Quantitative Bowtie Risk Model: An Agile Tool in the Utility Toolkit

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Abstract A major challenge faced by asset-intensive organisations is understanding the influence individual assets have on their parent facilities, and further, understanding the level of influence individual assets have on an organisation meeting its strategic goals. The need for an agile decision-making tool which provided this insight was identified and a Quantitative Bowtie Risk Model (QBRM) was developed. Probabilistic data such as condition rating, as-new failure frequency and barrier effectiveness are entered as modelling inputs. The quantitative likelihood and consequence outputs are then calculated and presented on the Bowtie graphic, which are mapped to the organisation's Corporate Risk Heat Map. Risk-dollars are used to demonstrate annualised fiscal risk exposure, providing cost-benefit optimisation of mitigation options. This allows the analyst to explore proposed mitigation options by altering inputs to represent the proposed options and then compare against the base case bowtie. The QBRM allows the analyst to explore TOTEX asset decisions, optimising risk, cost and performance across a combination of options. The QBRM also provides data confidence levels to the analyst by using qualitative and quantitative ratios to strengthen business case justification and helps identify knowledge areas needing improvement. This paper demonstrates the value of the QBRM through a real case study centred on a water pumping station.

1 Introduction

As more and more organisations seek to align their asset management practices to ISO 55000 [1], it is imperative that they can demonstrate data-led decision-making which shows a clear line-of-sight between their asset interventions and the beneficiaries.

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Brown and Humphrey state that in its most general sense, asset management is a business approach designed to align the management of asset-related spending to corporate goals. The objective is to make all infrastructure-related decisions according to a single set of stakeholder-driven criteria. The payoff is a set of spending decisions capable of delivering the greatest stakeholder value from the investment dollars available [2].

It is important for asset-intensive organisations to be able to quantify what influence assets have on the facility within which they are housed, and ultimately, the corporation's risk profile. Further, as facilities mature, safeguards may become less effective or degraded meaning risks may increase [3]. This insight into the risk profile of individual assets and the subsequent impact on the corporate risk position is essential for organisations in managing their assets in the most prudent and efficient manner. Nordgard and Solum note that in electrical distribution organisations, companies are developing strategies for maintenance and reinvestments, where the emphasis on cost effectiveness is balanced with other important dimensions of risk [4].

Evaluation of the author's employer, a large bulk water supplier, showed there was no risk methodology in use that quantitatively demonstrated the link between asset risk, facility risk and corporate risk. Further, there was no measurement of quantitative versus qualitative data sources to demonstrate decision-making robustness, or reporting of proactive versus reactive cost investment. Following an investigation into the various risk assessment methods available, a gap was identified in that a risk methodology was needed which provided the analyst with the ability to simulate asset interventions relating to changes in condition rating and system interventions using maximum acceptable outage times. The impact of changes at both the facility and system level needed to align with the organisation's specific risk categories and simulate real improvements to the organisation's risk position. The tool needed to present complex inputs and outputs on a single graphic and in such a way that it could be understood by a range of stakeholders with varying asset knowledge. To meet these requirements a Quantitative Bowtie Risk Model (QBRM) was developed. Because of their graphical nature, the biggest advantage of bowtie diagrams is the ease to understanding risk management by upper management and operations groups [5].

This paper firstly outlines the concept of the bowtie method and its advantages. Application of the concept as it aligns to an organisation's corporate risk matrix and risk categories is discussed. The proactive modelling input methodology for threat identification, condition rating and barrier effectiveness is described, followed by reactive modelling methods including consequence identification, consequence barrier effectiveness and risk-dollars. Finally, modelling outputs including costs and benefits of simulated asset interventions are presented.

2 Methods and Approach

The bowtie method is a risk assessment methodology commonly used in process safety assessment. This is primarily because it is an ideal way of representing qualitative and quantitative causes and effects that surround the event under analysis [6]. Probability bowties are used in managing the risks of major hazard facilities, being particularly useful where HAZOP teams have industry and plant-specific experience of the frequency of incidents and the effectiveness of control measures [7]. It is also used to determine adequate levels of incident barriers in assessment of safety cases [8]. The bowtie method has been used in other utilities, assisting in the decision-making and prioritisation of water pipe renewal [9], and risk-based decision making in the oil and gas sector [10]. Research in dynamic bowtie modelling has been undertaken [11] which has sought to overcome the static nature of the bowtie method. In considering the objectives referred to in Sect. 1, the bowtie method was recognised as being the most likely to facilitate meeting the challenges in the one tool.

