Institution: University of Strathclyde

Unit of Assessment: C17 Business and Management Studies

Title of case study: Enhancing decision-making through new modelling methods of dependent risks to improve engineered systems and complex projects

Period when the underpinning research was undertaken: 2000 - 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:
John Quigley	Professor, Management Science	9 June 1997 - present
Lesley Walls	Professor, Management Science	1 July 1994 - present
Susan Howick	Professor, Management Science	2 October 1995 - present
Colin Eden	Professor, Management Science	1 January 1988 - 31 December 2014
Matthew Revie	Professor of Practice	1 October 2007 - present
Euan Barlow	Knowledge Exchange Fellow	2 November 2009 - present

Period when the claimed impact occurred: August 2013 - December 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

Strathclyde research recognised that dependencies between events must be captured to properly assess risk; otherwise risk exposure will be understated and opportunities to learn from related events will be lost. Novel methods and tools, based on the research of the group, have been created for problem structuring, modelling, elicitation, inference and decision support. These have been used in technical risk management for new product development, informed modelling used for risk management of the GB rail system, reduced the costs of renewable energy project bids, influenced a large EU arbitration case, enabled city resilience planning and been referenced by international standards (ISO 31010, IEC 61164).

2. Underpinning research

The need to inform and improve decisions about problems where risk must be considered motivated the research. The problem characteristics considered in our research span degrees of complexity, uncertainty and ambiguity, where events, both anticipated and/or observed, might be realised in dynamic environments. Common to all problems is the potential for dependencies between events, which must be captured and modelled in order to assess risk properly. Failing to account for these dependencies will understate exposure to risk, as well as neglecting the opportunity to learn from related events and reduce inference error.

A theme in our research is understanding how systems – by which we mean complex projects or engineered systems – fail. The focus of early research (pre-2012) by Howick and Eden was project risk, while Walls and Quigley focused on technical risk. Joint work then followed, including colleagues Barlow and Revie, in order to further develop novel modelling methods. We have had a programme of UKRI, EC, government and industry funded research.

Initially, Strathclyde project risk research focused on forensic analysis to assess the causes of delays and disruptions for engineering projects. Engagement with experts and key stakeholders informed the identification of the lack of causal modelling as a fundamental shortcoming of traditional project risk analysis. New methodological processes were developed to support not only forensic [**R1**] but also prospective project risk analysis [**R2**], then subsequently evaluated and matured through a series of industry funded research projects (e.g. Bombardier, SSE) and the EC H2020 Smart Mature Resilient (SMR) project. New analytical tools were created, including the Risk Filter and Risk Systemicity Questionnaire (RSQ).

Simultaneously, Walls and Quigley worked on technical risk analysis problems in research funded by UK government and aerospace companies (REMM2 project). Similar shortcomings were identified in the models used to analyse and predict the changes (growth) in reliability associated with the removal of uncertain systemic weaknesses in engineering systems during new product development projects. Strathclyde researchers established that traditional growth modelling failed

to capture expert engineering judgement in a meaningful way to stakeholders. To address this, the researchers created a socio-technical modelling process [**R3**]. Subsequently, multiple industry cases (e.g. Agusta Westland, BAE SYSTEMS, Smiths Industries, Rolls Royce, TRW) evaluated the new process. A distinctive characteristic of the approach was the use of historical data to model an expert's uncertainty about possible events through analogy. Effectively relating possible future histories to the past allowed the model to be expressed probabilistically and so provided a coherent basis for inference to generate predictions [**R4**, **R5**]. Further development of these methods continued through theoretical research funded by EPSRC and applied research with organisations, such as RSSB and Irvin GQ.

Barlow and Revie developed a modelling framework to manage risk in the real-time planning and scheduling of complex projects. Their research funded by and aligned with the needs of a consortium of UK energy companies was conducted in collaboration with engineering researchers (2013-2015). Strathclyde researchers created a new methodological approach which combined analytical methods in such a way that networks of dependent uncertain events could be modelled to evaluate actions dynamically in time during a project [**R6**].

Strathclyde research supports more reliable quantitative measures of system performance, and also the modelling processes provide dialectic devices to challenge thinking about risk through explicating cause and effect relationships. Novel methods have been created for constructing models to explain dependencies in risk problems, through representing interactions of entities within a system [**R1**, **R2**, **R3**, **R6**] or modelling statistical dependencies to reduce estimation errors for rare events [**R4**, **R5**].

