CASE STUDIES ILLUSTRATE THE BENEFITS OF SIMULATION MODELING

Daniele Maggi (*Arthur D Little Spa., Italy*), Alfredo Verna (*Arthur D Little Ltd., UK*) and Geoff Stevens (*Risk Simulation Ltd., UK*)

This paper sets out to describe simulation modeling and the benefits it offers for improved analysis of Process Safety. The principle of the simulation approach is introduced using a general example and three further examples illustrate applications for Safety Performance, Plant Production and System Availability. The benefits for each of the main steps in safety analysis; hazard identification, consequence assessment and frequency estimation are demonstrated. But before describing this case work it is helpful to review the status of Process Safety Analysis to appreciate current shortcomings and the need for a change of approach.

CHALLENGES IN PROCESS SAFETY ANALYSIS

The key elements in the analysis of Process Safety each have practical challenges

– **hazard identification** requires methods which bring to light the main hazards without overlooking potentially hazardous situations. Provided systematic techniques such as Hazard and Operability Study (HAZOP) are used and attention is paid to skillful facilitation, complete recording and breadth of team experience the results can be satisfactory (Verna 2009). Further value can be added by prioritising the resulting recommendations (Beall 2007).
– **consequence assessment** needs to be transparent and consistent between different analysts. In practice the assessment is often left in the hands of an "expert" working with specialist software which may not be widely understood and can seen by non-initiates as "a black box" (Ayyoubi 2009). The scenario defined for the consequence modeling (such as hole of a certain size in a pipe operating at a given Pressure and Temperature, carrying a specific substance) is critical if credible results are to be derived. Over the past 30 years particular types of consequence modeling have been promoted to satisfy specific regulatory requirements such as safety case regimes in major hazard industries (Pasman 2009). But once regulatory approvals have been obtained in the early stages of the development, the risk assessment is often put to one side and not used to improve process safety.
– **frequency estimation** needs to be objective, transparent and relevant to the plant under study yet this is perhaps the area where there is most subjectivity. Methods such as fault tree analysis allow ample scope for variation in the structure used to build the fault tree. Use of generic data for base event frequencies and probabilities can introduce wide ranges of uncertainty (Stevens 1992). This occurs where outdated publications, data from other industries or ad-hoc estimates by the analyst are used for influential branches of the tree. Some regulatory authorities require the analyst to determine the impact of "credible events" to make sure the required prevention and protection measures are implemented. In Italy for example the "threshold of credibility" is taken as 10^{-7} per year tempting the analyst to demonstrate that events with large consequences have a lower occurrence and so can be ignored in the analysis. In audits we have found fault trees which are logically incorrect and/or with inappropriate base failure rates used to claim that events with historical precedence lie below the threshold of credibility and hence need not be considered in the process safety analysis.

The extent of specialisation involved in risk assessment can be illustrated from a study of papers published between 2000 and 2009 in four scientific journals concerned with Process Safety (Marhavilas 2011). Apparently only about 7% of over 6000 publications in the field of Process Safety dealt with Risk Assessment. This is consistent with developments in risk assessment becoming a specialist subject of concern to initiates rather than a topic in the mainstream.

The reliability of the output from risk assessments carried out for Process Safety Management has proved rather patchy. A comparative study twenty years ago examined risk analysis results from 11 teams from different European countries working on the same problem (Amendola 1992). The spread of risk results was over 5 orders of magnitude. The study was repeated ten years later in a similar exercise involving 7 teams and this time the spread in results was somewhat less but still the radius of a significant risk contour varied by a factor 3 between the various teams and societal risk differed by 2 orders of magnitude (Lauridsen 2002). The factors behind these variations included the choice of consequence model, which base event frequencies were used and how the scenario source terms for the assessment were defined.

In such a specialist field, the work too often involves an expert working alone, selecting source terms to input into software only he or she fully understands. Perhaps we should not be too surprised that the results turn out to be so variable and that project engineers and decision-makers have become skeptical of the approach, regarding it as a "necessary evil" for regulatory compliance but not adopting it as a tool to guide key decisions.