The approach used to develop the QBRM was to add the parameter of Maximum Acceptable Outage (MAO) (refer Fig. 1) and assign it to the top event and present the model inputs and outputs on a bowtie graphic aligning the consequences to the organisation's corporate risk categories (refer Fig. 2). In addition to the MAO, condition-based failure likelihoods were added to the individual threats, to simulate potential future asset improvement or deterioration. Values are assigned to modelling parameters such as failure frequency and barrier effectiveness. The quantitative likelihood and consequence outputs are then calculated and presented on the Bowtie graphic.

Risk-dollars are presented to demonstrate annualised fiscal risk exposure and provide cost-benefit optimisation of mitigation options. Conditional event probabilities are polarised against various categories (e.g. most probable event, longest outage event) and automatically mapped to the organisation's corporate risk matrix where risks are evaluated against the corporate risk appetite for the relevant risk category.

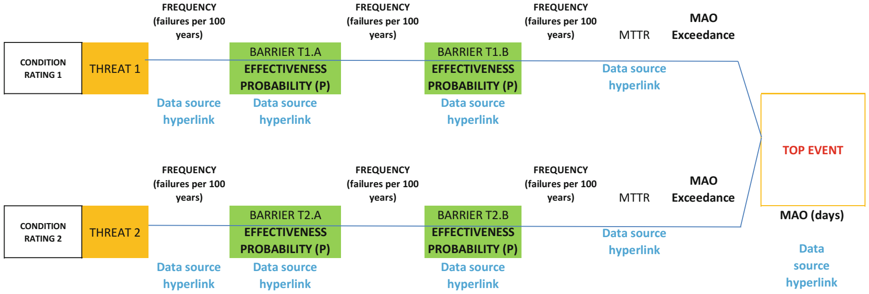

Fig. 1 Simplified QBRM proactive side

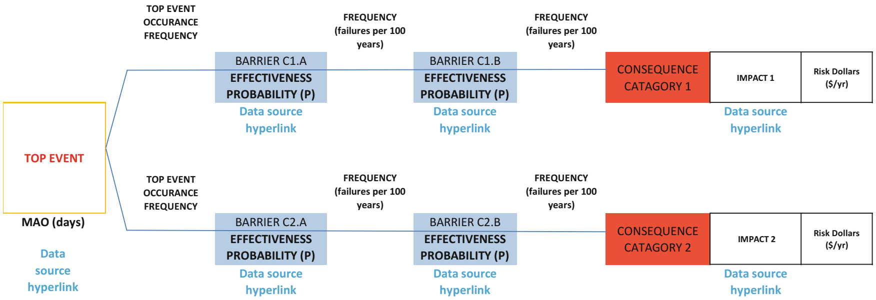

Fig. 2 Simplified QBRM reactive side

Once a top event is selected for analysis (e.g. pumping station failure) and all relevant parameters are entered, a “base-case” bowtie is produced. The base-case bowtie will highlight the threats which are of concern. The base-case is then presented to the various key stakeholders who are invited to propose the various mitigation options. Potential “future-state” bowties are then developed that represent the proposed mitigation options (or combination of options). Options that simulate a proposed future state can include “hard” interventions such as capital replacement or refurbishment, or “soft” interventions such as the installation of sensors or increased redundancy (i.e. barrier improvement). Each future-state bowtie is then compared against the base-case bowtie and assessed in terms of their net present value versus their commensurate reduction in risk.

3 Modelling Inputs

Causes that are identified as having a mean-time-to-recover (MTTR) greater than the MAO for the top event are assigned as threats, along with the relevant as-new (i.e. infant mortality) threat occurrence frequency. The source from which the data is collected must be recorded in the data entry table as a hyperlink. Failure to record where the data has been sourced will show as an alert on the graphic. The data source must also be assigned a qualitative or quantitative descriptor for future assessment of model strength.

Following specification of the relevant threats, a condition rating is assigned to the assets that represent the threats. The condition rating failure frequency (F_c) overrides the as-new threat occurrence frequency resulting in a condition-modified occurrence frequency in accordance with the organisation’s agreed asset condition rating matrix (refer Table 1).