3. References to the research (Strathclyde affiliated authors in **bold**)

R1 **S. Howick, C. Eden**, **F. Ackermann,** T. Williams (2008) Building confidence in models for multiple audiences: the modelling cascade, *European Journal of Operational Research*, 186: 1068-1083 https://doi.org/10.1016/j.ejor.2007.02.027 [REF2 in 2014]

R2 F. Ackermann, **S. Howick, J. Quigley, L. Walls, T. Houghton** (2014) Systemic risk elicitation: Using causal maps to engage stakeholders and build a comprehensive view of risks, *European Journal of Operational Research*, 238(1): 290–299 https://doi.org/10.1016/j.ejor.2014.03.035 [REF2]

R3 **L. Walls, J. Quigley** (2001) Building prior distributions to support Bayesian reliability growth modelling using expert judgement, *Reliability Engineering & System Safety*, 74(2): 117-128 https://doi.org/10.1016/S0951-8320(01)00069-2

R4 **L. Walls**, **J. Quigley**, J. Marshall (2006) Modeling to support reliability enhancement during product development with applications in the U.K. aerospace industry, *IEEE Transactions on Engineering Management*, 53(2): 263-274, https://doi.org/10.1109/TEM.2006.872342

R5 **J. Quigley**, **G. Hardman**, **T. Bedford**, **L. Walls** (2011) Merging expert and empirical data for rare event frequency estimation: Pool homogenisation for empirical Bayes models, *Reliability Engineering & System Safety*, 96(6): 687-695 https://doi.org/10.1016/j.ress.2010.12.007 [REF2 in 2014]

R6 **E. Barlow**, **D. Tezcaner Öztürk**, **M. Revie**, **K. Akartunali**, **A.H. Day**, **E. Boulougouris** (2018) A mixed-method optimisation and simulation framework for supporting logistical decisions during offshore wind farm installations, *European Journal of Operational Research*, 264(3): 894-906 https://doi.org/10.1016/j.ejor.2017.05.043 [REF2]

Notes on the quality of research: All articles have been peer-reviewed and are published in leading international journals. The researchers have attracted GBP2,006,620 of competitive funding related to the underpinning research. Key funders include: EPSRC; Industry (e.g. Revie et al., *TIC LCPE: Analysis and optimisation of offshore wind farm installation logistics*. SSE, Technip Offshore Wind, Scottish Power consortium, GBP218,019, 01/10/2013-28/02/2015); EC H2020 (e.g. Howick, Eden et al., Smart Mature Resilience. Total: EUR4,641,233.25, Strathclyde: GBP424,296, 01/06/2015-31/06/2018).

4. Details of the impact

By enhancing risk and reliability assessment methods, Strathclyde's research has enabled companies to improve reliability growth analysis in new product development and risk analysis for complex projects. The research resulted in methods to address systemic technical and project risk problems recognised by industry but for which no coherent analytical models previously existed. The use of the methods has informed decisions to allocate resource for risk mitigation and resulted in new processes for industry in the UK and globally.

Enhanced risk and reliability assessment methods in international standards

The 2019 edition of the international standard ISO 31010 [**S1a**] references Strathclyde methods developed in **R2** and **R3**. This global standard aids users in selecting and applying risk assessment methods applicable for a wide range of contexts, including technological systems, engineered products and complex projects. Users include Grundfos, a Danish pump company for whom reliability is a key operating objective given the worldwide use of their pumps in critical infrastructure including water and energy systems, industrial processes, agriculture and irrigation. As confirmed by the company's Senior Manager for Product Safety, *'Grundfos engages with and adopts international standards, including ISO31010, because these represent best practice guides, developed through global collaboration and knowledge sharing, for assessing reliability and risk'* [**S2**].

The international standard for reliability growth analysis, IEC 61164 [**S1b**], reconfirmed in 2018 and adopted by national standards agencies (including the British Standards Institution), includes a model created by Quigley and Walls [**R3**, **R4**]. Users of this standard include the UK Ministry of Defence (MOD) directorate responsible for managing complex projects to procure, support and supply the services and equipment required by the three armed services. The senior MOD Dependability Engineer explains, *'Standards, including IEC61164, are vital to my team because we use them to guide our response plans for major procurement projects. Such standards are valuable because they provide a common language to guide the MOD as procurer and the companies as contractors in developing useful frameworks for reliability assurance… Strathclyde expertise has led the development of these international standards'* [**S3**]. This body of research [**R3**, **R4**] has also informed the 2018 Issue of the Society of Automotive Engineers (SAE) International Guidelines for Preparing Reliability Assessment Plans for Electronic Engine Controls (ARP5890). Acknowledging the inclusion of the approach based on Strathclyde's methodological research as an example of aerospace industry best practice, the Chair of the SAE International Standards Aerospace Propulsion Division highlights that *'this document has been cited by regulatory organisations (e.g. FAA) as the preferred approach in their rulemaking'* [**S4**].

