# UNCERTAINTY ANALYSIS OF COASTAL PROJECTS

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## Abstract

*The nature of uncertainty in coastal engineering is discussed with reference to an empirical study of practising coastal engineers in the UK. This study provided evidence which indicates that a complex multi-disciplinary set of issues are taken into account in decision making only some of which are explicitly articulated. It is argued that current approaches to handling uncertainty based on reliability theory provide an important but incomplete perspective on a rich and complex topic. An approach to uncertainty modelling based on Interval Probability Theory is proposed. Process modelling is used to track the sources of uncertainty in analysis, design and decision making and to integrate different types of evidence. This approach to uncertainty analysis, which involves exploring and accounting for the sources and nature of uncertainty in decision making, is illustrated with reference to sea defence projects on the East Coast of the UK.*

## Introduction

The coastal engineer is confronted with uncertainty in the random nature of hydraulic loads, in the complexity of structural, morphological and environmental responses, in the diversity of decision objectives and in the fallibility of the human systems which implement coastal defences. The engineer is, nonetheless, expected to make dependable, timely and transparent decisions. To do so requires an understanding of the nature of uncertainty and appropriate techniques for managing it.

The research described in this paper is a merger of three streams of enquiry:

1. a programme of interviews with UK experts and practitioners in coastal engineering to elicit contemporary knowledge on the sources and management of uncertainty;

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2. investigation of theoretical approaches to representing uncertainty in hydraulic engineering including probability theory (both frequentist and Bayesian), fuzzy sets, the Dempster-Shafer theory of evidence and interval probability theory;
3. contemporary developments in generic modelling of human and physical processes.

The research is based on a systems approach which takes account of the richness of sensitivities and interactions which characterise both the natural and human aspects of the coastal zone. This research, which lies on the socio-technical interface, is intended to provide a link between the scientific and largely reductionist theoretical approach to engineering practice and the difficulties of actual practice itself. The research has resulted in development of new methods for assessment and management of uncertainty in coastal engineering projects.

This paper begins with a description of an empirical study of the nature and sources of uncertainty in coastal engineering. Some of the limitations of a purely probabilistic approach to representing uncertainty are discussed before introducing an new approach based on process modelling and interval probabilities. An implementation of this approach for decision support is discussed with reference to example projects.

## Descriptive study of practising coastal engineers

Worthwhile decision support tools must be founded on an understanding of the problem domain to which they are to be applied. Decision support systems have failed in the past because they are culturally incompatible with the organisation in which they are applied (Platt, 1994). These problems can be minimised by careful descriptive analysis of the problem domain before proceeding towards decision support.

Descriptive analysis of complex processes on the socio-technical interface is not straightforward. Many of the issues taken into account in decision-making are unquantifiable and may not even be made explicit. To make sense of these issues an investigative technique called Grounded Theory developed by Glaser and Strauss (1967) for field work in the social sciences was used to analyse the problems which coastal engineers encounter in practice. Grounded Theory is a general methodology that aims to develop theory from qualitative data. Theory is in the form of conceptual models of the phenomenon under consideration. The word 'grounded' derives from the concept that the theory generated is 'grounded' in data. Grounded Theory is therefore believed to provide more reliable and more complete understanding than is achievable by conducting an informal consultation exercise or questionnaire surveys. Details of the Grounded Theory study and analysis are reported in Hall et al. (1998a). A series of semi-structured interviews were held with eight practising flood and coastal defence engineers from a variety of backgrounds in the UK. The interview data was analysed in detail with a view to identifying

- characteristics of the decision making process in coastal engineering;
- sources of uncertainty in decision making;
- current approaches to coping with uncertainty.

The interview data demonstrated that

- A complex set of socio-technical issues are taken into account during decision-making only some of which are explicitly stated. Technical issues play an important part but interact with other issues and are not necessarily paramount.