If the failure frequency based on the condition rating matrix has a lower return interval than the as-new failure frequency, then the as-new failure frequency is used. Condition rating assessments are noted in terms of their quantitative or qualitative nature, e.g. ultrasonic thickness testing on a discharge pipe is quantitative, however a purely visual assessment would be qualitative.

Table 1 Condition rating matrix

As New	Initial signs of deterioration	Satisfactory	Poor	Urgent action
Expected failure well above 25 years	Expected failure within 25 years	Expected failure within 10 years	Expected failure within 5 years	Expected failure within 12 months
$F_c = F_{new}$	$F_c = 0.04$	$F_c = 0.1$	$F_c = 0.2$	$F_c = 1$

Following the assignment of condition ratings to the various asset threats, consideration of threat barriers and their relevant effectiveness probabilities are entered in the model (refer Eq. 1). An equivalent process is followed to define any secondary threat barriers and the resulting secondary residual threat frequency (refer Eq. 2). Costs are assigned to each primary and secondary barrier and summed to give a total proactive cost.

The top event frequency (refer Eq. 3) represents the total likelihood of any threat materialising. Upon consideration of the relevant threats to the top event, consequence categories are assigned in line with the organisation's corporate risk matrix, e.g. water security, water quality, financial, environmental WHS, etc., and risk impacts are also assigned to each category. The top event frequency for a given risk category is calculated by summing the frequencies applicable to the relevant risk category (refer Eq. 4).

To account for the variable effectiveness consequence barriers had in mitigating the various threats contributing to a consequence category, a weighted effectiveness is used and presented on the bowtie (refer Eq. 5).

4 Case Study: Raw Water Pumping Station

To demonstrate the real value of the QBRM, a base-case bowtie model was developed for the Raw Water Pumping Station (RWPS) at Tailem Bend in South Australia. The top event was defined as the "loss of required throughput". Workshops were held with key stakeholders so that threat and consequence data could be collected and verified. The MAO was set at 0.521 days (based on available downstream storage) and the threats, conditions, proactive barriers and MAO exceedances were identified as shown in Table 2.

The pump station is designed such that in the event of an outage, a mobile diesel pump can be connected to supply limited water. This is the only reactive measure that can be taken; however, this measure is not effective against the threat of main isolation valve failure, due to the mobile pump discharge tie-in point being upstream of the valve. Consequently, the mobile pump had an overall weighted effectiveness of 9.92%. The consequences were aligned with the applicable consequence categories on the corporate risk heat map, namely Water Supply Security and Financial (ref. Fig. 3).

Table 2 Threat, barrier and MAO exceedance identification

Threats	Condition	Primary barrier	Secondary barrier	MTTR (days)	MAO exceedance (days)
Pump	Satisfactory	Redundant pump set	Redundant pump	3	2.48
Motor	Satisfactory	Redundant pump set	Redundant pump set	3	2.48
Switchboard	Initial signs	Electromechanical relay	–	5	4.48
Main isolation valve	Poor	None	–	7	6.48
Internal pipework	Satisfactory	NDT monitoring	–	14	13.48

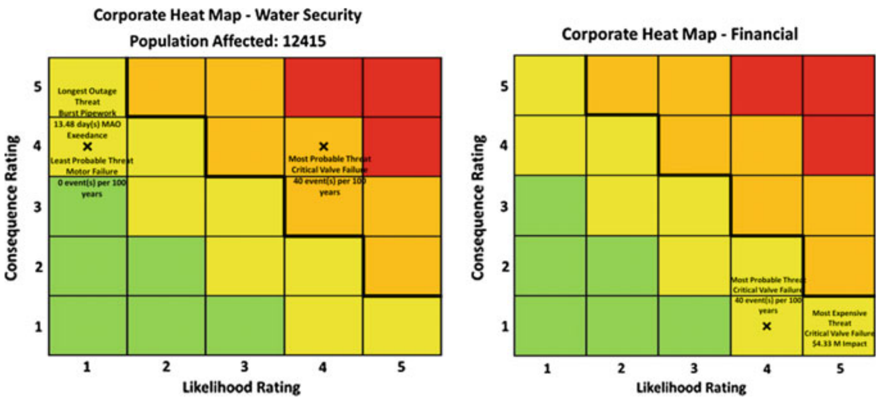

Fig. 3 Corporate risk heat map outputs of base-case bowtie

It was identified from the model that the main isolation valve was the principal threat driving the high risk (Water Security) at the facility due its poor condition, lack of proactive barriers, and ineffective reactive barrier.