Improved reliability growth analysis when innovating engineering systems

The research led by Quigley and Walls resulted in novel methods to capture and express the rich engineering knowledge about uncertainties associated with technology innovation in order to enable meaningful assessment of reliability growth through product design and development [**R3**, **R4**, **R5**]. Leading aerospace and defence companies with global markets continue to be impacted by this research over the period 2013-2020. For example, Rolls Royce Engine Controls, who were involved in the original REMM2 project, state that the resultant modelling guide authored by Strathclyde on the basis of **R3** and **R4**, provided *'a new way of approaching reliability growth analysis for the UK aerospace sector'* which *'still forms the basis of the way we continue to approach reliability'* [**S4**]. By enabling *'the elicitation of structured judgement about engineering concerns'* and providing *'a transparent mechanism to show how this translates to forecasts of reliability for new products',* the approach has resulted in *'greater effectiveness and efficiency…during the product development process'* [**S4**]. Likewise, Irvin GQ (whose products include aerial delivery solutions and rescue, safety and survival equipment) have used Strathclyde's methods [**R3**, **R5**], developed through multiple projects, to support reliability assessment. According to Irvin GQ's Engineering Manager, the methods delivered a *'combination of scientific ability and practical relevancy'* that has *'allowed us to prioritize major technical risk drivers and to allocate product development resource'*; this *'has led to changes in our routine approach to reliability-in-design…to inform reliability assessment and the consequent decisions to*

be taken' [S5]. As a result, the research *'impacted key engineering projects, as well as some standard operating practices'* [S5].

The application of analytical approaches (based on R3 and R4) through industry funded projects has also brought benefits to Leonardo MW Ltd, one of the biggest suppliers of defence and security equipment to the MOD. As outlined by Leonardo's Emerging Technologies Manager, these range from *'more effective and efficient internal processes for reliability in new product development through to contributing to the overall competitiveness of the business since reliability and supportability of our products is a critical operating objective'* [S6]. Furthermore, *'the process has allowed us to better manage technical risk in new product development and to deliver on strategically important programmes for innovative sensing technologies, for UK and international (North America, Europe and RoW* [rest of the world] *clients'* [S6].

Providing a customer perspective on the improvements made by such companies, the MOD's Senior Dependability Engineer states that *'Over the period 2014-2020 I have seen the real difference Strathclyde research has made to the approach contractors use for assessing reliability. This has enabled the MOD to be more effective in assuring the capability of the innovative equipment procured on behalf of the armed forces. This capability is paramount to successful defence operations'* [S3].

Improved risk assessment in complex projects

Strathclyde research has led to new modelling methods being used to support risk-informed decisions across different lifecycle stages for systems in multiple industry sectors, as well as to support city resilience planning.

Informed modelling used for risk management of the GB rail system

The Railway Safety & Standard Board (RSSB) objective is to lead and facilitate the British rail industry (the regulatory body, owners and maintainers of rail infrastructure, and operators of services on the rail network) to achieve continuous improvement in the health and safety performance of the railways in Great Britain (GB). RSSB have developed and maintain a Safety Risk Model (SRM), which is a quantitative representation of the risk arising from the operation and maintenance of the GB rail network and underpins the industry's evidence and risk based approach to safety management. Strathclyde research on inference to support prediction of risks [R5] was developed further through an RSSB funded research project to embed the inference methods within the company's model [S7]. As confirmed by RSSB's Principal Risk Analyst: *'The application and continued use of the University of Strathclyde work has been very beneficial in enabling RSSB to carry out our risk assessment and analysis work. By providing a risk profile of the GB rail network, the SRM informs design of safety management systems, supports development of long-term risk management strategies, feeds into cost-benefit analysis of risk mitigation actions and provides assurance that risk is managed in line with UK law'* [S7]. More specifically, *'Strathclyde's research has enabled RSSB to overcome the little or no data challenge with rare events within the SRM allowing us to obtain robust estimates for infrequent safety events to the rail industry'* [S7].