STATUS OF PROCESS SAFETY

Before going on to consider ways to improve the situation we should ask first if it matters. Annual statistics from major companies engaged in the process industries indicate an improved performance in occupational safety with reductions of 8–10 fold reported over the past 15 years (Pitblado 2011). But such improvements have not been mirrored by comparable improvement in Process Safety and major process property losses continue even after the peaks of the late 1980's (Marsh 2012). This finding confirms the conclusions of the Baker Report criticising lack of attention to Process Safety following the events at Texas City (Baker 2007). Despite the clear lessons to be learned from past incidents we still find operating companies who seem to treat Process Safety Analysis as an unavoidable expenditure or bureaucratic burden to "appease" the regulatory authorities, not as a central tool for Process Safety Management (PSM).

BARRIERS TO PROGRESS IN PROCESS SAFETY

Recently there have been calls from the HSE for a change of pace on Process Safety to get Business Managers to focus on the topic recognising that when PSM goes wrong the results can be catastrophic. (Hackitt 2011). Achieving the necessary sustained focus will not be easy because process safety losses are rare episodes, uncertain to predict and somewhat less tangible than the business situations managers confront on an daily basis. Indeed a way of thinking has developed which views such catastrophic losses as quite unexpected, the so called "Black Swan" events which are not thought credible until they have occurred (Beall 2008).

In practice this viewpoint is rarely justified because on many occasions new incidents repeat old accidents (Pilkington 2011). For example one recurring issue is multiple shortcuts and skipping of procedures (such as the overriding of an interlock system) which removes one or more critical layers of protection (Chemical Sciences Board 2011). During more than 20 PSM audits of refinery and petrochemical plants carried out in recent years we have come across numerous instances of by-pass of interlocks (Pagnini 2010). These are not short term matters; sometimes interlocks remain by-passed for months or even permanently without any management of change study to support the decision. The reasons offered include:

- During the history of the plant, operators had not experienced the process deviation for which an interlock has been installed.
- The deviation may have occurred in the past, but with no safety related consequences so the operator comes to think that the interlock is "useless".
- Explicit or implicit pressure to maintain production may lead operators or shift supervisors to bypass an interlock without consulting or informing management even in cases where the site procedure requires this to be done.

Clear explanations are rarely forthcoming when audits reveal such conditions and this can reflect a culture of avoidance where "everybody knows but everybody pretends not to know". Other authors have attributed the willingness to take such short-cuts to causes such as lack of transparency, poor data sharing (Pilkington 2011) and deficiencies in safety training even at the graduate engineer level (Pitt 2012).

This paper tries to address these challenges to Process Safety Management and to characterise a simulation approach which overcomes these problems.

THE SIMULATION APPROACH

The simulation approach formalises the iterative process through which we develop our understanding of potential hazards and their associated risk. It confronts each of the barriers to progress in Process Safety introduced in the previous paragraph

- Lack of transparency
  The method like HAZOP is based on teamwork achieved through facilitated workshops. It takes its input not from the lone specialist but from the various disciplines engaged in the project (Verna 2008).
- Poor data sharing
  Assessments of risk inputs such as frequency and consequence are recorded and shared to all participants at each iteration of the process. One effective way is to include these in a Risk Register (Stevens 2011)
- Safety Training
  The workshop approach makes it easy for junior staff to participate alongside more experienced engineers. The contribution of less experienced participants can be discounted in the aggregated results but participation in discussion often proves a valuable learning experience (Verna 2009).

The approach we advocate using Microsoft Excel as a spreadsheet platform for the simulations ensures that the calculations remain open to all and the coding protocol ensures clear annotation of each step in the calculation. Through such transparency and group engagement the risk assessment exercise is presented as a group consensus, divergent opinions are accommodated and the outcome avoids coming across as a massaging of numbers or a manipulation of inputs to derive answers which avoid embarrassment or inconvenience.

SIMULATION MODELS; A HISTORICAL EXAMPLE

The first model example is intended to illustrate the simulation approach, to show it has a broad field of application and demonstrate it embraces uncertainty from the outset to provide results within explicit ranges of confidence. The approach is unlike a deterministic model which provides single value outputs suggesting precision even though the result is typically an approximation, validated over a limited parameter range.