Following consideration of the principal threat, four mitigation options were identified aimed at treating the risk of major valve failure including a system intervention downstream of the facility (Option 1a), simulated by increasing the MAO. Replacement of the valve was simulated by toggling the condition rating. The comparative results of each intervention bowtie are presented in Table 3.

The cost associated with each threat was modelled using net present value financial evaluation over a 30-year period. Consequence costs included lost revenue, collateral damage, and water carting.

Following evaluation of the model outputs it was clear that the optimised decision was to implement Option 1d. It was evaluated that whilst Option 1b had a lower

Table 3 Summary of water security base-case and intervention bowties

	Base case	Option 1a	Option 1b	Option 1c	Option 1d
Description	Current state OPEX	Increase system storage by 9 ML CAPEX	Valve replacement (avoid failure) CAPEX	Use pipe spool in lieu of valve (accept failure) OPEX	Combination of option 1b and option 1c CAPEX
MAO (days)	0.521	0.8	0.521	0.521	0.521
MAO exceedance for failure mode (days)	6.48	6.2	6.48	0.48	0.48
Top risk event frequency (p.a.)	0.454	0.454	0.054	0.454	0.054
Corporate failure residual frequency (p. a.)	0.409	0.409	0.010	0.209	0.009
Risk dollars ($k/year)	(1733)	(1658)	(3.6)	(128)	(0.27)
NPV ($k)	(3385)	(3239)	(100)	(343)	(115)
Likelihood rating	4	4	1	4	1
Consequence rating	4	4	4	1	1
Corporate risk rating (security of supply)	16	16	4	4	1

Table 4 Vulnerability ratios and data source quality

Vulnerability ratios		Source data quality	
Threat-barrier quick ratio	0.83	Quantitative references	18
Consequence-barrier quick ratio	2.00	Qualitative references	14
Proactive-reactive cost ratio	2.95	Quantitative-qualitative ratio	1.29

life-cycle cost, investing in Option 1d at an increased cost of \$15 k provided a reduction in risk by 3 orders of magnitude, and therefore a greater cost-benefit ratio.

The model provided qualitative versus quantitative ratios (refer Table 4) for the data used in the model, so that confidence levels could be used to strengthen the business case and identify knowledge areas needing improvement.

The QBRM enabled a data-led, effective and targeted asset management decision to be made, resulting in the addition of Option 1d to the delivery team's 4-year program of work.

5 Conclusions

Modern asset-intensive organisations must be able to demonstrate prudency in their asset decision-making. The QBRM revealed the most critical assets within the pumping station facility and allowed for the optimisation of capital and non-capital interventions.

This modelling approach allowed the analyst to simulate the effectiveness of threat and consequence barriers, facilitating the exploration of trade-offs between hard and soft asset interventions. By using risk-dollars, it is possible to quickly evaluate the costs and benefits across various asset interventions. The automatic reporting of key modelling ratios such as threat-barrier, consequence-barrier, and qualitative-quantitative data sources provides the asset manager with confidence levels relating to the development of business cases. The QBRM is simple and agile in its application and provides a clear representation of individual asset influence on corporate risk categories that can be communicated to stakeholders with varying asset knowledge. It proved to be an effective tool for evaluating the links between asset risk and corporate risk.

6 Equations

$$F_{tp} = F_c\left(1 - P_{tp}\right) \tag{1}$$

$$F_{ts} = F_{tp}(1 - P_{ts}) \tag{2}$$

$$F_t = \sum_{i=1}^{N} F_{ts,i} \tag{3}$$

$$F_{tr} = \sum_{i=1}^{N} F_{tsr,i} \tag{4}$$

$$E_w = \frac{\sum_{i=1}^{N} \left(F_{ts,i} \times P_{cp,i}\right)}{\sum_{j=1}^{N} F_{ts,j}} \tag{5}$$

where:

F_{tp}	primary residual threat frequency
F_c	condition rating failure frequency
P_{tp}	primary threat barrier effectiveness probability
F_{ts}	secondary residual threat frequency
P_{ts}	effectiveness probability of secondary threat barrier
F_t	top event frequency
N	total number of threats applicable to the risk category
F_{tr}	top event frequency for a given risk category
F_{tsr}	secondary residual threat frequency by risk category
E_w	weighted effectiveness
P_{cp}	effectiveness probability of primary consequence barrier
$F_{ts,i}$	secondary residual threat frequency for a given category

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