- Individual decisions are integrated in an ongoing infrastructure management process.
- In the UK intuitive and implicit methods of taking uncertainty into account in decision-making are currently much more prevalent than explicit methods. This is despite increasing emphasis on risk-based methods from government and researchers.
- Sources of uncertainty in decision-making are diverse but can be categorised as being 'modelling issues', 'values issues', 'communication', and 'environmental constraints'. The term 'modelling' is being used in the most general sense. The term 'environmental' is used here to refer to surrounding institutional, political and cultural issues outside the immediate control of the decision-maker.

The findings of the empirical study have guided the subsequent research which aims to satisfy identified needs

- to provide a systematic overview of the coastal management process;
- to address the issue of model uncertainly;
- to support the *process* of obtaining and manipulating data and then making decisions;
- to provide a measure of the *dependability* of the processes which lead up to a decision;
- to keep track of the sources and sensitivities to uncertainty in a decision.

## Methods of representing uncertainty

Uncertainty is a rich and diverse topic which has been addressed in quantitative, linguistic and symbolic terms. Of all the methods for handling uncertainty, probability theory has by far the longest tradition and it is the best understood. That of course does not imply that it should be beyond criticism as a method of handling uncertainty. It does, however, mean that it is relatively well tested and well developed and can act as a standard against which other more recent approaches may be measured (Krause and Clark, 1993).

Blockley et al. (1983) argued that the additivity axiom or law of excluded middle in probability theory is an assumption which can be difficult to justify under circumstances involving sparse data and incomplete and possibly inconsistent knowledge. This and other re-evaluations of the axioms of probability theory since the 1970s have lead to the development of various alternative and generalised calculi for quantitative handling of uncertainty, including fuzzy set theory, the Dempster-Shafer theory of evidence, mass assignment theory and interval probability theory which is discussed later in this paper. Hall et al. (1998b) proposed a pragmatic approach to uncertainty where the axioms of the probability calculus are matched to the characteristics of the situation in hand. The fundamental problem with quantitative uncertainty methods is one of mapping messy real world situations onto precise mathematical syntax. Several different approaches can provide useful evidence on which to base a decision.

In coastal engineering, as in other fields, probability theory has been developed into a sophisticated and useful tool. Reliability theory and probabilistic risk assessment are now well established methods for coping with the uncertainty inherent in many of the parameters which coastal engineers input into their models. However it is inevitable

that some of the response functions used in probabilistic models will be more dependable than others. For example quantitative models of breaching the low clay embankments which act as flood defences in many areas of the UK are still of limited dependability. Doubtless quantitative understanding of more challenging failure mechanisms will increase in future. More effective and less intrusive methods of obtaining information about the strength of coastal defence structures will be developed, though for the time being methods of obtaining detailed information about the internal constitution of flood defence embankments are very costly. Nonetheless, there will always be a limit to the level of risk analysis that it is practical and economic to undertake. Some failure mechanisms will always be better understood than others. Decision processes need to reflect that fundamental disequilibrium of information. Without some understanding of the dependability of input distributions and of response functions, the data generated by probabilistic methods can be difficult to interpret and in the wrong hands quite misleading.

It is important to recognise that the numbers generated by reliability calculations are hardly scientific (in the Popperian sense) as they cannot normally be falsified. They are better viewed as deductions from a set of premises. Some of those premises will be better supported by evidence than others. Yet unless a procedure is adopted for recording and auditing the premises used in a reliability calculation the ultimate deduction will be of limited value.

Some attempt has been made to address the issue of modelling or systems uncertainties in the theoretical representations of the physical behaviour of structures by use of one or more extra basic variables in the constitutive reliability equation. The value assigned to this variable may for example depend on whether physical model studies have been conducted or not. The empirical evidence supporting this approach is questionable and, as Blockley (1998) argues, its use is inadequate because the level of sophistication of handling such a difficult and important part of the total uncertainty is very much less than for the relatively straightforward issue of parameter uncertainty.

