2. Description of the proposed research and its context

2.1 Background

Analysis of the potential impacts of climate change on the built environment, transport and utilities reveals a plethora of sector-specific potential impacts. However, it also reveals a number of cross-cutting themes relating to uncertainty handling (particularly with respect to climate scenarios), system simulation, risk analysis and decision-making. This collaborative proposal aims to develop and demonstrate new methods for handling uncertainty and making robust decisions for the sustainable management of infrastructure systems in the face of climate change. It will build on the framework for decision-making to be published in the EA/UKCIP report *Climate Adaptation: Risk, Uncertainty and Decision-Making.* Uncertainty handling, risk-based design and system optimisation are generic to all aspects of modern infrastructure management and are not uniquely climate change issues. There is, therefore, the opportunity to build on existing non-climate-related research, methodologies and best practice. However, climate change presents particular challenges, which the proposed research aims to address:

- Each step in the process of generating climate scenarios introduces uncertainties. Inter-model comparisons indicate that uncertainties in some of the high resolution climate variables and extremes required for modelling the built environment, transport and utilities will be very significant.
- The systems under consideration are often too complex for 'full' uncertainty analysis involving large numbers of highly-detailed simulation model runs. Meanwhile, simpler parametric models or analytical descriptions of system behaviour may be suitable for uncertainty analysis but do not reflect complex non-linear system behaviour.
- The extended time frame of climate change places particular challenges on modellers to predict long term system response, on designers to generate adaptable solutions and on decision-makers to make robust decisions that do justice to future generations.

The proposed research addresses these challenges. The proposal has emerged from the concerted process of research programme development on *Impacts of Climate Change on the Built Environment, Transport and Utilities* managed by EPSRC and UKCIP (referred to hereafter as the EPSRC/UKCIP programme). Research programme development has involved a wide range of stakeholders from industry and government, whose needs are reflected in this proposal.

Climate uncertainty is seldom the only or indeed the main uncertainty confronting decision-makers responsible for managing infrastructure, the built environment and utilities. The response to climate change has to be addressed in the broader context of developing profitable and sustainable business solutions. Although a range of methods for uncertainty handling, system simulation and risk-based decision-making are available in the literature, their take-up in practice in the design and management of the built environment, transport and utilities has been patchy. The move to consider climate change represents an opportunity to introduce methodologies that will be of much broader business and environmental benefit.

2.2 Aims, objectives and novelty

The aim of the proposed research is to develop new methodologies for analysing uncertainty and making robust risk-based decisions for infrastructure design and management in the face of climate change. The proposed research will conduct new analysis of the uncertainties in downscaled climate scenarios, apply new methods in the analysis of system response to climate change and evaluate a range of methods for making robust risk-based decisions. It will demonstrate the use of these advanced methods in the context of case studies of infrastructure design and management.

Specifically, the research has the following objectives:

1. to explore the cascade of uncertainty involved in the construction of climate scenarios for infrastructure and the built environment and to develop new methods for expressing these uncertainties in an appropriate form;
2. to develop practical methods for the quantitative assessment of system sensitivity to uncertain input variables; and
3. to demonstrate in climate adaptation decisions the use of risk-based multi-criteria decision-making and methods for decision-making under severe uncertainty.

2.2.1 Timeliness and novelty

The proposed research is timely in that it coincides with important related initiatives in which the project partners are playing leading roles:

- The EA/UKCIP report *Climate Adaptation: Risk, Uncertainty and Decision-Making* (to be published in Autumn 2002) provides a framework for decision-making under uncertainty. New uncertainty and decision tools and methodologies are now required to enable the practical implementation of this important document.
- EU Framework 5 projects MICE, STARDEX (both co-ordinated by UEA) and PRUDENCE, are developing new methodologies for analysing extremes and uncertainties in climate predictions and will run from 2002 to 2005.
- DTI have, through the Partners in Innovation (PII) programme, funded a project being led by Arup on 'Climate change and the internal environment of buildings'. This project will begin in July 2002 and will involve ensemble runs using building environment models – an approach which the proposed research aims to inform and advance.
- CIRIA is in the process of launching a project on 'Climate change – a guide to technical risk assessment for the construction industry'. This project presents an opportunity to disseminate the risk methods developed in CRANIUM.
- The second round of projects to be funded by the Tyndall Centre for Climate Change Research are now beginning, and include a range of projects on risk, uncertainty and decision-making, most notably the project 'Uncertainties in the integrated assessment process' which involves significant input from Dr Hall and colleagues in the Department of Engineering Mathematics at Bristol.

