Institution: University of Warwick

Unit of Assessment: B10 Mathematical Sciences

Title of case study: The design of methodologies for a nuclear emergency management system

1. Summary of the impact

Professors Smith and French designed the overall information flows and outline methodologies for forecasting and decision analysis now incorporated into RODOS, a widely-installed decision support system for responding to nuclear emergencies. Their design uses:

- Bayesian statistics to forecast contamination spread and Bayesian spatio-temporal models to estimate contamination in the longer term;
- multi-criteria decision analysis (MCDA) for the evaluation of strategies;
- an explanation system to translate the numerical outputs into plain language.

RODOS and closely related systems are now installed for operational, emergency planning and training use by many national, regional and local European governments and several other countries world-wide (22 countries overall).

2. Underpinning research

The 1986 Chernobyl Accident stimulated much European R&D to become better prepared for handling nuclear emergencies. Central to this has been the development of the RODOS system (Real-time Online Decision suppOrt System for nuclear emergency management). In 1990-91 it became apparent that uncertainty handling, data assimilation and evaluation were major issues in its design. How could it track and predict the spread of contamination? How reliable would such estimates and forecasts be? In the longer term, how would it estimate the spatial distribution of contamination? How might it support the evaluation of countermeasures when so many factors needed to be taken into account? Professor Smith at Warwick, and Professor French, who was then at Leeds and Manchester, but joined Warwick in 2011, suggested that Bayesian statistics and decision analysis would provide the necessary framework. A proof-of-concept project (begun in 1992, completed in 1993), to test Kalman filtering for assimilating monitoring data for short-range atmospheric dispersion prediction was funded under the EU Framework R&D programme and was successful in demonstrating the efficacy of the Bayesian approach [1, 2]. Smith and French, supported by several European Framework contracts through the 1990s, joined the RODOS team to develop further the Kalman filtering methodology, and design more general methods for uncertainty handling, data assimilation and evaluation within RODOS.

RODOS is a comprehensive system which deals with all timescales from threat to long-term recovery and across all geographical scales and thus its development has involved very many European and former Soviet Union Institutes. Much of French and Smith's work was to draw on their research on Bayesian statistics and decision analysis and advise many other groups across the RODOS project. By the end of the decade their involvement in many aspects of the RODOS design had extended their conceptual work from short range atmospheric dispersion modelling into medium and long range modelling, ground deposition, hydrological modelling, as well as the chaining of uncertainty throughout RODOS and further developing a multi-criteria decision analysis (MCDA) process to underpin evaluation [3, 4].

The implementation of the ideas stimulated theoretical advances: recasting some of the problems as dynamic belief nets stimulated the development of fast algorithms [5, 6]. A project, undertaken by French and Smith joint with NNC Ltd, part of AMEC since 2005, showed that Bayesian belief nets could predict source terms during the threat phase of a radiation accident [3]. Bayesian spatio-temporal hierarchical models were developed to provide long term models of ground contamination [3]. Bayesian versions of deterministic hydrological models were discussed and have since been developed. French and Smith's design [3, 4] of the MCDA process for evaluation was novel for the mid 1990's in introducing three stages: a *coarse expert system* based on constraint satisfaction to construct countermeasure strategies which met a range of constraints; an *evaluation system* based on multi-criteria value theory to help rank the strategies; and a *fine expert system* which output the results into everyday language and terms both to help user understanding and to provide an audit trail.

3. References to the research

Publications:

1. D. Ranyard and **J. Q. Smith,** "*Building a Bayesian model in a scientific* environment: managing uncertainty after an accident" In S. French, and J. Q. Smith, Eds (1997). The Practice of Bayesian Analysis. London, Arnold, Chapter. 245 – 258. (1997) ISBN: 978-0340662403
2. **J.Q. Smith** and S. French "*Bayesian updating of atmospheric dispersion models for use after an accidental release of radiation*" The Statistician 42(5), 501-511. (1993)
3. G. Caminada, S. French, K. Politis and **J.Q. Smith,** "*Uncertainty in RODOS*". Revised RODOS Research Report RODOS (B)-RP(94)05. FZK, Karlsruhe, Germany. (2000) Available at http://www2.warwick.ac.uk/fac/sci/statistics/staff/academic-research/french/research_interests/crisismanagement/uncertainty_in_rodos.pdf This is an updated version of an earlier report: S. French, D. Ranyard and **J.Q. Smith,** Uncertainty in RODOS. RODOS Report RODOS (B)-RP(94)05, FZK, Karlsruhe, Germany. (1995)
4. S. French, K.N. Papamichail, D.C. Ranyard and **J.Q. Smith** '*Design of a decision support system for use in the event of a radiation accident.*' In F. Javier Girón and M. L. Martínez (Eds) Applied Decision Analysis. Boston, USA: Kluwer Academic Publishers p. 2-18. (1998) ISBN: 0792382501
5. **J.Q. Smith,** and K.N. Papamichail, "*Fast Bayes and the dynamic junction forest*" Artificial Intelligence 107(1) 99-124. (1999) DOI: 10.1016/S0004-3702(98)00103-9
6. M. Drews, B. Larsen, H. Madsen and **J.Q. Smith** "*Kalman Filtration of Radiation Monitoring Data from Atmospheric Dispersion of Radioactive Materials*" Radiation Protection Doisometry, 111(3) 257-269 (2004) DOI: 10.1093/rpd/nch339