Structural reliability calculations are therefore now widely recognised as only one part of the assessment of structural safety. The results of such calculations are not 'true' probabilities of failure, rather they are 'notional' probabilities of failure. Even in the relatively constrained context of the process industries, calculations of failure probabilities conducted by independent expert teams around Europe have been shown to typically differ by up to three orders of magnitude and in some cases differences were as large a five orders of magnitude (Lemkowitz et al., 1995). It is not unreasonable therefore to have misgivings about the numbers which are generated in reliability calculations in coastal engineering. These calculations do not generally include the behaviour of individuals and almost never include organisational factors such as organisational culture.

It is clear from the analysis conducted in the UK that engineers have difficulty in communicating even quite basic probabilistic concepts of flood risk, not to mention the distinction between notional and statistical probabilities, to the populations at risk. Reliability calculations are seldom transparent to stakeholders who have an interest in the outcome of those calculations. The consequence of adopting authoritarian technocratic approaches which are not transparent is that the co-operation from politicians and the public, which is necessary to implement flood defence works, will not be forthcoming (Beck, 1992). If therefore engineers are not to undermine their own best endeavours on society's behalf for safety, efficiency and sustainability they need to recognise the social construction of risk and acknowledge that their reliability calculations provide but one rather incomplete perspective on a complex phenomenon.

The normative theory of decision making under risk and uncertainty provides a rational theoretical framework for decision making in coastal engineering. By linking risks with costs it, in theory, provides a mechanism for optimising investment in coastal engineering. However, besides the problems associated with computing probabilities described above, there are profound difficulties in eliciting the value (or utility) functions required to compare the attributes of different options. It may be extremely difficult to project some fuzzy values onto a numerical scales. For example it may be hard to state precisely whether a particular coastal defence is sustainable or not. In order to make a decision experts will usually resort to linguistic descriptions of the sustainability, which cannot be manipulated within normative decision theory.

Moreover, all of the possible outcomes of a decision must be predetermined in precise terms for a probabilistic decision analysis. This limits the applicability of probability theory for coping with fuzzy events or incomplete situations. These problems are becoming more apparent when we address more complex multi-disciplinary problems. For example, there is currently much interest in making the coast more resilient. To do so involves restoring natural systems and enhancing flexibility and diversity. Much of the value of a resilient coastline is its capacity to cope with the unforeseen and unpredictable, in particular climate change. These benefits cannot be fully evaluated in probabilistic terms. Moreover, a resilient coastline will be highly dependent on human systems of monitoring and management. Predicting the reliability of these systems represents a particular challenge in complex, dynamic situations because some behaviour is truly unforeseen and so by definition is not included in the reliability model. Unfortunately many engineering failures are the unforeseen consequences of human actions (Blockley, 1980). Collingridge (1980) suggests that unforeseen outcomes in socio-technical systems can be controlled by:

- monitoring,
- reducing the cost of error,
- reducing the corrective response time,
- reducing the cost of remedy,
- keeping one's options open (adopting flexible solutions, enhancing variety).

The intention of these strategies is to improve the robustness of a plan or design in the face of events which are not predictable by the models available to the planner or designer at the moment of decision making. It may be necessary to weigh the apparent loss of expected value involved in adopting a robust decision, against the apparent loss of flexibility in adopting the "optimal" decision. The balance will tend to favour robustness in conditions of high uncertainty (Rosenhead et al., 1972).

The foregoing arguments should not lead to the rejection of reliability calculations and probabilistic decision theory. Thesc approaches provide important evidence on which to base decisions. However, engineers should recognise the need to broaden their perspective and explore ways of enriching current methods in order to merge qualitative and quantitative perspectives. A systems approach recognises that an infrastructure can be described at a number of different levels of resolution and from a number of different perspectives. Reliability theory can be fitted within this more general framework.