The proposed research will benefit from links with these current initiatives and with other projects in the EPSRC/UKCIP programme. However, the research is distinct and novel in significant respects:

- The research is analysing the whole climate risk management cycle, from climate uncertainties and system response to design and decision-making. This will provide methodologies to support the conceptual risk framework developed by EA and UKCIP in *Climate Adaptation: Risk, Uncertainty and Decision-Making.*
- New uncertainty analysis of climate scenarios will be conducted with particular reference to climate variables relevant to the built environment, transport and utilities.
- New and emerging methods for analysis of system response to uncertain loading will be demonstrated.
- The applicability of a range of methods for decision-making under uncertainty will be evaluated in the context of climate impacts analysis.
- The methods and technologies will be applied, often for the first time, to case studies relating to the built environment, transport and utilities.

2.3 Methodology

The proposed methodology follows the stages in risk analysis and decision-making in relation to climate impacts and adaptation, from analysis of climate scenarios, to analysis of system response and finally to appraisal of options and robust, risk-based decision-making. It is structured around three tasks of (1) uncertainty analysis in climate scenarios, (2) analysis of system response and (3) decision-making. The third task will be the main integrating mechanism within the project and link with other projects in the EPSRC/UKCIP research programme. Methodological developments in each of these three tasks will be conducted in the context of case examples. In Tasks 1 and 2 the case studies have been selected to provide specific methodological insights, whereas Task 3 will provide a broader coverage of sectors and issues, linking with other projects and stakeholders.

2.3.1 Task 1: Uncertainty analysis in climate scenarios for built environment, transport and utilities

Task 1 will analyse uncertainties in key climate scenarios for analysis of built environment, transport and utilities and provide means of communicating them to modellers and decision-makers. The Climate Scenarios Project (CSP), which is to provide climate scenarios for all of the projects in the EPSRC/UKCIP programme, will provide time series of climate variables. Task 1 will focus on the development of new uncertainty analysis methods, starting from the CSP scenario time series and downscaling models.

1a Analysing uncertainties in high resolution climate scenarios

The CSP will provide scenarios of climate variables of relevance to the built environment, transport and utilities at daily and hourly timescales for selected case-study locations. Task 1a will analyse the uncertainties in these scenarios and, based on the CSP downscaling models, develop a new Bayesian methodology for incorporating a broader range of uncertainties than are included in UKCIP02. The different sources of uncertainty will be addressed by using:

- a wider-range of emissions scenarios than the UKCIP02 and CSP scenarios;
- output from models other than the Hadley Centre models used in UKCIP02 and the CSP, together with ongoing international work on climate sensitivities[1];
- output from ensemble simulations and observed/simulated studies of natural variability; and,
- results from ongoing studies comparing different downscaling methodologies.

Based on (i) analysis of climate model output available from the Climate Impacts LINK project and the IPCC Data Distribution Centre, (ii) results from ongoing European Union-funded projects such as STARDEX and PRUDENCE, and (iii) literature review[2,3,4], expert judgement will be used to develop prior distributions of the downscaling model parameters for the present-day and future time periods. These will then be used for Monte Carlo sampling in a Bayesian approach to scenario construction[5]. This type of approach, which provides information in the form of probability distribution functions, is recommended by the IPCC Third Assessment Report and elsewhere[6,7], but these methods have neither been fully implemented nor evaluated.