Reduced the costs of renewable energy project bids

Using the modelling framework created as part of the energy consortium funded research project to manage risk in the real-time planning and scheduling of complex projects [R6] allowed SSE Renewables to support installation strategy decisions for offshore wind farm projects. According to SSE Renewables' Director of Engineering and Innovation, *'Systemic risks related to weather downtime, vessel utilisation, activity durations, vessel reliability, etc., can make it extremely challenging to accurately predict the cost and duration of installation activities, which can consequently require developers to be more risk-averse when bidding in energy auctions by having to retain higher levels of contingency within a projects financial model'* [S8]. Validated by two external organisations, the Strathclyde model has been embedded within the company's processes so that the *'Engineering team view the tool as an essential part of their toolkit, evidenced by SSE Renewables continuing to invest in the development and maintenance of the tool'* [S8]. The new modelling has changed the level of bidding to the ultimate benefit of energy consumers. For the Beatrice wind farm (2016), analysis using the Strathclyde model *'contributed towards the shareholder decision making process to sanction the project and the debt financing process for*

this major capital project' [**S8**]. Similarly, for the Seagreen and three Dogger Bank projects (2019), *'the Strathclyde tool was used by both teams to develop and refine aspects of the bids',* allowing SSE Renewables to reduce *'the estimated capital expenditure within the project Financial Models by c. GBP20,000,000'* [**S8**].

Influenced the outcome of a large EU arbitration case

Howick and Eden acted as expert witnesses in the largest ever arbitration case in Europe at the time (companies to remain anonymous), a multi-billion euro arbitration with respect to a claim for disruption in a complex construction project. Invited on the basis of their recognised expertise in modelling the causes of project overruns, Howick and Eden delivered four expert reports to the tribunal (2013-2016) and provided evidence at two hearings in 2016. Drawing on their research, including **R1**, Howick and Eden presented a case to the tribunal that demonstrated the other side's simulation models (which were being used to evidence 70% of the case) were flawed and should not be relied on to determine the causes of the overrun. The tribunal accepted their arguments and concluded that the other side's model was not reliable and thus should not be used to inform an award [**S9**]. Confirming this contribution and the wider benefits to the international law firm involved, White & Case note: *'In addition to the work performed by Dr Eden and Dr Howick within the arbitration process, their published research has been helpful in seeking to understand the science behind dynamic simulation and how it can be used in assessing and predicting project performance'* so that *'lawyers within White & Case have been able to develop considered views of the strengths and weaknesses of the method in the context of construction claims'* [**S9**].

Enabled city resilience planning

In 2017, the Risk Systemicity Questionnaire (RSQ) (developed through the European Commission Smart Mature Resilience project, drawing on **R1** and **R2**) was utilised by city planners in four European cities (Glasgow, Kristiansand, San Sebastian, Rome) to understand risk interdependencies and identify priorities [**S10a**]. These analyses directly informed each city's Resilience Action Plan, as well as improving internal communication between municipal departments. Taking the City of Rome as an example, use of the RSQ to identify priorities resulted in *'a comprehensive outline of recommendations for an effective Resilience Action Plan based on a thorough, scientific-based risk assessment'* [**S10b**]. These recommendations were subsequently implemented through various initiatives, including the development of early warning systems for extreme weather conditions.

5. Sources to corroborate the impact

S1 Extracts from international standards showing reference to methods from Strathclyde research:
- **a.** ISO 31010 Risk Management: Risk Assessment Techniques;
- **b.** IEC 61164 Reliability Growth – Statistical Test and Estimation Methods.

S2 Factual statement from Senior Manager, Product Safety, Grundfos (15/02/2021).

S3 Factual statement from Senior Dependability Engineer, Logistic Support Operating Centre, Defence Equipment and Support, Ministry of Defence (26/02/2021).

S4 Factual statement from Chair of the SAE International Standards Aerospace Propulsion Division and Engineering Associate Fellow for Controls Maturity and Reliability at Rolls Royce Engine Control Systems (25/08/2020).

S5 Factual statement from Engineering Manager at Irvin GQ (02/04/2020).

S6 Factual statement from Emerging Technologies Manager, Leonardo MW Ltd (16/03/2020).

S7 Factual statement from Principal Risk Analyst, RSSB (23/05/2020).

S8 Factual statement from Director of Engineering and Innovation, SSE Renewables (02/04/2020).

S9 Factual statement from Partners at White & Case LLP (22/12/2016).

S10 Evidence of use of Risk Systemicity Questionnaire in four European cities:
- **a.** Peer Review Meeting Report for SMR – SMART MATURE RESILIENCE - project, March 2017;
- **b.** Factual statement from Risorse per Roma SpA on behalf of the City of Rome (24/10/2019).