## Process Modelling

The issues raised in the proceeding discussion have been addressed by broadening attention from specific data (which are the focus of probability theory) to include the *process* of obtaining and manipulating data and then making decisions. The quality of a design will inevitably reflect the process by which it was produced (Platt and Blockley, 1994). Modelling both human and physical processes in generic terms is now an important research theme at the University of Bristol. One of the main theoretical and practical challenges is establishing an appropriate model structure. The structure represents the flow of information and control during a project, and in particular the flow of information towards important design and management decisions. Both hierarchical and cyclic models have been explored. In hierarchical terms, process can be modelled using a series of sub-processes. Figure 1 illustrates some of the processes in one of the case studies examined in this research. The hierarchy represents and integrates processes which manipulate evidence of different pedigree, from numerical model studies to more qualitative geomorphological analysis. Note that the process model is a descriptive commentary of how the processes *were conducted*, not a normative model of how the process *should have been conducted.*

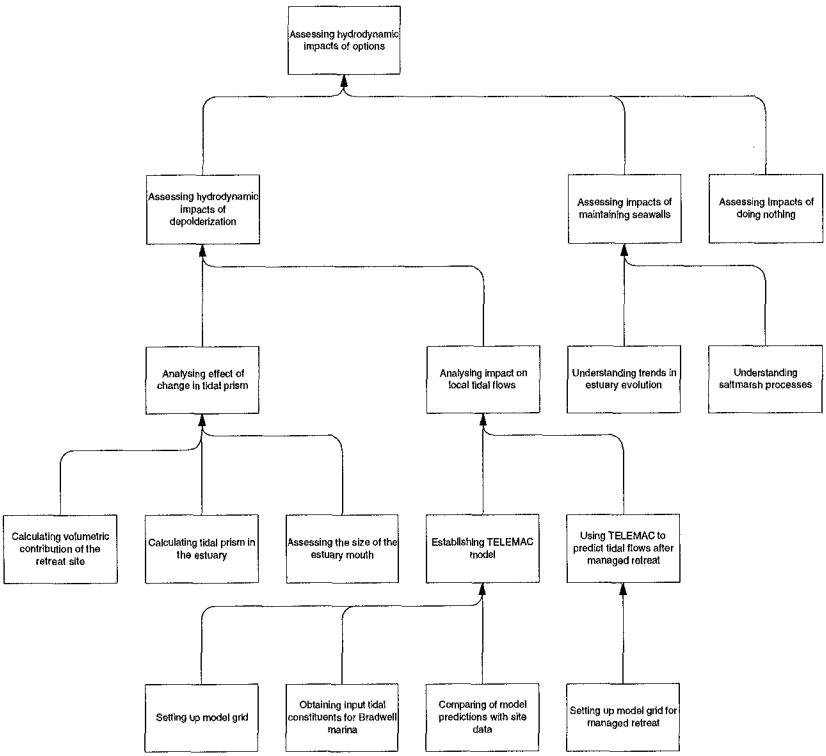


*Figure 1 A section of the process hierarchy relating to the Orplands project*

Engineers should be concerned with the *dependability* of a process to deliver an appropriate level of function - its quality, or fitness for purpose. An understanding of the dependability of a process can be gained by scrutinising the activities which are

involved in that process and considering evidence of their dependability and the interactions between them. Evidence will range from the size of data sets to testimony of the experts involved.

Looking upwards through the process hierarchy, processes become increasingly general in definition. Thus statements of national policy which represent the top level in a hierarchy of concepts are necessarily expressed in fuzzy linguistic terms such as "sound" and "sustainable". In the UK, Shoreline Management Plans are the next stage below national policy in the hierarchy of concepts, defining policy for a given stretch of coastline. Precise statements, often expressed in numerical rather than linguistic terms, are necessary at project and operational levels. Process modelling enables coherent integration of the hierarchical decision making which characterises modern coastal management. The interface between human and organisational processes and physical processes is handled using the same language which should enable clearer and smoother flow of information.