The first model example deals not with technical issues but political and historical ones relating to the outbreak of

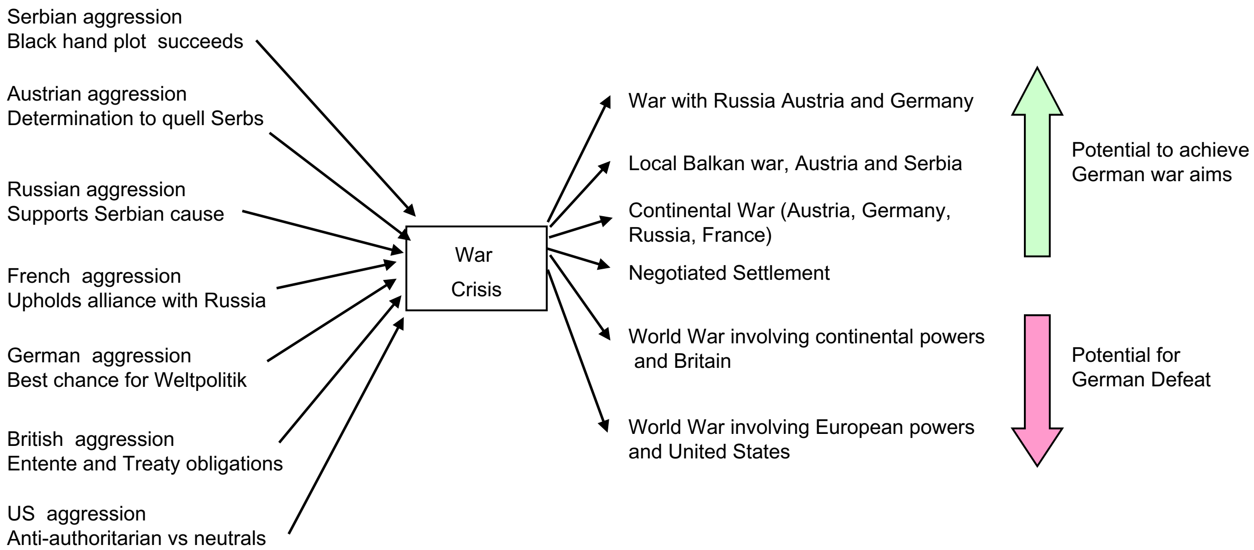

Figure 1. Bow-Tie diagram illustrating the events which contributed to the July 1914 crisis, the range of war outcomes and the extent to which these contributed to German political aims

First World War. There are so many books or publications on this question one might imagine that every last fact has been sifted through to establish an accepted explanation but this is not so and controversy continues almost one hundred years after the fact (Marwick 2000). The outbreak of war in August 1914 developed from the crisis precipitated by the assassination of the heir apparent to the Austro-Hungarian throne in Sarajevo on 28th June 1914. The events contributing to the crisis and the range of possible outcomes can be summarised using a diagram combining a Fault Tree with an Event Tree (Figure 1). The diagram was quantified for modeling by assessing the probability that those engaged in the crisis intended war and thought the outcome could align with their political aims. Of course definitive contemporary assessment is not available but ranges can be based on the diversity of expert opinion from the many historians who have subsequently researched this question. The results of the simulation which took a couple of days to research and set up illustrate clearly the role of what Donald Rumsfeldt (2009) called "known unknowns" and "unknown unknowns". From the Imperial German viewpoint the question of British neutrality in 1914 could be considered a "known unknown". So long as there was a fair chance that Britain would remain neutral the prospects to achieve their war aims illustrated in Figure 2 seemed quite good. Had the Imperial German calculations also considered the position of the United States and its reaction to unrestricted submarine warfare, a very different set of prospects in Figure 3 might have presented themselves. With a much greater chance of world war the likelihood for Imperial Germany to achieve its war aims appears greatly reduced. The diagrams show that defeat was not certain and indeed neither was war; diplomatic turns at several stages might have averted the conflict.

The point of this illustration is to show the benefit of a short modeling exercise and to draw out some of the essential characteristics of the simulation model

- The method embraces uncertainty. Instead of "best estimate" or even "conservative" single point values, the full range of values are included.
- The ranges of simulation inputs values are derived from many sources embracing different professional viewpoints in an inclusive and verifiable manner (in this case academic publications).
- The model is set up using an excel spreadsheet laid out to solve the problem being addressed. It is not a question of interpreting the problem to get it to fit available software.
- The process of setting up the model clarifies the problem boundaries and highlights assumptions in a transparent manner.