1b Extreme value analysis of non-stationary processes

Changes in the frequency and magnitude of extreme events are likely to have more of an impact on the built environment, transport and utilities than changes in mean climate. Relatively few scenarios of extremes have been constructed, much less used in impact studies for these sectors. Thus Task 1b will involve detailed analysis with respect to extremes (including joint probability analysis) of the scenarios from the CSP. A starting point for this work will be the diagnostic software tool for the calculation of indicators of extremes developed as part of the STARDEX project. Additional indicators based on the other variables which are output from the UEA downscaling models will be analysed as part of the CRANIUM work.

The demonstration application for this work will be extreme value analysis of rainfall. It is apparent that recent decades of extreme rainfall observation exhibit trends in some regions (notably Scotland). No accepted methodology exists to establish design parameters robustly from non-stationary observed records, with the added complication of likely further change during the design life of planned structures (*e.g.* dams and urban drainage systems). A new methodology will be developed, initially using a Monte Carlo framework to inform a more sophisticated approach using Bayesian methods, which will allow design and upgrade plans for a number of exemplar dams and urban drainage systems to be tested. This represents a particularly interesting case study because methods for extreme hydrological analysis of reservoirs have been the subject of considerable controversy even in the absence of climate change[8,9]. Data for Scottish reservoirs will be provided by Scottish and Southern Energy.

1c Communicating climate uncertainties to designers and decision-makers

The information on uncertainty in climate scenarios is inevitably complex, hence methods for communicating key uncertainties to end users, designers and decision-makers involved in the CRANIUM case studies will be developed. Alternative methods for presentation of uncertainties will be evaluated through production of a short briefing document, face-to-face interviews and a workshop. Methods that will be evaluated will include probability distributions, interval bounds, expert commentaries and graphical outputs. An additional aim of this task will be to develop and disseminate best practice in the application of climate scenarios to real-world risk-related problems based on the CRANIUM case studies.

2.3.2 Task 2: Simulating system response to uncertain climate scenarios

Having, in Task 1, analysed the uncertainty in climate scenarios, the next stage in impacts analysis is to assess the response of the system under consideration to uncertain forcing. The impact of uncertainty in the forcing needs to be combined with analysis of uncertainty in system response. Whilst great progress has been made in the analysis of system response to uncertain input parameters, the use of these methods in climate impacts analysis is patchy. As probabilistic climate scenarios have begun to emerge, naïve Monte Carlo analysis has been used in a few studies, but is not practical for very expensive computer models and where knowledge of the full dependency structure of input parameters may not be available. Moreover, whilst the focus of Task 1 is probabilistic representation of uncertainty, climate uncertainties may also be expressed as intervals, or linguistic statements that can be represented as fuzzy sets.

The methods in Task 2 will in the first instance be demonstrated for slope stability analysis using the CHASM combined slope hydrology/stability model, which is a finite difference model of moderate complexity. CHASM is immediately available to the investigators at Bristol, who are familiar with its use and behaviour. It will demonstrate issues of uncertainty in slope stability analysis, including impacts of climate-induced changes in hydrology, evapo-transpiration and vegetation species/growth rate. The analysis will begin by consideration of simple idealised slopes, but will progress to railway/highway embankment/cutting case studies provided by Halcrow, Arup and Railtrack. However, rather than merely providing insights into geotechnical engineering, the objective of the analysis will be to demonstrate generic aspects of uncertainty handling in system response. The methodologies will then be tested by application to a more complex (high dimensional, less stable and more computationally expensive) system model. The proposed integrated urban drainage model in the EPSRC/UKCIP programme is a good candidate and, subject to satisfactory progress, will be the subject of uncertainty analysis once the methods have been demonstrated in CHASM. An alternative candidate study will be to extend the slope stability analysis to address reactivation of complex landslides on the South Coast of England using case studies held by Halcrow.