**Interval Probability Theory**

Having established a logical hierarchy of processes the next stage is to find a means of expressing uncertainty in each process. The approach adopted here has been to express the dependability of each sub-process using an interval number and calculate how the various uncertainties affect the processes above them using Interval Probability Theory (Cui and Blockley, 1990). An interval number, on the range [0,1], is used to represent the belief in the dependability of a concept.

$$P(E) = [S_n(E), S_p(E)]$$

where

$P(E)$ is the measure of belief in the dependability of a concept $E$,

$S_n(E)$ represents the extent to which it is certainly believed that $E$ is dependable,

$1 - S_p(E) = S_n(\overline{E})$ represents the extent to which it is certainly believed that $E$ is not dependable, and

$S_p(E) - S_n(E)$ represents the extent of uncertainty of belief in the dependability of $E$.

Evidence or belief is mapped onto interval numbers using membership functions similar to those used in fuzzy set theory. Three extreme cases illustrate the meaning of this interval measure of belief:

$P(E) = [0,0]$ represents a belief that $E$ is certainly not dependable,

$P(E) = [1,1]$ represents a belief that $E$ is certainly dependable, and

$P(E) = [0,1]$ represents a belief that $E$ is unknown.

The interval $S_n(E) = S_p(E)$ implies that there is no uncertainty in the evidence and corresponds to the theory of classical probability. Thus, whilst Interval Probability Theory is founded on the axioms of probability theory, it allows support for a conjecture to be separated from the support for the negation of the conjecture. It can therefore handle situations where incompleteness is an important issue, because the problem domain need not be completely specified in order to obtain meaningful inferences.

The idea of interval representation has attracted numerous researchers (Dempster, 1969, Shafer, 1976 and Baldwin, 1986). Cui and Blockley (1990) developed previous

work by introducing the parameter ρ which represents the degree of dependence between evidence. Inference rules based on the assumptions of dependence (notably fuzzy set theory (Bier, 1992)) or independence are therefore special cases of IPT.

If ρ is expressed as an interval number $[\rho_l, \rho_u]$ the intersection is

$$S_n(E_1 \cap E_2) = \rho_l(S_n(E_1) \wedge S_n(E_2))$$

$$S_p(E_1 \cap E_2) = \rho_u(S_p(E_1) \wedge S_p(E_2)).$$

The inference mechanism is the total probability theorem

$$P(H) = P(H|E)P(E) + P(H|\overline{E})P(\overline{E})$$

which can be rewritten as

$$P(H) = P(H|E)P(E) + P(H|\overline{E})(1 - P(E)).$$

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

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

and

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

Dubois and Prade only dealt with one item of evidence $E$. Recently Hall et al. (1998c) have developed a generalised approach to finding the least conservative bounds on the inference for any number of items of evidence. In multi-dimensional problems the simplex algorithm is used to find the least conservative bounds.

An interval approach is attractive because of the much increased flexibility it provides for representing uncertainty knowledge when compared with conventional probability theory. On the other hand it significantly increases the dimensionality of the inference problem. Analysis of any inference problem is therefore a compromise between, on the one hand, having degrees of freedom constrained in a way which does not do justice to the complexities of the situation and, on the other, having to input large amounts of instance-specific information or generating large amounts of uncertainty. The method used will depend on the nature of the problem under consideration. Interval Probability Theory is suitable in situations involving sparse or conflicting data, whilst more precisely defined situations can be effectively tackled with more conventional quantitative approaches.

**Implementation of IPT for process modelling**

A software tool has been developed which combines visual representation of hierarchical processes with uncertainty propagation using Interval Probability Theory. By combining Interval Probability Theory with process modelling an overall measure of the dependability of the process leading up to a decision can be obtained.