SIMULATION MODELS; SUPPORTING HAZARD IDENTIFICATION

HAZOP studies typically generate a large number of recommendations and relatively simple matrix ranking techniques based on assigning ranges of values for frequency and consequence can be used to prioritise implementation (Stevens 2001). By getting members of the HAZOP team to individually assess risk before and after the implementation of a recommendation it is possible to rank recommendations in order of risk reduction. The approach can be extended to benefit-cost analysis in cases where the cost of implementing the recommendation has also been estimated. Such exercises typically add a few hours to a HAZOP study. Simulation of the completed matrix for all the hazards identified allows a

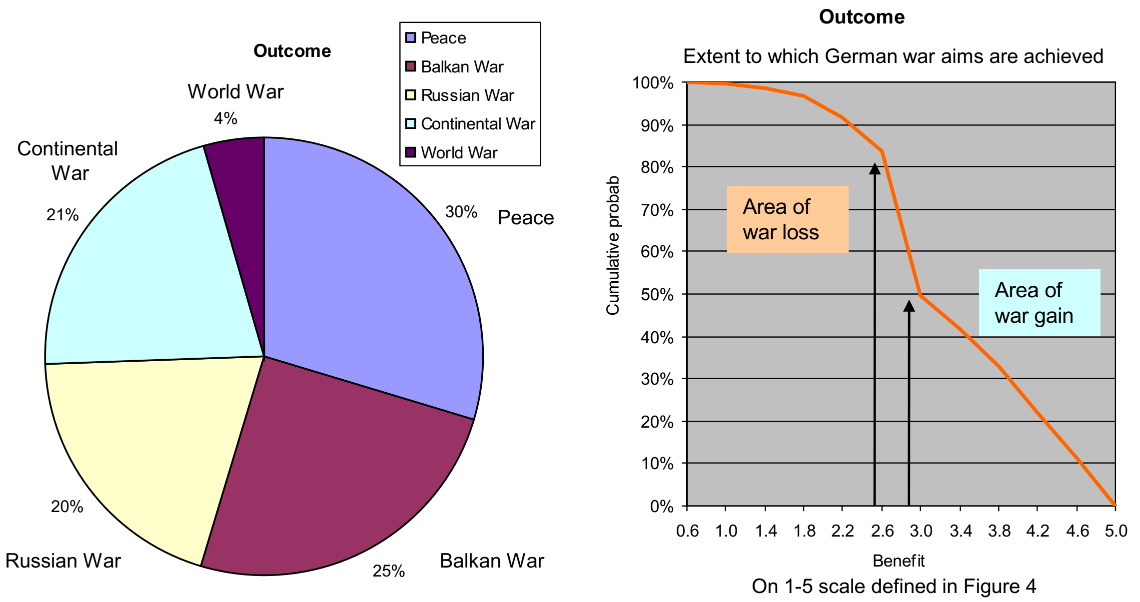

Figure 2. Simulation outcome from July 1914 crisis according to Imperial German assessment of uncertain British neutrality (US neutrality assumed)

cross-check between the profile of loss estimated for a specific plant subject to HAZOP study and the curves from Industry Loss statistics (Stevens 1992, 1998, 2001)

Once the assessment has been checked in this way, risk registers can be compiled capturing the main hazard description from the HAZOP record and combining that with the HAZOP team's matrix ranking exercise (Beall 2007). The approach illustrates the features of simulation modeling

- Input based on multiple sources of expertise relevant to the study (in this case the HAZOP team)
- Use of simple excel spreadsheets for data collection, simulation by visual basic macro routines and graphical representation of the simulation output
- The findings of a study lasting several weeks can be condensed into a single representation by plotting the benefit-cost ratio against the total loss aversion expected if the recommendation is implemented.

