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| **Institution: Queen Mary University of London** | | |
| **Unit of Assessment: 11** | | |
| **Title of case study: Causal Bayesian reasoning tools for critical decision making** | | |
| **Period when the underpinning research was undertaken: 2000-31 Dec 2020** | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** | **Role(s) (e.g. job title):** | **Period(s) employed by submitting HEI:** |
| Norman Fenton | Professor | Mar 2000-present |
| Martin Neil | Professor | Mar 2000-present |
| **Period when the claimed impact occurred: 2014-31 July 2020** | | |
| **Is this case study continued from a case study submitted in 2014? N** | | |

**1. Summary of the impact** (indicative maximum 100 words)

Fenton and Neil founded Agena Ltd in 1998 based on their research on Bayesian Networks (BNs). Its software, AgenaRisk, incorporates their algorithms and has gained over 4,500 new users since 2014. The software combines data and expert knowledge to improve decision making and prediction for risk assessment. Thus, Fenton and Neil's research has made BNs directly accessible to decision makers without advanced mathematical and statistical skills, and helped them to improve predictions and decision making in situations that are highly uncertain and where data is often limited.

AgenaRisk is being used to model and predict cybersecurity risk, in operational risk management, to evaluate the safety of medical devices and support medical decision making for trauma patients and to support planning and decision making in major developing world infrastructure, environment, and food resource projects. Fenton and Neil's algorithms have also been used to develop a set of guidelines for lawyers and forensic scientists for efficiently processing pre-trial evidence.

**2. Underpinning research** (indicative maximum 500 words)

Typically, most mathematical approaches to risk assessment and decision analysis are not appropriate in circumstances where there is uncertainty, such as catastrophic banking failures or terrorist attacks. This is because they require 'big' data and rely on assumptions that are typically made in statistical analysis. Moreover, even for common risks with extensive historical data, for example, in medicine, law and finance, crucial information about causal and explanatory factors is typically missing, even though it is known to subject matter experts. Conventional mathematical and statistical approaches do not work in these situations and Bayesian Networks (BNs) can address these problems. However, most work in BNs involves 'machine learning', where it is assumed that causal structures and relationships can only be learnt from data. For risk assessment, even of highly constrained problems, with small numbers of variables, the machine learning approach is only viable when very large volumes of data are available and the majority of relevant relationships are observable. In other words, when BNs are typically 'learnt from data' the causal mechanisms underlying the problem are poorly identified, and so provide little new insight or make inferences that are difficult to explain.

Queen Mary Profs. Fenton and Neil have developed a range of novel elicitation and modelling techniques that make it much easier for subject experts who are not trained in Bayesian methods or statistics to build and use models. This includes breakthrough work on tailoring BN idioms [3.1], which provide common templates for building BNs to particular subject areas [3.2]; ranked nodes [3.3], which significantly reduce the burden on defining probability tables required for BN models; and making the most of messy and incomplete data [3.4]. They have also developed an alternative 'smart data' approach that combines data with expert knowledge to produce causal BN models. This research has been incorporated into the software system, AgenaRisk [3.5], commercialised by the company Agena Ltd. Agena Ltd was founded by Fenton and Neil in 1998. Since, in practice, it is often very difficult for decision makers to directly use BN algorithms, a focus of Fenton and Neil's research has been on maximising the usability of the approach and software, ie making sophisticated probabilistic modelling accessible to non-statisticians.

Since 2014, Agena Ltd have used Fenton and Neil's research to develop a significant new 'learning' component in the AgenaRisk desktop software, which enables users both to automatically learn all Bayesian network parameters from data, even if the data are incomplete, and also easily incorporate expert knowledge. The underlying philosophy has also led to a methodology for a) measuring and predicting resilience and vulnerability in complex systems such as banking and b) modelling and evaluating sensor technologies in real world settings such as psychology, privacy and the law.