2a Projecting uncertainties through system models

Task 2a will evaluate methods for projecting uncertainties (represented as probabilities, intervals or fuzzy sets) through system models. The probabilistic work will focus on methods for projecting probability distributions through numerical functions (*i.e.* in situations where no algebraic expression exists). The method proposed by Craig *et al.*[10] for Bayes linear approximation to computer models will be demonstrated and evaluated. The approach uses only means and variances, but no assumption of normality is made. This provides the opportunity for combining expert knowledge and other prior information with a small number of model runs. The method will be compared with the full Bayes solution in a sufficiently simple study and then extended to more complex cases.

Methods for projecting fuzzy and random sets through an arbitrary function or model are established in principle and engineering applications have been reported[11]. Work by Hall and Lawry[12] has demonstrated how random sets can be used to approximate more general uncertainty measures and project them through simple functions. This work will be demonstrated, evaluated and developed in the context of increasingly complex case examples. The computation efficiencies that are achievable by exploiting knowledge about the behaviour of the model, for example monotonicity, will be explored.

2b Approximating system response

In situations where system models are too expensive for 'full' uncertainty one solution is to construct fast numerical approximations to system response using machine learning methods. The approximation can then be used for the uncertainty analysis. Candidate methods that will be evaluated are response surface methods, artificial neural networks, fuzzy rules and decision trees. Fuzzy rule based methods and decision trees are particularly attractive because the numerical approximation is, in some sense, intelligible to model users. These approaches will first be evaluated using model systems that are simple enough to apply Monte Carlo analysis for comparative purposes, before extending to more numerically expensive cases. The suitability of this approach in generalised uncertainty handling (using the fuzzy and random set methods developed in 2a) will be evaluated and demonstrated for case studies.

Together, tasks 2a and 2b will result in methods for predicting system response to uncertain climatic loading that take account of the format of uncertain information about model parameters and other prior knowledge of model dependability.

2.3.3 Task 3: Decision-making under severe uncertainty

Tasks 1 and 2 will enable the identification of potential climate impacts on system performance, together with some understanding of the associated uncertainties. Task 3 will address how, in the light of these insights, decision making about operation of, or investment in, the system in question could be managed or modified to reflect potential climate change impacts and specifically the uncertainties surrounding them. Methodologies for decision-making under uncertainty range from conventional risk-based approaches to methods for decision-making under very severe uncertainty. Even though the application of risk-based optimisation and decision making, at least in research studies, is quite widespread, it is less well established in practice in the industries that are the subject of the current research. Decisions responding to climate change impacts need to not only recognise the direct system response uncertainties, but also the existence of multiple evaluation criteria and that decision making is embedded in a dynamic social context reflecting multiple perceptions and hence perspectives of different stakeholder groups. For example, within the transport sector, there exist relatively sophisticated models of system performance (*e.g.* land-use transport interaction models) but these are not well adapted to assessment of alternatives when there are simultaneously multiple criteria and severe uncertainties to be taken into account.

Task 3 will seek to advance the application of structured decision processes in areas of application pertinent to the industrial sectors on which the study as a whole focuses. It will do so through two separate but related sub-tasks and case studies:

3a Matching process to context

This sub-task will concentrate directly on good decision process and on the matching of techniques to application needs. It will critically assess available procedures for decision-making under climate change impact uncertainty, taking as its starting point the foundations developed in *Climate Adaptation: Risk, Uncertainty and Decision-Making*. Through analysis of a range of problem domains, a generic classification framework will be established for categorising decision support processes (*e.g.* scenario planning, linear partial information methods, *etc*.), application contexts (by sector, time scale, scale of decision, *etc*.), nature of uncertainty (modelling uncertainty, lack of clarity about evaluation criteria, inadequate data, *etc*.) and types of response (robust design, operational flexibility, laying off risk through insurance, *etc*.). It will then establish guidelines for linking particular support procedures with different problem contexts. In seeking to do so, it will critically assess and seek to improve on existing guidelines. In judging what constitutes 'better' over-riding concerns will be practicality from the perspective of practitioners involved in application, and, secondly, full recognition that decisions take place in a world of multiple criteria, many stakeholders, political influence, and so forth. Communication of risk is an important concern, and Task 3 will link to sub-task 1c in this area. Sub-task 3a will be a focus for collaboration with the CRANIUM stakeholders and with other projects in the EPSRC/UKCIP programme. It will involve consultative interviews and a workshop and will then target specific case studies as examples of decision methodologies and problem domains. These will include the case studies being addressed in other CRANIUM tasks (reservoir hydrology, slope stability and urban drainage) but will extend where appropriate across the scope of the whole EPSRC/UKCIP programme.