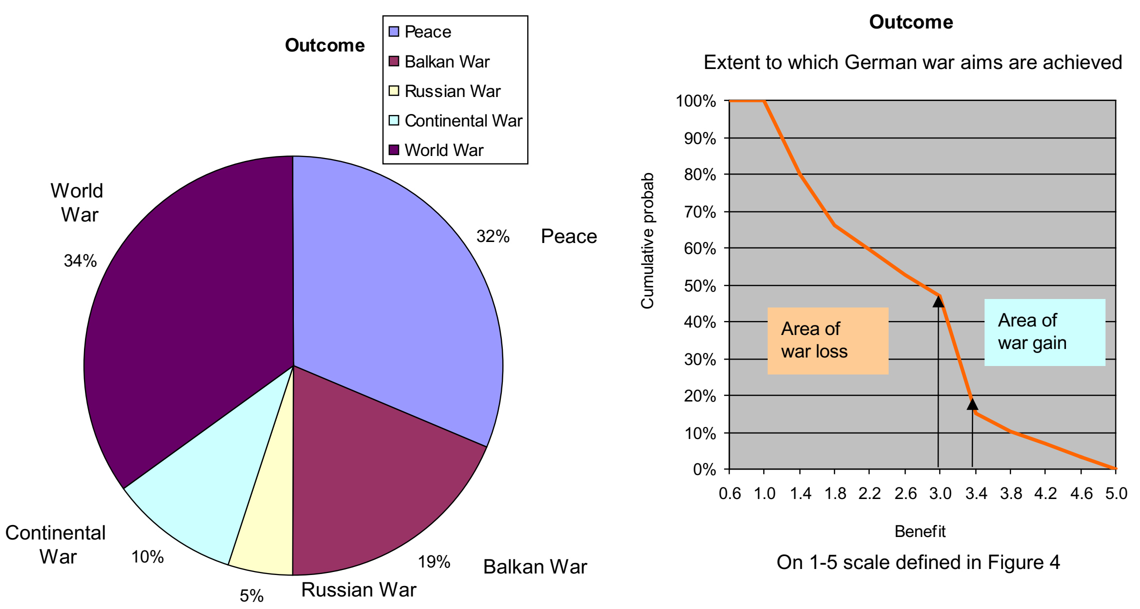

Figure 3. Simulation outcome from July 1914 crisis if neither British nor US neutrality is assumed

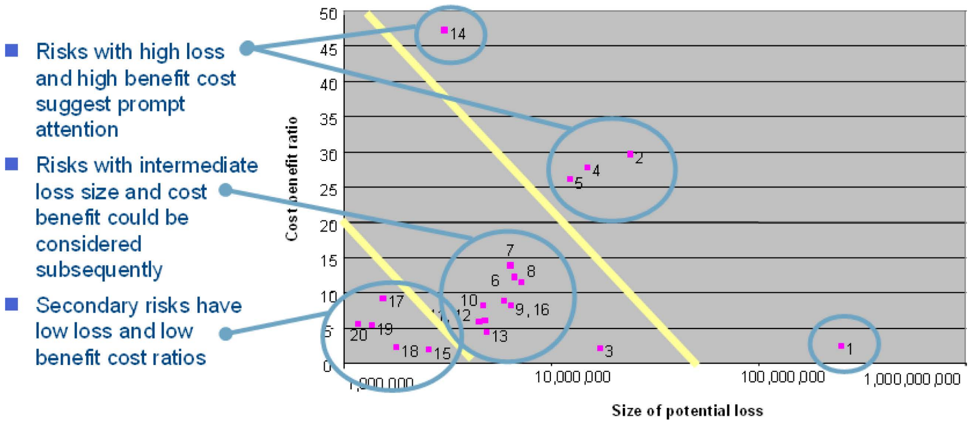

Figure 4. Plotting the Benefit-Cost ratio and the size of potential loss facilitates implementation of recommendations with large impact and good pay-out

Such a plot as shown in Figure 4 encourages a focused approach to the implementation of process safety by highlighting the recommendations with good benefit-cost ratios and worthwhile loss aversion.

SIMULATION MODELS; QUANTIFYING CONSEQUENCES

Deterministic consequence models typically provide effect distances for various hazardous scenarios which need to be combined either as contours for individual risk of fatality or as F-N curves to be interpreted against regulating authority criteria (Hobbs 2003). Simulation models however, derive consequences directly in terms of the parameters chosen for the particular problem; these can be F-N curves (Stevens 1992) Financial Loss (Stevens 2001) or in the case discussed here, Plant Production tonnages. This complex simulation model was developed in a week following visits and interviews across the site of an Ethylene Steam Cracker to understand which equipment failures contributed to production losses. The model was structured using fault trees to enumerate the many possible failure events and event trees to show which failures might lead to scenarios involving lost production. Wherever possible failure rate data from the site maintenance database was used in the model, specifying ranges for failure rate and repair times rather than single point "best estimates". An important step was to calibrate the model to simulate the actual production losses and the results in Figure 5 show model output compared to historical data for the loss in ethylene production and the number of plant outages per year.