Fenton and Neil have also developed a breakthrough dynamic discretisation algorithm [3.6], which enables modellers to use continuous variables alongside discrete ones without going through the time consuming and intrinsically inaccurate process of static discretisation. This enables a broader class of risk assessment problems to be solved with much greater accuracy. Their binary factorisation algorithm [3.7] enables much larger models with continuous variables to be computed. As a result, Agena Ltd have developed new functions in the AgenaRisk desktop software to compute a) hybrid influence diagrams, and b) value of information. These two important new tools used Fenton and Neil's published papers [3.6] [3.3] [3.7] describing the necessary algorithms. While there are several other tools that compute influence diagrams and values of information, AgenaRisk is the only one that can do this accurately for hybrid models (ie those with both discrete and continuous variables).

**3. References to the research** (indicative maximum of six references)

[3.1] Neil, M., Fenton, N. & Nielsen, L. (2000). Building large-scale Bayesian networks. *The Knowledge Engineering Review, 15(*3), 257-284. https://doi.org/10.1017/S0269888900003039

[3.2] Fenton, N., Neil, M. & Lagnado, M. N. (2013). A general structure for legal arguments about evidence using Bayesian networks. *Cognitive science, 37 (*1*)*, 61-102. https://doi.org/10.1111/cogs.12004

[3.3] Fenton, N. E., Neil, M. & Caballero, J. G. (2007). Using ranked nodes to model qualitative judgements in Bayesian networks. *IEEE TKDE, 19(*10*),* 1420-1432. https://doi.org/10.1109/TKDE.2007.1073

[3.4] Constantinou, A. C., Fenton, N., Marsh, W. & Radlinski, L. (2016). From complex questionnaire and interviewing data to intelligent Bayesian network models for medical decision support. *Artificial Intelligence in Medicine, 67,* 75-93. https://dx.doi.org/10.1016%2Fj.artmed.2016.01.002

[3.5] Fenton, N. E., Neil, M., Hearty, P., Marsh, W., Marquez, D., Krause, P. & Mishra, R. (2007). Predicting software defects in varying development lifecycles using Bayesian nets. *Information & Software Technology, 49*, 32-43.1. https://doi.org/10.1016/j.infsof.2006.09.001

[3.6] Neil M., Tailor M. & Marquez, D. (2007). Inference in hybrid Bayesian networks using dynamic discretisation. *Statistics and Computing, 17(*3*),* 219-233. https://doi.org/10.1007/s11222-007-9018-y

[3.7] Neil, M., Chen, X. & Fenton, N. (2012). Optimizing the calculation of conditional probability tables in hybrid Bayesian networks using binary factorization. *IEEE Transactions on Knowledge and Data, 24(11)*, 1306-1312. https://doi.org/10.1109/TKDE.2011.87

**Evidence of the quality of the research:**

[EQR. 1] Fenton, N. & Neil, M. (Feb 2019-Jan 2020). Knowledge Discovery from Health Use Data. *Turning Institute*. https://www.turing.ac.uk/research/research-projects/knowledge-discovery-health-use-data. GBP100,000.

[EQR. 2] Fenton, N. [Principal Investigator] & Neil, M. [Co-Investigator]. (June 2017-May 2020). Patient Managed Decision-Support using Bayesian Networks [EP/P009964/1]. *EPSRC*. Research Grant. GBP1,538,497.

[EQR. 3] Fenton, N. [Principal Investigator] & Neil, M. [Co-Investigator]. (Jan 2017-Jan 2020). Improved Understanding of Causal Models in Dynamic Decision-making [RPG-2016-118]. *Leverhulme Trust*. Research Project Grant. GBP385,510.

[EQR. 4] Fenton, N. (2016). Simons Fellowship. *Newton Institute for Mathematical Sciences, University of Cambridge.* https://www.newton.ac.uk/event/fos

[EQR. 5] Fenton, N. [Principal Investigator]. (April 2014 - March 2018). Effective Bayesian Modelling with Knowledge Before Data [339182]. *European Research Council*. Advanced Grant. https://cordis.europa.eu/project/id/339182. EUR1,572,562.

