentially threateningly) broad in seeking not only to address specific technical issues but also explicitly addressing how these issues collectively contributed to overall organisational and business performance.

From the outset it was clear that the industrial sectors targeted were a subset of a much broader range of sectors to which the research was of potential significance. The choice of sectors was motivated by the recognition by engineers within those sectors of the problems that the research sought to address, as well as by the background of the Investigators. As the research has progressed the potential for much broader applicability has become increasingly clear, as is evidenced by the current commercial application for the Highways Agency, described at the end of this report.

The academic disciplines that research sought to bring to bear on the problems of condition monitoring and asset management were the following:

- *Process modelling*. Modelling of processes is well established in systems and management science. 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 the CMAM project the aim was not 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, drawing on previous work on the topic by Blockley[i,ii], as well as ideas of Rummler and Brache[iii] and developments in process modelling using UML.

- *Uncertainty handling*. The research has built on well-established work on reliability theory, including fuzzy and imprecise generalisations. These approaches, which make use of information in a range of (not necessarily probabilistic) formats, had found limited application in the sectors under consideration, even though their justification is, arguably, particularly strong in these complex and information-scarce situations that are dominated by expert judgements.

A further motive for the research has been the move towards performance-based engineering on both sides of the Atlantic. Performance-based engineering has attracted most attention in the context of seismic engineering of structures in the USA[iv]. Performance-based engineering represents a departure from simple codified objectives for engineering systems (typically labelled as 'ultimate' and 'serviceability' limit states) towards a more explicit treatment of the demands that may be placed on a system and the levels of service that the system is expected to deliver under increasingly severe demands. In developing a methodology that can support performance-based engineering we have drawn extensively upon previous and well-established work on multi-attribute value theory[v,vi].

## KEY ADVANCES AND SUPPORTING METHODOLOGY

The key advances achieved during the research are summarised in order of importance as follows:

1. A new methodology for modelling the performance of complex infrastructure systems has been developed. The methodology merges hierarchical modelling of processes, multi-attribute measurement of performance and uncertainty handling with interval probabilities.

2. The performance modelling methodology has been implemented in a software tool called Perimeta. Perimeta combines a hierarchical process-modelling tool with a database of performance indicators and an inference engine for propagating uncertain information through the hierarchy. A Perimeta model provides a visual overview of system performance and a platform for testing alternative intervention options.

3. New methods for estimating bounds on the probability of failure of deteriorated flood and coastal defence structures, which make use of uncertain information in the form of intervals and fuzzy sets as well as probability distributions, have been developed.

4. A review of current practice in the dam and flood defence sectors has identified main sources of uncertainty in decision-making, limitations of current practice and cases of best practice.

The methodology by which these advances were achieved is discussed, beginning with the review of the current and best practice.

## DESCRIPTIVE ANALYSIS OF THE PROBLEM DOMAIN, UNCERTAINTY AND BEST PRACTICES

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 focussed on Scottish and Southern Energy (SSE) and the Environment Agency (EA). The results of the analysis are reported in the PhD theses of Emma Baker and Richard Dawson, to be submitted in January 2003. In the light of the analysis, 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 facilitate dialogue between experts and other decision stakeholders.

A further key aspect of best practice that emerged at this stage was the move towards a framework for performance-based engineering mentioned in the introduction to this report.

## DEVELOPMENT OF A METHODOLOGY FOR REPRESENTING THE PERFORMANCE OF COMPLEX INFRASTRUCTURE SYSTEMS

The challenges outlined above have been addressed by the development of a methodology for evidence-based performance characterisation of infrastructure systems. The following key principles were 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*[vii], 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 using a combination of interval bounds and interval probabilities.

8. Evidence is propagated through the hierarchy using Interval Probability Theory, modelling the interaction between different sub-processes in the process model.

9. 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.

10. 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 mentioned in (5) above) and a hierarchical system model. The performance indicators are associated