3b Info-gap decision theory

In conditions of very severe uncertainty, it may not be possible to distribute any measure (be it probabilistic or fuzzy) over possible system states, in which case theories of decision-making under risk or fuzziness are not applicable. It is under these circumstances that info-gap decision theory has been proposed by Ben-Haim[13]. An info-gap model represents a nested family of models, parameterised according to their distance from the expected system behaviour. Ben-Haim has developed a theory of robust decision-making that helps to weigh up immunity to the harmful impacts of uncertainty against the potential for beneficial impacts. The theory is of great potential relevance in the context of climate impacts. Through a series of demonstrations, procedures for application to typical climate problems will be established. A PhD studentship will be dedicated to evaluation and demonstration of info-gap decision theory in the context of climate impacts analysis. This will begin by analysis of very simple systems that can be described in algebraic terms and simple design decisions, for example the investment in new capacity that delivers some climate-related benefit at an uncertain cost. The work will proceed to examine more complex systems identified in Task 3(a) and identify the limits of applicability of Ben-Haim's theory.

2.4 Dissemination and exploitation

The following dissemination mechanisms are planned:

- The CRANIUM industrial advisory panel and the EPSRC/UKCIP Integrating Framework will provide links to key stakeholder organisations. The industrial advisory panel will advise on dissemination, particularly in view of their experience and ongoing role in producing guidance documents for the construction industry.
- The research will run in parallel with CIRIA's project 'Climate change – a guide to technical risk assessment for the construction industry', which will proceed through production of a report and an awareness raising campaign. We will seek to disseminate the results of CRANIUM by linking with this programme.

- Research advances will be reported in refereed journal and conference publications. Conferences and publications both of international academic standing and those aimed at end users will be targeted.
- Short articles, for example for the ICE's Research Focus newsletter will be produced.
- Collaboration with related climate impacts research projects listed in Section 2.2.1 (*e.g*. Tyndall Centre and EU Frameworks 5 and 6) will provide links to the dissemination mechanisms established for these projects.

2.5 Justification of resources

Each of the three tasks in CRANIUM are substantial and require the following staff effort:

Task 1: 19 months (equivalent) PDRA and 1 PhD studentship (Newcastle); 12 months (equivalent) Senior RAs (UEA)

Task 2: 33 months PDRA (Bristol)

Task 3: 23 months PDRA (Leeds); 1 PhD studentship (Bristol)

Travel and subsistence resources are required to cover travel to meetings, workshops and site. This includes collaboration with other projects in the EPSRC/UKCIP programme and with the Integrating Framework. Funding is sought for registration, travel and accommodation at international conference for each participating university group.

High performance computing facilities are available at Newcastle and UEA; a contribution to computer support for these facilities is requested. New PCs are required for the RAs and PhD student recruited to Tasks 2 and 3.

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Appendix 1: Project management

Research management

Overall responsibility for research management will lie with Dr Jim Hall in the Department of Civil Engineering at the University of Bristol. CRANIUM will be the fourth major collaborative EPSRC project that Dr Hall has managed and experiences and management techniques developed during these previous successful projects will be applied to CRANIUM. Co-ordination of work tasks will be conducted by Dr Hall at Bristol primarily through email reports from the task leaders and telephone conversations. Six-monthly meetings of the research partners (which may coincide with the Advisory Group meetings proposed below) are proposed.