Grants awarded:

J.Q Smith (PI): Proof of concept of Kalman Filtering, EU DG12, 1992-93, ECU 25,000 (Warwick component)
J.Q. Smith (PI): Uncertainty handling in RODOS, EU DG12, 1996-99, ECU 192,000
J.Q. Smith (PI): Dynamic Probabilistic Expert Systems, EPSRC GR/K72254/01, 1996-99, £124,025
H.P. Wynn (PI), **J.Q. Smith** (CI): Decision Support in Nuclear Incidents, EU DG12, 2000-2004, £142,200

4. Details of the impact

"*RODOS is now used operationally for emergency preparedness (planning), for training and for emergency response in case of a nuclear accident in several European countries including Germany, Finland, Spain, Portugal, Austria, the Netherlands, Poland, Hungary, Slovakia, Ukraine, Slovenia, and the Czech Republic*" [18]. RODOS is in continual use in these countries, and is also implemented in research, training and planning centres in many other countries (30 installations in 22 countries overall [18]), and used at European and international levels to plan and run exercises, providing the tools for a coherent, consistent and harmonised response. India has developed a version, IRODOS, for evaluation and research. The UK, while not planning to use a full system such as RODOS, uses many of its modules in stand-alone or smaller systems. During the Fukushima Crisis of 2011 RODOS was used in several studies for individual countries and internationally as part of the assessment of the impacts [16, 19].

The current version of RODOS incorporates many modules which implement the designs and methods proposed by Smith and French in the 1990s [7, 8, 9]. These implementations have been engineered into the operational version of RODOS by many partners to the project during the last decade. Comparing the 25 papers in the special issue of *Radioprotection* [7], which summarises much of the functionality of current RODOS implementations, with the early design paper [3] shows the strong influence that this paper has had in shaping the current system.

The impact of the work by Smith and French has been to influence public policy towards response to nuclear contamination, increasing the security and safety of populations living near nuclear plant and, indeed, those further afield. Their research “shaped the design of uncertainty handling, data assimilation and evaluation within the RODOS system” which was important because “the treatment of uncertainty in a consistent manner throughout the system was (however) identified at an early stage as a key area for development” [16].

The current co-ordinator of the RODOS Development Activities states “I can confirm that many of the concepts ideas and advice that you promulgated in the development teams over the years have been implemented within the operational versions of RODOS” [17] and this view is supported by the Chairman of the International RODOS Users Group “The current version of RODOS incorporates many modules which implement the designs and methods proposed by Smith and French”. Recently the RODOS system has “performed well in predicting the impact of the accidental releases from the Fukushima Daiichi NPP in March 2011 – both in Japan and more widely – and in effectively informing relevant decision makers” [16, 19].

Specifically, RODOS and related systems draw on the impetus given by Smith and French in using:

- Belief nets to estimate the probabilities of different source terms during the threat stage [10].
- Kalman Filtering and related Bayesian forecasting methods in short-, medium- and long-range atmospheric dispersion models and in hydrological models [9, 11].
- Bayesian spatio-temporal models to provide estimates of ground contamination into the long term [7].
- MCDA modules to support the evaluation of different countermeasure strategies including an exploration of constraint satisfaction to construct feasible strategies and an explanation system to interpret the outputs into natural language [7-9, 12-14].

In addition, many of the RODOS modules and design features are shared with the Danish ARGOS system, which is used within several Scandinavian countries and elsewhere in the World. ARGOS implements the same methodologies but using a different system architecture. The underlying understanding of nuclear emergency response and recovery, evident in the designs of Smith and French [3, 4], have also been incorporated into the motivation of the NERIS platform (www.eu-neris.net), which provides a forum for dialogue and methodological development between all European organisations and associations taking part in decision making of protective actions in nuclear and radiological emergencies and recovery in Europe. NERIS, in which Warwick is a UK partner along with Public Health England (PHE), is concerned, among other things, to integrate RODOS into local, national and international emergency management processes and develop its use with a broad range of stakeholders.