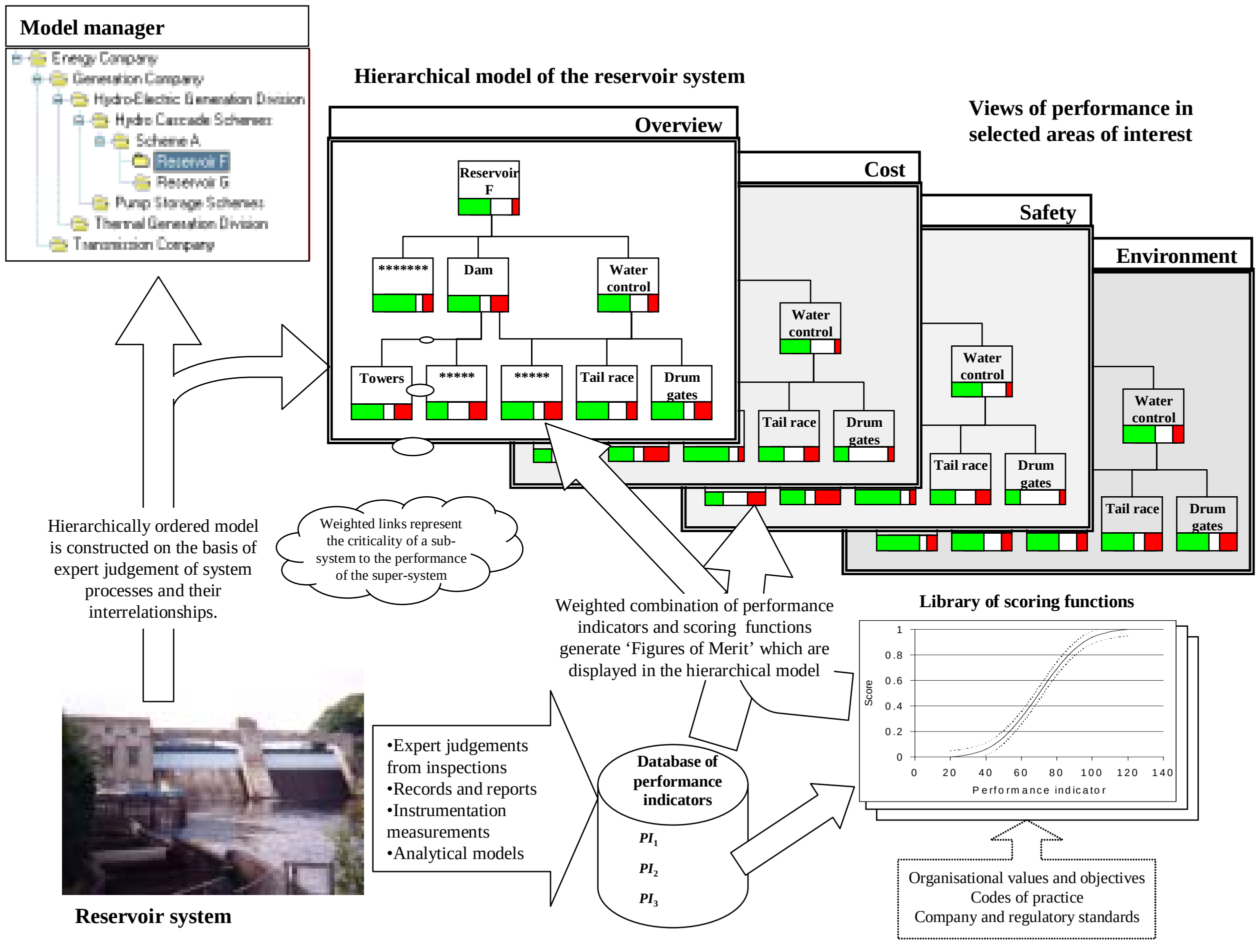


**Figure 1: Overview of the performance monitoring methodology**

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. The figure of merit is expressed as an interval probability of belief that the sub-system or process under consideration is performing satisfactorily. The interval probability is represented as a coloured icon 'Italian flag' where the left hand green portion represents the lower bound on the interval probability of success, the right hand red portion represents the lower bound on the interval probability of failure and the white in the middle represents the uncertainty. A revised set of weightings is used to generate figures of merit for specific aspects of system behaviour.

## PERFORMANCE CHARACTERISATION USING IMPRECISE INFORMATION

Research on condition characterisation did not address new methods of acquiring information about infrastructures. Rather it sought to establish how existing rather scarce and imprecise information could be used better to inform judgements of system performance and decision-making. This approach was motivated by the practical reality of organisations like the EA who are responsible for some 35,000km of flood defence about which they have only limited information and yet have to make efficient decisions about investment in maintenance and upgrading. The format of available information does not lend itself to probabilistic analysis, and transformation to a probabilistic format may result in an unintended overstatement of the information content in the available evidence. The approach adopted has therefore been based on the use of imprecise probability and fuzzy sets to construct imprecise fragility curves (conditional failure probability distributions) for system components. The essentially probabilistic approach means that the information generated can be used in risk analysis of systems, yet the imprecise aspect means that the role of uncertainty becomes quite explicit. The approach has been demonstrated in the context of flood defence embankments:

- The use of the theory of random sets as a general mechanism for handling intervals, probabilities and fuzzy sets has been demonstrated for a flood defence example[viii].
- A new method to use scarce experimental measurements of revetment failure in order to construct imprecise limit state functions and hence generate imprecise estimates of the probability of failure has been developed[ix].
- The use of fuzzy sets to represent imprecise classification of condition grade of defences has been demonstrated[x].
- The effect of structural deterioration and toe scour on the conditional probability of failure has been illustrated for rock revetments and steel sheet pile walls had been demonstrated using simulated time series of wave conditions and imprecise values for the parameters governing structural and beach behaviour[xi].