Management of work tasks will be devolved to the task leaders: Chris Kilsby for Task 1, Dr Jim Hall for Task 2 and Prof Alan Pearman for Task 3. They will be responsible for detailed planning of the tasks, day-to-day monitoring of progress of RAs and PhD students and co-ordination of activities not taking place in their own institutions.

Role of collaborating partners

A project Advisory Panel, comprising of the collaborating partners listed in Table 1 will oversee the progress of the project and provide stakeholder input at key stages in the project. An annual meeting of the Advisory Panel will serve to report on progress and gain input and guidance from stakeholders. Two workshops are planned (see work programme):

1. Workshop 1 will review existing decision-making process and begin Task 3a research.
2. Workshop 2 will review methods for communicating climate uncertainties (Task 1c).

The Advisory Panel will help to disseminate the research within their own organisations and will advise on broader dissemination mechanisms.

The contribution of the Advisory Panel will be significant, through contribution of staff time and data. An estimate of the value of this contribution has been included on the proposal form. Management of the project Advisory Panel will be co-ordinated by Dr Hall at Bristol. Co-ordination with stakeholders involved in specific case studies will be devolved to task leaders.

Co-ordination with other projects in the EPSRC/UKCIP programme and the Integrating Framework

The CRANIUM project seeks to collaborate with the other projects in the EPSRC/UKCIP programme through direct links and via the proposed Integrating Framework. Moreover, we recognise the benefits of the Stakeholder Panel to be established within the Integrating Framework and will make use of this panel to gain additional inputs from stakeholders and as a dissemination mechanism. Proposed integrating mechanisms are as follows:

Task 1 will link with the proposed Climate Scenarios project (CSP), which forms part of the Integrating Framework. Task 1 will be conducted by the University of Newcastle and UEA, with consultative input from the Hadley Centre, so will benefit from involving the same partners as the CSP. It will extend the work in the CSP by scrutinising uncertainties and developing new probabilistic methods. Briefing notes will be circulated and a workshop will be held, to which end users and stakeholder representatives from all projects will be invited, on the handling of uncertainty in climate scenarios.

Task 2 will in the first instance use case studies provided by the CRANIUM partners. The landsliding studies will be conducted in collaboration with the proposed Transportation project, with Dr Neil Dixon (Loughborough University) as the first point of contact. Towards the end of the CRANIUM project it is intended to make use of the integrated urban drainage model being developed by the Urban Drainage project. The contact for this collaboration will be Prof Richard Ashley at Bradford University.

Task 3 will involve a broad analysis of design and decision problems and as such will involve a survey of all of the sectors being addressed in the EPSRC/UKCIP programme. This will therefore be a truly cross-cutting activity. It will involve a workshop to which representatives from all projects will be invited. This will be followed up with bilateral discussion and development of selected case studies.

Table 1 Members of project Advisory Group and role

Organisation	Representative	Specialism	Role
Arup	Dr Jake Hacker	Fluid dynamics. Climate impacts on buildings	Built environment issues. Liaison with PII and CIRIA
Arup	Dinesh Patel	Geotechnics	Advice and provision of geotechnical case studies
Halcrow	Dr Roger Moore	Geotechnics/geomorphology. Climate impacts on slope stability	Advice and provision of geotechnical case studies
Halcrow	Roger Allport	Transportation	Advice on transportation issues
Halliburton KBR	Dr Andy Hughes	Reservoir safety	Engineering implications of reservoir hydrology
Environment Agency, Centre for Risk and Forecasting	Ian Meadowcroft	Risk analysis and climate impacts	Advice on practical use of risk methods. Link to EA/UKCIP framework for climate adaptation.
Railtrack	Julie Gregory	Weather strategy for transportation systems	Advice on transportation issues. Access to slope stability case studies.
Scottish and Southern Energy	Neil Sandilands	Reservoir engineering and hydro power	Engineering implications of reservoir hydrology
Scottish and Southern Energy	Neil Lannen	Hydrology	Provision of hydrological data
Met Office Hadley Centre	Dr Richard Betts	Climate modelling and earth surface processes	Advice on climate modelling