The use of Kalman filtering in atmospheric dispersion is implemented to varying degrees at short, medium and long ranges; some implementations are stand-alone [7, 9, 11]. Constraint satisfaction approaches to the coarse expert system are not in the current implementation, but the methods augmented by case-based reasoning methodology are being evaluated in the newly funded EU FP7 PREPARE project (http://cordis.europa.eu/projects/rcn/106584_en.html, €6.4m). The early issues relating to the tractability of Kalman filtering led to theoretical developments of dynamic belief nets and fast algorithms [5, 6]. There is a current recognition of the need to develop explanation systems for MCDA and other decision support tools, and the success of the explanation tool within the fine expert system of RODOS is being taken a key example [15].

Smith and French are partners in a research project *Management of Nuclear Risk Issues: Environmental, Financial and Safety* (NREFS), funded by the EPSRC as part of a UK-India Civil Nuclear Research Collaboration. Its objective is to re-evaluate, following Fukushima, some of the fundamental thinking about the emergency management of a radiation accident, particularly in early phase decisions on evacuation and the establishment of exclusion zones.

5. Sources to corroborate the impact

7. Special Issue of *Radioprotection* (2010) Volume 45 Issue 5. Cambridge University Press. Table of Contents at: http://www.radioprotection.org/action/displayIssue?decade=2010&jid=RAD&volumeId=45&issueId=05&iid=8803740

8. Ehrhardt, J. and Weiss, A. (2000). '*RODOS: Decision Support'.* Off-Site Nuclear Emergency Management in Europe. EUR19144EN. Luxembourg, European Community.

9. EURANOS Project final summary report: ftp://ftp.cordis.europa.eu/pub/fp6-euratom/docs/euranos-publishable-summary-final_en.pdf

10. M. Zavisca, H. Kahlert, M. Khatib-Rahbar, E. Grindon and M. Ang (2004) 'A Bayesian Network Approach to Accident Management and Estimation of Source Terms for Emergency Planning.' Paper Presented at the PSAM7/ESREL'04 Conference 14-18 June 2004, Berlin, Germany.

11. K. Politis and L. Robertson (2004) 'Bayesian updating of atmospheric dispersion after a nuclear accident' *Journal of the Royal Statistical Society* **C53**(4) 583-600

12. Bertsch, V., French, S., Geldermann, J., Hämäläinen, R. P., Papamichail, K. N. and Rentz, O. (2009). "Multi-criteria decision support and evaluation of strategies for environmental remediation management." *OMEGA* **37**(1): 238-251.

13. Papamichail, K. N. and French, S. (1999). "Generating Feasible Strategies in Nuclear Emergencies - A Constraint Satisfaction Problem." *J. Op. Res. Soc.* **50**: 617-626.

14. N. Papamichail and S. French (2013) `25 years of MCDA in Nuclear Emergency Management'. *IMA Journal of Management Mathematics*. In press and published online.

15. Greco, S., Knowles, J. D., Miettinen, K. and Zitzler, E. (2012). Learning in Multiobjective Optimization. Report from Dagstuhl Seminar 12041. Dagstuhl Reports Dagstuhl Publishing, Germany, Schloss Dagstuhl – Leibniz-Zentrum für Informatik. 2(1): 50–99.

16. Letter received from retired official of EU DG Research who led the EU post Chernobyl Actions within the European Commission from 1988 to 2008 quotes:
"The current version of RODOS fully embodies their design of information flows, uncertainty handling and decision analytic support"
"The RODOS system is installed widely in emergency centres in many European countries and beyond. It performed well in predicting the impact of the accidental releases from the Fukushima Daiichi NPP in March 2011 – both in Japan and more widely - and in effectively informing relevant decision makers. Requests for its installation in China and in several countries in South East Asia have been made and are being given consideration under the auspices of the European Commission's programme on International Nuclear Safety Cooperation."

17. Letter received from current co-ordinator of all RODOS related R&D activities, quotes "your work with Professor French within the RODOS community in which you helped shape our thinking on uncertainty handling, data assimilation and decision support…has been maintained as RODOS has matured into implementation. Moreover, similar systems such as ARGOS have developed along the same sort of lines."

18. Letter received from Chairman of the International RODOS Users Group quotes: "Their conceptual work and advisory role for many other developer groups mainly covered the areas of source term assessment based on belief nets; uncertainty handling; data assimilation in atmospheric dispersion models, food chain models and hydrological models based on the Kalman filter approach; multi-criteria decision analysis modules to support the evaluation of different countermeasure strategies. The current version of RODOS incorporates many modules which implement the designs and methods proposed by Smith and French."

19. See http://atmos.physic.ut.ee/~muscaten/YSSS2011/YSSS2011-Posters/Poster_SvitlanaDidkivska.pdf