[EQR. 6] Fenton, N. & Neil, M. (2018). Fellows. Turning Institute. https://qm-rim.org/2018/10/17/rim-turing-fellows/

**4. Details of the impact** (indicative maximum 750 words)

AgenaRisk is now in use by organisations to support risk assessments. Typical benefits to users are solving safety and reliability problems, solving cost benefit problems and satisfying regulators. Since 2014, AgenaRisk has added over 4,500 registered users, including several hundred commercial users with paid licences [5.1, 5.2]. Over 70% of Agena Ltd's income is from organisations outside the UK.

**Evaluating the safety of medical devices**

The world's largest medical devices company Medtronic has 40 licences of AgenaRisk, which are used in evaluating safety of devices, as well as for project decision making. Since 2015, Medtronic has used AgenaRisk to model SureValve (used in heart failure management) and PlasmaBlade (used in surgery) for single use or mission reliability. It has also used AgenaRisk to model the probability of patient harm due to issues with an Accelerometer used in Micra and LinQ pacemakers. This enabled a timely and successful launch for the Micra device, which was recognised by US News and World Report as Medical Product of the Year for 2016. Eric Maas, senior Director at Medtronic, has said that the deterministic modelling that Medtronic engineers use does not adequately address the "manufacturing variations, variations in patient anatomy, variations in usage by medical personnel, and variation in the environment of use," which are not directly controlled by development engineers. Thus, the modelling needs to be "augmented with a probabilistic or stochastic modelling approach. AgenaRisk not only provides such a tool – it enables the engineers to THINK probabilistically. It allows them to visualise the variations in use conditions and optimise the design of our medical devices so as to maximize the probability of successful medical applications and minimise the likelihood of harmful actions*"* [5.3].

**Supporting clinical decision making**

In partnership with trauma surgeons at the Royal London Hospital, one of the busiest trauma centres in Europe, Profs. Fenton and Neil have developed two clinical decision support (CDS) tools to construct "causal networks" that reproduce the reasoning pathways that clinicians use when working out if a patient is likely to be at risk of a particular condition or outcome [5.4]. The first tool has been shown to be as accurate as specialised blood tests for coagulation, but in a way that obviates the need for sophisticated laboratory equipment. This allows the clinical team to offer damage control resuscitation to patients who need such treatment, and spare patients who do not need it from the potential side effects of this treatment. Similarly, the Limb Salvage CDS tool is designed to help doctors make decisions about how to save an injured patient's limb(s). Nigel Tai, consultant Trauma & Vascular Surgeon at the Royal London hospital confirms, "these decision-support tools, designed to meet the needs of time-poor clinical decision-makers working under pressure, will improve patient care – especially so in under-resourced settings where sophisticated laboratory kit or the absence of senior surgical support threatens optimal patient care" [5.5].

**Informing Government decisions on an agriculture for nutrition strategies [5.6, 5.7]**

*Kenya*

In collaboration with Fenton and Neil, the ICRAF (part of the World Agroforestry Centre in Kenya) calculated costs and benefits of two alternative agricultural development project proposals over a period of 10 years to enable decision making. A group of subject experts defined the primary risk factors that could affect the outcomes of the projects. The projects benefit the local community by improving the quality of food and water supplies. They also have environmental benefits by decreasing the ecological footprint. One of these proposals had higher costs and uncertainty but could also lead to more benefits. The other project was a safer option requiring a smaller budget but its potential return was also smaller. Fenton and Neil built a model to calculate the costs and return on investment of the projects.

*Uganda*

Uganda Vision 2040 provides development paths to operationalise Uganda's Vision statement: "A Transformed Ugandan Society from a Peasant to a Modern and Prosperous Country within 30 years" as approved by Cabinet in 2007. It aims to transform Uganda from a predominantly low-income country to a competitive upper middle-income country. The Vision 2040 agricultural and nutrition strategy addressed poverty, food insecurity and malnutrition in the country but lacked clarity about household nutrition. Therefore, Fenton and Neil used AgenaRisk to develop an impact model of the strategy. The strategy, among other objectives, sought to transform the country's agricultural landscape from traditional systems to large-scale commercial agriculture. Model results suggested that the strategy was likely to have negative outcomes for the rural livelihoods it intended to support with no appreciable influence on household hunger but, by influencing preferences for and access to quality nutritional foods, increased the prevalence of micronutrient deficiency. The results highlighted to the Government the trade-offs to be negotiated to support decision making around agriculture for nutrition.