Figure 2 shows a typical working screen. The processes are arranged in a logical

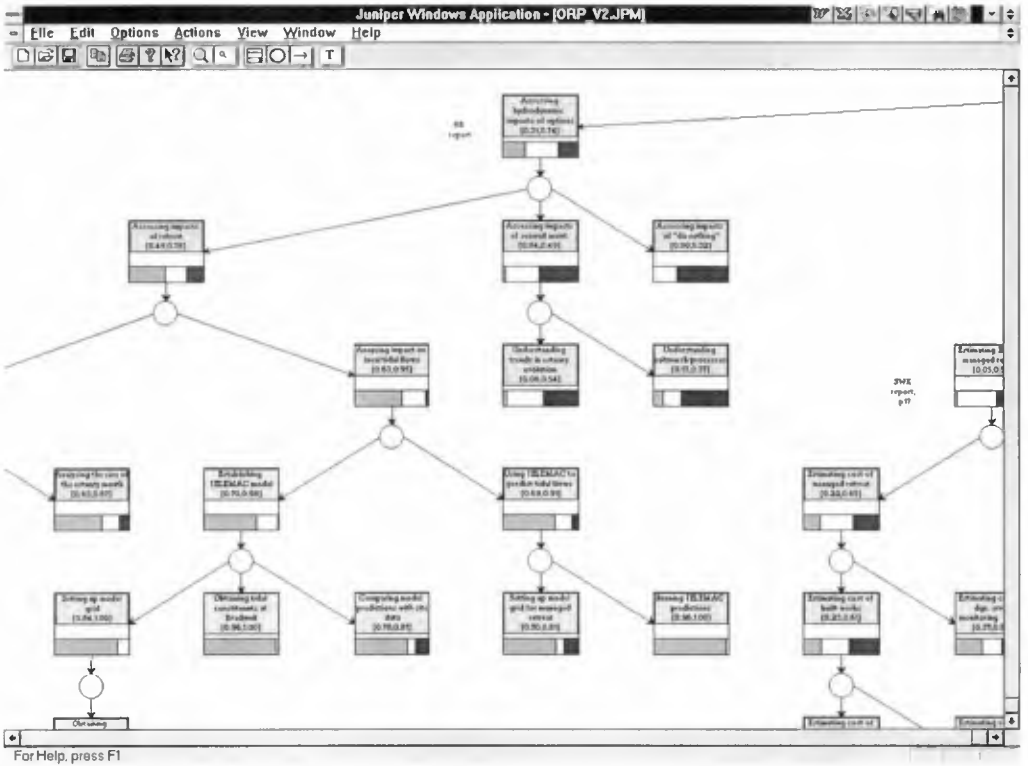


*Figure 2 A process model showing the evidence relating to the decision to implement depolderization at Orplands*

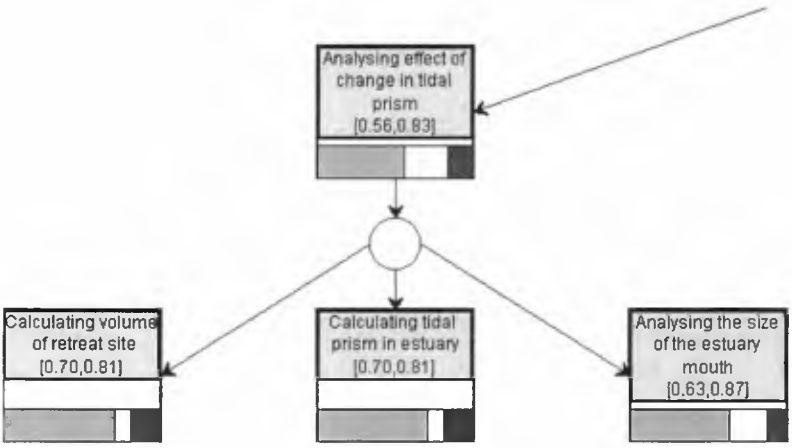


*Figure 3 Detail from the process hierarchy*

hierarchy. Each process is analysed to identify sub-processes which contribute to the success of the process. The process is decomposed in this way down to a level of resolution appropriate for the problem in hand.

Figure 3 is a detail from the screen shown in Figure 2. The processes are titled and the probability intervals shown as pairs of numbers under the title and graphically as coloured bars at the bottom of each process box. The left bar is coloured green and the right bar red, representing the evidence for or against the success of the process respectively. Between the two bars is a white area representing the uncertainty.