## DEVELOPMENT OF A DECISION-SUPPORT TOOL

The methodology described in Section 2.2 above could not be implemented, or indeed seriously developed and tested, without the help of a software tool for process modelling, storing performance indicators and conducting interval probability calculations. A Window-based prototype written in C++ was coded during the first year of the research and tested at the second workshop of industrial partners. This was subsequently linked to a spreadsheet that acted as database and inference engine and could be used as a development tool for testing different algorithms. Having agreed upon the proposed approach, a near-commercial quality software tool written in Java was developed during the final six months of the research. The final tool was tested during a full-day workshop with industrial partners who developed a range of process models, making use of a pre-prepared database of performance indicators. It has since been used in industrial settings as discussed in Section 4 below.

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 aspects of the system.

3. A database of performance indicators.

4. A library of parameterised value functions, which can be chosen and adapted by the user.

5. An inference engine for implementing Interval Probability Theory.

## DEMONSTRATION THROUGH CASE STUDIES

Two substantial case studies were conducted during the course of the research. The first addressed the hydro-electric reservoir system of SSE[xii]. The study stretched over almost the entire duration of the project, beginning with scoping visits to SSE's offices and hydro-electric facilities near the start of the project, and followed by iterative development of the model structure and more focussed visits to acquire information on specific performance indicators. The study was conducted jointly by the PhD student Emma Baker and the PDRA Dr Jason Le Masurier. Towards the end of the project Ms Baker and Dr Le Masurier reported on the study to SSE's staff in Perth and made final revisions to the model, based on feedback from SSE staff. The model of SSE addressed all levels in the organisational structure, from high level business processes to detailed technical processes associated with a particular reservoir. In other words only one 'branch' of a hierarchical structure was developed, but the entire height of the hierarchy was represented.

The Environment Agency case study addressed the flood defence system for the town of Burton-upon-Trent. The model included both structural and non-structural (e.g. flood warning, public awareness raising and development control) flood management measures. One of the objectives of the study was to demonstrate how a process model could include all of the individual flood defences and components that are the focus of every day operations and maintenance activities. Associated with these detailed aspects of the system was the monitoring information recorded by the EA on a day-to-day basis.

The two case studies illustrated the following benefits of the proposed approach:

- In both cases the system under consideration was complex and no process model of the whole system existed before the study. The Perimeta model provided a coherent overview of the whole system and an indication of its performance at a range of levels.
- The process of identifying performance indicators and value functions encouraged rational analysis of performance targets.
- The model provided an indication of the sources and implications of uncertainty.
- The model provided a platform for testing potential interventions in the system and the impacts of different information collection strategies. In the SSE case study this was illustrated by assessing the impact that increasing turbine efficiency or improving the condition grade of plant would have on overall performance. In the EA case study the impact of improving condition grade of flood defences was illustrated.

## PROJECT PLAN REVIEW AND EXPLANATION OF EXPENDITURE

The original project plan comprised of four tasks besides project management:

1. *Descriptive analysis of the problem domain, uncertainty and best practice*.

2. *Process modelling*.

3. *Application of uncertainty methods*.

4. *Development and demonstration of condition characterisation*.

5. *Implementation and demonstration of decision support tools*.

These tasks were addressed as explained in Section 2 above. Project expenditure was consistent with the budgeted sums. Mr Janjanam Durgaprasad held the RA post from November 1999 to February 2001 at the grade indicated on the research proposal. His main research activities involved literature review, development (with the Investigators) of the performance modelling concepts, and implementation in C++ and Excel the first mock up and a working research version of the decision support tool. When Mr Durgaprasad left to pursue a more lucrative career in the software industry it was decided to divide the remainder of the budget between two RAs with contrasting skills.

1. Dr Jason Le Masurier held the RA post from January to November 2001, the latter four months being part time with a post as SW regional co-ordinator of Movement for Innovation (M4i). Using the research version of the decision support tool developed previously, Dr Le Masurier implemented the detailed case study for SSE and drafted a journal paper on the methodology and study.

2. Mr Jonathan Evans held the RA post from November 2001 to July 2002 with the sole task of implementing the final near-commercial standard Java version of the Perimeta tool.