**Modelling and predicting cybersecurity risk**

Five US and Indian technology companies are using AgenaRisk to model and predict cybersecurity risk. The international collaborative project BARD [5.8] - funded by the US Intelligence and Research Agency (IARPA) - used AgenaRisk across all its sites to tackle a variety of intelligence related problems. The companies considered problems where agents were presented with multiple pieces of evidence from different sources of varying accuracy, some of which could be contradictory. Fenton and Neil worked as consultants to develop intelligence related models and train users to build and run the models. Since the end of the project, Monash University, Australia has been using the AgenaRisk application programming interface (API) as a platform for its own web-based intelligence modelling system.

**Developing tools and training for law and forensics**

Fenton led the prestigious 6-month Programme on Probability and Statistics in Forensic Science (FOS) at the Isaac Newton Institute for Mathematical Sciences (INI), University of Cambridge, which was heavily focused on the use of BNs in law. The programme not only attracted the world's leading legal and forensic scholars, but also attracted many high-level judges, lawyers and decision makers. A significant output of the programme was a set of guidelines for lawyers and forensic scientists [5.9], which led to the decision by the International Criminal Court in the Hague to train all their judges and lawyers in the use of Bayesian methods to efficiently process pre-trial evidence. In July 2017, Fenton was invited to provide the majority of the training. Fenton and Neil's work is also cited as recommended reading in the new Guidelines for Advocates document produced by the Royal Statistical Society and the Inns of Court College of Advocacy [5.10]. Finally, Fenton and Neil have developed an on-line tool, jointly with researchers at the Dutch Forensic Institute, which automatically generates the necessary BN models for forensic analysis of cases of linked crimes [5.11].

**Assessing financial risk**
AgenaRisk is used by eight of Milliman LLC's (the world's largest independent international actuarial firm) clients for operational risk management, risk tolerance and for other financial/insurance risk applications such as pricing and investment performance assessment [5.12].

**5. Sources to corroborate the impact** (indicative maximum of 10 references)

[5.1] *Bayesian Network Software for Risk Analysis and Decision Making*. AgenaRisk. https://www.agenarisk.com/. 26 October 2020.

[5.2] E Tranham. Commercial Director. *Agena Ltd* (testimonial letter, 27 April 2020). [Corroborator 1]

[5.3] E Maas. Senior Director. *Medtronic* (testimonial letter, 10 March 2019). [Corroborator 2]

[5.4] *Trauma models, prognostic models for trauma care*. Queen Mary University of London. www.traumamodels.com. 26 October 2020.

[5.5] N Tai. Consultant Trauma and Vascular Surgeon. *Queen Mary University of London* (testimonial letter, 29 September 2020). [Corroborator 3]

[5.6] C.Whitney , D Lanzanova, C Muchiri , K D. Shepherd, T. S. Rosenstock, M Krawinkel, J R. S. Tabuti, R Luedeling (2018). Probabilistic Decision Tools for Determining Impacts of Agricultural Development Policy on Household Nutrition. *Earth's Future, 6*, 359-372. 10.1002/2017EF000765

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[5.8] A Nicholson. Deputy Dean, Research. *Monash University* (testimonial letter, 20 June 2019). [Corroborator 4]

[5.9] Probability and Statistics in Forensic Science (2017). *Twelve Guiding Principles and Recommendations for Dealing with Quantitative Evidence in Criminal Law*.

[5.10]The Inns of Court College of Advocacy, The Council of the Inns of Court. Royal Statistical Society (2017). *Statistics and probability for advocates: Understanding the use of statistical evidence in courts and tribunals*.

[5.11] *Generate BNs for crime linkage problems with one offender*. Bayes Knowledge. http://bayes-knowledge.org/index.php/2015-06-23-01-41-28/generating-models/crime-linkage-one-offender. 26 October 2020.

[5.12] N Cantle. Principal. *Milliman* (testimonial letter, 4 March 2019). [Corroborator 5]