Interval values are input by the user for all of the 'leaf' processes in the hierarchy. At every node in the hierarchy values of the dependency parameter ρ and of the conditional probabilities which express the structure of the inference problem are input by the user. Using this information the software calculates the interval probability which represents the evidence for success of the top process in the hierarchy, which is a logical consequence of all of the interval probabilities input elsewhere in the hierarchy. It is therefore possible to explore the influence of low level processes on the uncertainty in the overall design, modelling or decision making process. Knowledge of the overall dependability, which is provided by the top level interval number can be used to inform and enhance decision making. In this way the process model and interval numbers provide commentary on the process of obtaining and manipulating evidence. The decision maker thereby obtains a means of comparing different predictions (which may be expressed in probabilistic or deterministic terms) which have been obtained from different models. Hall et al. (1998c) also proposed an approach whereby the interval probabilities generated from modelling the dependability of an analysis process can be combined with the probabilistic information generated by that process, for example in the form of a probability of failure, to generate bounds on probability of failure.

## Case Studies

Uncertainty analysis which combines process modelling with interval probability theory has been applied to two contrasting flood defence projects on the East Coast of England.

Orplands seawall managed retreat project

One of the projects is a depolderization (managed retreat) project on an estuary in Essex. The dykes which protected a few square kilometres of low grade agricultural land were in need of major repair. To avoid the high cost of repair it was decided to abandon the dykes and retreat the defence line inland. This has had the added benefit of reinstating an area of saltmarsh habitat and reducing stress on the eroding estuary. The scheme was planned based on the experience of the experts involved, supported with some quantitative analysis which was carried out by consultants. The uncertainty analysis was carried out to assess the dependability of the process of choosing to implement the depolderization rather than any of the other options.

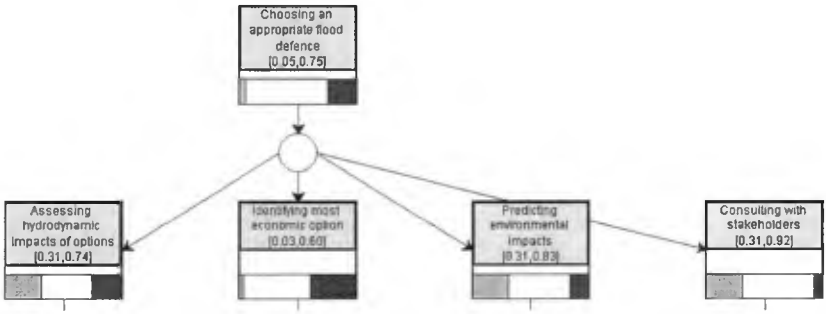


*Figure 4 High level processes in the Orplands model*

Figure 4 shows the high level process in the process model. The hierarchy shown in Figure 1, 2 and 3 are lower level parts of the same process model. The model was constructed using documented evidence in the form of reports and correspondence relating to the project, together with testimony of the engineers involved. On the basis of this evidence the support for the top process of "choosing an appropriate flood defence" was calculated to be [0.05, 0.75] which represents rather low dependability with low confidence in that assessment. The uncertainty model therefore demonstrated that there was substantial uncertainty in the overall process of choosing an appropriate defence option when this was not necessarily made clear in the documentation relating to the project.

The interval probabilities relating to the sub-processes shown in Figure 4 are listed in Table 1. The main reason why the dependability of the top process was calculated to be low was because of the low support for the economic appraisal process which in the UK has a great influence on the overall dependability of the decision making process. The economic appraisal was found to have dependability [0.03, 0.60]. The lower bound on this interval is a dominant influence on the lower bound of the top process. The economic appraisal was found to be of low dependability because of the complexity of the failure mechanisms at the site, upon which the economic assessment of flood risk depended. Failure probabilities (which are necessary aspects of the economic benefit assessment) were assigned using expert judgement and were not

particularly dependable. To reduce uncertainty in the decision making process would require investment in an improved assessment of flood risk.