Once the model had been calibrated, it was used in a series of workshops to test individual ideas for production improvement. Individual engineers or engineering teams could suggest improvements and all participants were asked their opinion on the effect expected in terms of equipment failure rate or time to repair. As would be expected there were a range of opinions and these were managed using a Delphi procedure in which views were collected, averaged and those at the extremes asked to explain the technical thinking behind their opinion prior to a second round of assessment. This procedure allowed for better consensus to be reached without "topping and tailing" extreme values. The effect of some 25 ideas were tested in this way and ranked by comparing the expected impact on ethylene production against the cost of implementing each measure. The outcome illustrated in Figure 6 shows this systematic approach to prioritization not only ranked projects but also sorted "the wheat from the chaff" demonstrating that only a handful of suggested improvements actually offered good benefit-cost ratios.

This model illustrates several of the practical benefits of simulation modeling

- Calculation of consequences in parameters of direct interest to Business Managers and calibrated against historical data for the site
- Encouragement to use site specific frequency data (in this case provided by participants from maintenance department from their site records)
- Ensuring inclusiveness and transparency by using the model in real time in a workshop setting to test the benefits of technical schemes proposed by participants from different departments in the organisation.

SIMULATION MODELS: FOCUS ON EVENT FREQUENCY

The last simulation model discussed here focuses on values for event frequencies. The operator of a petrochemical complex which received power and steam from external suppliers wanted to understand the impact on operations if a new boiler were constructed. Numerous configurations were proposed mainly focused on detailed aspects of the design such as drivers for boiler feed water pumps or redundancy in power interconnections. Technical time and energy had been absorbed in arguments between specialist departments and their competing claims for the limited funds available. Rather than adopt a "single value" fault tree approach it was decided to offer a simulation model.

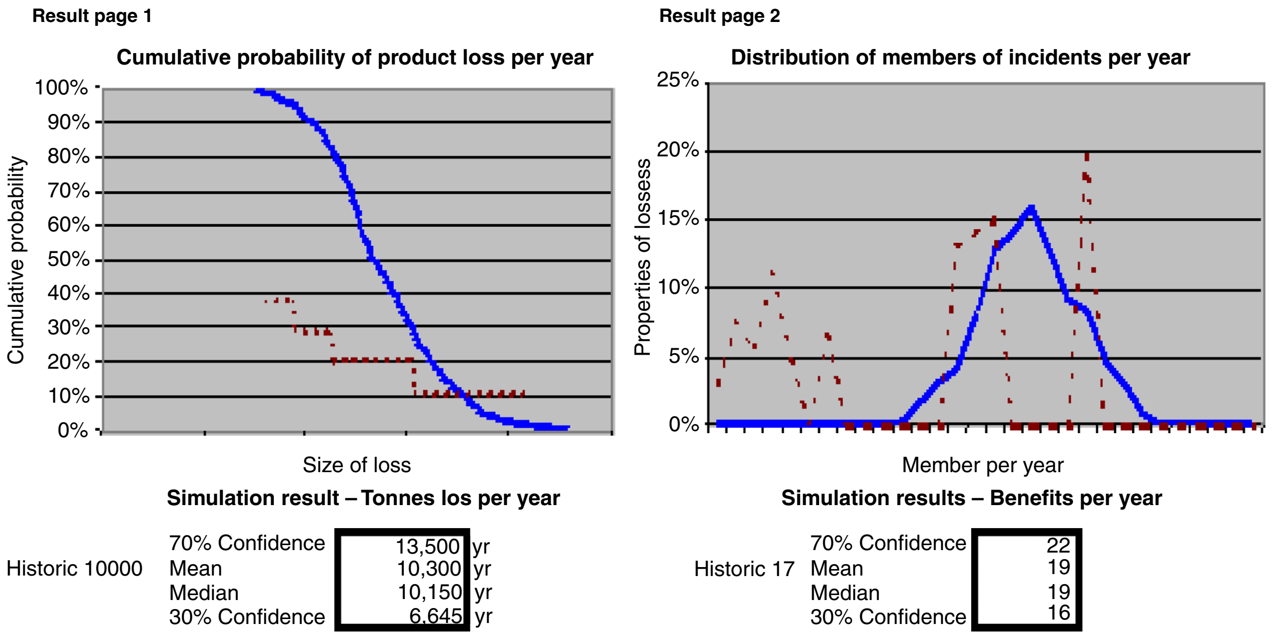

Figure 5. Output from the reliability model (blue lines) is compared with the actual experience of production loss or the number of outages (brown lines)

This approach added about 2 days to the modeling but the more inclusive approach allowed all parties to give full expression to the range of their opinions in the final results.