The RA time on the project therefore totalled 31 rather than the programmed 36 months but consumed all of the allocated staff budget because Dr Le Masurier and Mr Evans were recruited at higher grades on account of their skills and experience.

Substantial travel costs were associated with liaison with collaborating partners. Two national and one international conference visit were funded from the grant. Additional funding for conference travel was obtained from the Royal Academy of Engineering. Main consumable items were software license and components for development of the Perimeta tool.

## RESEARCH IMPACT AND BENEFITS TO SOCIETY

During the course of the research it has become increasingly clear that the CMAM project has addressed a challenge of widespread industrial significance that has not been resolved in the course of previous academic and industry research. We have been approached by organisations from a variety of sectors who are investing large sums of money in acquiring performance information but are struggling to make sense of that information and use it to target priority areas for investment. The changing infrastructure management environment in Public Private Partnerships and the regulated utilities is placing new emphasis on monitoring the outcomes that are delivered by infrastructure systems.

The CMAM research has demonstrated how a coherent whole system model can be quite readily constructed and then populated with performance indicators. The model provides an overview of system performance and can then be interrogated to provide an auditable route to the performance indicators from which the overview has been abstracted. It can be integrated with an organisational database of performance indicators.

The significance of the CMAM research is demonstrated by the investigators being approached by several industrial organisations who with a view to licensing Perimeta. A contract for £68k has been signed with Halcrow for five software license and consultancy services. The focus of this pilot project for Halcrow has been development of a performance regime for Managing Agent Contracts for the Highways Agency. If this initial project is successful there is considerable potential to extend the approach more widely to asset management within the Highways Agency. A programme of in-house training courses for Halcrow has been agreed upon for 2003. Sale of five Perimeta licenses to FaberMaunsell is currently under negotiation. FaberMaunsell are investigating a range of potential applications in the highways, railway and water industries.

A license agreement has been established with TMX for software support.

The influence of the project is however, broader than the commercial success of Perimeta. The conceptual developments have proved to be of significant impact and will, for example, form the basis for DEFRA's new Flood and Coastal Defence Project Appraisal Guidance Note 6 on

Performance Evaluation. Dr Hall has been contracted to write the conceptual principles of this Government guidance document. The principles are also reflected in a software tool being developed for CIRIA called PPPcom which aims to support the management of risk and value in PPP projects. Although PPPcom does not include all of the functionality of Perimeta it embodies the concepts of hierarchical modelling and use of performance indicators.

## FURTHER RESEARCH OR DISSEMINATION ACTIVITIES

The eight industrial partners involved in the research have been an important dissemination mechanism to industry. Seven conference presentations have been made on the research. Papers reporting on the research have been submitted to the *ASCE J. Infrastructure Systems*[xii] (the paper is now in its second round of reviews), *Structural Safety*[ix] (conditionally accepted) and *Civil Engineering and Environmental Systems*[xiii]. A further paper will shortly submitted to *Water and Maritime Engineering*.

The paper for the *3rd International Conference on Decision-Making in Urban and Civil Engineering*[xiv], held in London in November 2002 was submitted to the 'Industry Challenge' in which a panel comprising of three experienced members, chaired by Prof. Rodney Howes (chair of Construction Industry Council Innovation & Research Committee) identified three showcase papers according to the following criteria:

1. *There must be an identifiable and complete product or process for immediate exploitation by the industry.*

2. *The showcase must be the product of a substantial research work.*

3. *The practical uses and advantages should be clearly explained.*

The paper on the CMAM methodology was ranked second in the short-listing and was showcased during a plenary session of the conference in a joint presentation by Ms Baker and Prof. Patrick Godfrey of Halcrow.

In addition to applying the research in practice, negotiations are under way with Halcrow and FaberMaunsell with a view to funding further research work to extend the methodology developed in the EPSRC project.

The concepts and methodology have been welcomed by the Environment Agency who have decided to include them in the development of a Performance-based Asset Management System (PAMS). The PAMS R&D project, in which Bristol is a research partner, will stretch from 2003-2006, costing £440k. Moreover, it is the Environment Agency's intention to see the asset management concepts developed in the CMAM project carried forwards into research on infrastructure management which will form part of the EPSRC/DEFRA/EA/UKWIR Interdisciplinary Research Consortium in Flooding.

The CMAM concepts will underpin the research to be conducted under our recently approved project "Generic Process for Assessing Climate Change Impacts on the Electricity Supply Industry and Utilities" (GR/S18922/01) which has been funded under the EPSRC Environment and Infrastructure Programme: Impacts of Climate Change on the Built Environment, Transport and Utilities.

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