*Table 1 Support for top level sub-processes after revisions*

| | Sub-process | Support interval | Verbal mapping |
|---|---|---|---|
| *A* | Assessing hydrodynamic impacts of options | [0.31, 0.74] | Moderate dependability with moderate confidence |
| *B* | Identifying the most economic option | [0.03, 0.60] | Low dependability with low confidence |
| *C* | Predicting environmental impacts | [0.31, 0.83] | Moderate to high dependability with low confidence |
| *D* | Consulting with stakeholders | [0.31, 0.92] | Moderate dependability with low to very low confidence |

The findings of the uncertainty model should not be used in isolation but should complement the information relating to the options which was generated during the economic appraisal, hydraulic and environmental assessment and consultation exercise. These indicated that depolderization was a favourable option which was robust to changes in key parameters in the decision making process. Testing of the uncertainty model suggested that for a project of this size (the estimated cost of the project was only £87k) it would on balance be appropriate to proceed cautiously without further analysis, especially in view of the high cost associated with reducing the uncertainty of key processes.

Construction and use of the uncertainty model forced reflection on how the different activities and studies which had been undertaken contributed to the strategic decision to implement the depolderization project. The final model structure was confirmed by the Environment Agency's project manager to be a good representation of the processes leading up to the strategic decision.

The Lincshore beach nourishment project

The second project used as a case study was a £71 million beach nourishment scheme which is being implemented over a number of years. The scheme has been the subject of detailed numerical model studies and is being intensively monitored. There was therefore much more evidence on which to base the design of the scheme than at the Orplands site.

The first phase of the uncertainty analysis for this project proceeded in the same way as the Orplands project described above, examining the strategic decision to implement beach nourishment rather than any of the other options evaluated during the feasibility study. This demonstrated once again that the risk assessment and economic appraisal process were the main sources of uncertainty in the overall decision. The analysis then proceeded to model the current decision making process relating to the renourishment strategy for the coming five years. This demonstrated how probabilistic modelling to optimise the beach nourishment programme could be combined with hierarchical modelling of the decision making process using Interval Probability Theory.

## Conclusions

A descriptive study, using methods developed in the social sciences, has identified principal sources of uncertainty in decision making. Descriptive studies of this type are an important precursor to the design and development of decision support systems.

It has been argued that reliability theory provides an important but incomplete picture of uncertainty in coastal engineering. It cannot be assumed that traditional methods of dealing with uncertainty are as efficient as they could be or that they will continue to be effective in increasingly complex coastal management systems in which more interactions and sensitivities are taken into account. Engineers need to be prepared to explore new methods to give efficiency, safety and sustainability in the defences for which they are responsible. A range of techniques are available for managing uncertainty so engineers should be prepared to draw upon appropriate techniques, remembering that all measures of uncertainty are not absolute measures but are aids in the process of managing uncertainty (Blockley, 1985).

Interval Probability Theory has been found to be a useful approach which accounts for the incompleteness and dependency between items of evidence in an evidential reasoning framework. Interval Probability Theory is an appropriate way of modelling uncertainty in complex situations involving sparse of conflicting information.

Process models of coastal engineering projects have been constructed with Interval Probability Theory. These supplement and enhance existing approaches to uncertainty including reliability methods. These models have been used to support the management of coastal engineering projects on the East Coast of the UK. Two case studies have demonstrated the extent of uncertainty in key decisions during project planning and design. They have highlighted that the a key source of uncertainty and indicated where investment would have to be directed to reduce uncertainty. Moreover, the analysis forced reflection on how the different activities and studies contributed to strategic decisions.

Uncertainty analysis involves giving a overview of where uncertainty lies in a decision. By identifying the most significant sensitivities and sources of uncertainty and by making the most of available information it helps to enable better decision making for coastal engineering projects.

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