The need to understand and simulate the full system, including the external supplies, obliged participants to broaden their thinking which had previously been limited to their department responsibilities. It became clear that there was too little information available about the reliability of external supplies to offer a "before" and "after" risk comparison. The new boiler itself required external gas supply and Figure 7 shows that availability of this fuel was critical to the overall success of the project. A reliable supply had been assumed but the simulation illustrated it was important to confirm that understanding by further investigation and verification from the supplier.

This example illustrates ways in which simulation modeling can add value

- The effort required to define the model (needed either for conventional fault trees or for simulation modeling) was in itself an instructive process obliging specialists to think across the full scope of the problem rather than the details of their specialist field.
- Ad-hoc estimation of frequencies had a strong effect on the model outcomes encouraging a more thorough investigation of the systems available at the site.

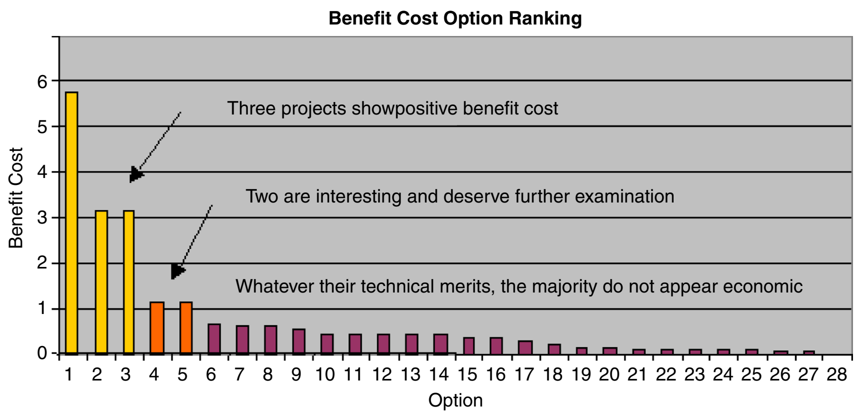

Figure 6. Benefit-cost comparison of proposed engineering improvements obtained by real time running of a production simulation model in a workshop environment

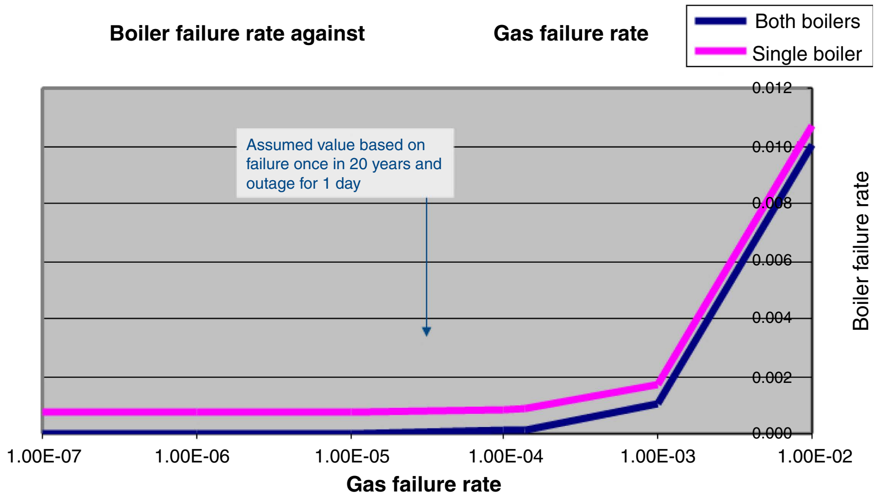

Figure 7. Simulated Boiler failure Rate against fuel gas failure rate

The modeling exercise in this case did not lead to a specialist approach understood by a few technical staff but instead provided a common platform for differing specialist views to be articulated in a transparent and even handed manner. Rather than having to arbitrate between competing technical factions, the results allowed management an overview of the entire project including aspects within its control and those where a successful outcome depended on external suppliers.

CONCLUSION

Simulation modeling offers users very different characteristics to the deterministic models often used for Process Safety analysis. By making the model transparent, directly applicable to the Business decision under study and open to embrace a range of opinion about the technical uncertainties, Simulation Models offer many advantages for improving Process Safety.

REFERENCES

Alfredo Verna & Geoff Stevens (2008) I*s HAZOP always the method of choice for identification of major process plant hazards?* IChemE Hazards XX (April 2008) Manchester England

Alfredo Verna, Silvia Fernandez & Geoff Stevens (2009) *Improving the performance and consistency of HAZOP facilitation and recording* IChemE Hazards XXI (November 2009) Manchester England

Amendola, A., Contini, S. and Ziomass, I. (1992) *Uncertainties in Chemical Risk assessment: results of a European Benchmark exercise* Journal of Hazardous Materials 29, 347–363.

Arthur Marwick, Clive Emsley, Annika Mombauer and Chris Williams (2000) *Europe in 1914* Milton Keynes Open University reprinted 2007 ISBN 9780749216979

Ayyoubi, M. (2009), *Consequence Modeling Lack of Accuracy and Its Effects on Quantitative Risk Analysis Results* 43rd Loss Prevention Symposium (Session 24d) AIChE April 2009

Beall, P. & Stevens, G. (2007) Making HAZOP the method of choice for identification and assessment of process hazards 9th Process Plant Safety Symposium. AIChE Houston.

Chemical Sciences Board "*Bayer CropScience explosion"* The Chemical Engineer March 2011, p. 11.

Donald Rumsfeldt (2009) sourced at http://www.youtube.com/watch?v = EIzRYEeW_Xk

Gary Pilkington (2011) *"Same old Story"* The Chemical Engineer March 2011 p. 45

Hobbs, M. & Stevens, G.C. (2003) *"How does safety performance affect Corporate Value*" Paper 55 in IChemE Hazards XVII (March 2003) Manchester England

James A Baker (2007) The report of the BP U.S. Refineries independent safety review panel R sourced at http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/SP/STAGING/local_assets/assets/pdfs/Baker_panel_report.pdf

Judith Hackitt (2011) "*Its not about the handrails*" The Chemical engineer May 2011, p. 3.

Lauridsen, K., Kozine, I., Markert. F., Amendola, A., Christou. M. & Fiori, M. (2002) Assessment of uncertainties in risk analysis of chemical establishments The ASSURANCE project sourced from www.risoe.dk/rispubl/sys/syspdf/ris-r-1344.pdf

Marhavilas, P.K., Koulouriotis, D. & Gemeni, V. (2011) "*Risk analysis and assessment methodologies in the work sites :*" Journal of Loss Prevention in the Process Industries 24 477–523

Marsh (2012) The Hundred Largest Losses 1972-2011 Large property losses in the hydrocarbons Industry 22nd Edition sourced at http://usa.marsh.com/NewsInsights/ThoughtLeadership/Articles/ID/20660/The-100-Largest-Losses-1972-2011-in-the-Hydrocarbon-Industry.aspx

Marco Pagnini, Stefano Milanese, Alfredo Verna, and James Perry (2010) *Practical implementation of "risk assessment" through Process Safety Management Systems* sourced at www.aidic.it/cet/10/19/programma.html

Martin Pitt (2012) "*How best to teach safety?*" The Chemical Engineer March 2012 p. 43

Pasman, H.J., Jung, S., Prem, K., Rogers, W.J. & Yang, X. (2009) "*Is risk analysis a useful tool for improving process safety?*" Journal of Loss Prevention in the Process Industries 22 769–777.

Philip Beall, Rodolfo Guzman, David Lyon, Geoff Stevens, Eleonor Kramarz (2008) *Black Swan Events – Should you be concerned?* Prism Vol 1 2008, p.11–28

Robin Pitblado (2011) *Global process industry initiatives to reduce major accident hazards* Journal of Loss Prevention in the Process Industries 24 (2011) 57e62

Stevens, G.C. & Humphreys A.M. (1992) Calibrating HAZOP studies paper33 IChemE October 1992 Major Hazards 1 Symposium series 130

Stevens, G.C. (1998) *Risk Ranking HAZOP recommendations as part of a coherent Risk Management Program* Society of Petroleum Engineers International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production held in Caracas, Venezuela, 7–10 June 1998

Stevens, G.C., Verna, A. & Marchi, M. (2001) *Getting full value from HAZOP. A practical approach to the assessment of risks identified during studies on process plants* IChemE Hazards XVI (October 2001) Manchester England.

Stevens, G.C. (2011) *Risk Quantification and Risk Management in Renewable Energy projects* Midlands Energy Graduate School symposium Uncertainty and Risk in Energy Futures Nottingham 8th-9th September 2011