Transforming ‘value engineering’ from an art form into a science – process resilience modelling

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Abstract

The resilience of a treatment facility should be an important part of its design and operation throughout its service life to ensure it meets compliance and production expectations. This has traditionally been difficult to assess and quantify, and as a consequence its management has largely been ignored, or has been reduced to a function of how many treatment stages are provided with redundancy and/or backup ‘stand-by’ facilities. Without proper resilience assessment there will always be a tendency to undertake ‘gold-plate’ engineering producing specifications much higher than the business need. This consequently leads to higher capital and operational expenditure over the life of a treatment asset. Value engineering then ends up an art form, where negotiating the line between risk and cost is often more to do with good luck than judgement. Resilience assessment makes value engineering a science rather than an art, as well as providing a critical means of influencing and assessing investment decisions and operational and maintenance planning to minimise the overall cost of compliance. Asset resilience assessment techniques have been developed in other industries over the last 15 years. Recently the authors have applied these tried and tested approaches to water and wastewater treatment assets.

Key words: asset management, reliability, resilience, risk based planning, value engineering

INTRODUCTION

For as long as engineers have been designing major water and wastewater treatment facilities they have had to decide not only on the treatment techniques to be used but also the degree of ‘robustness’ or redundancy to be provided in their designs. In making these decisions they have had to balance the competing requirements of providing additional or spare equipment to allow the facility to continue to perform in the event of equipment failure, and providing a facility at a cost the end-user can afford.

In recent years, as the cost and complexity of facilities has increased, the techniques of value engineering have been more commonly applied in the water industry. These techniques have provided a structured approach to determine the balance between robustness and cost, however this still relies on the judgment of engineers and operators to determine what will be acceptable for long-term operation. While there have been many successes using this approach there have also been a number of occasions where value engineering has resulted in plants with poor operability or insufficient capacity to maintain the required quality and quantity criteria. In these cases additional equipment has had to be added. As this has been done as a retrofit it has cost significantly more than if it had been done as part of the original project. One good example of this is a wastewater treatment plant that removed two final clarifiers during value engineering then had to build them a few years later when the plant was unable to meet solids consent during peak flow events.
Various forms of Reliability Assessment, or Resilience Assessment have been long used in other industrial sectors such as oil and gas, and Nuclear (OREDA 2009). This paper describes the application of these tools in the Water industry in concert with engineering judgement to provide a more consistent and defined output from ‘value engineering’ in the design and construction phase, as well as providing a tool for sustainable operation and maintenance of the asset to minimise both whole of life cost and environmental footprint. Resilience assessment tools are also of great benefit in this context as they can be used in a business-as-usual fashion to investigate poor performance, identify critical equipment, quantify risk to public health, optimise capital investment and guide maintenance regimes. The proposed approach goes beyond previous reliability studies of water and wastewater systems that have considered failure rates or critical instrumentation (Corominas et al. 2011) or simulated plant performance under a range of conditions by applying statistical methods to vary output of steady state process models [3 & 4]. In particular, this approach uses actual failure rates for all components across a complete asset register for both conventional and advance water treatment process, including membrane systems. The work is timely because of the growth in the use of membrane systems, particularly in wastewater recycling (Seah et al. 2003) and that again, previous work on membrane systems has been narrowly focused on the failure of single components (Childress et al. 2005).

**RELIABILITY ANALYSIS AND RESILIENCE**

Reliability analysis is used to predict the likely performance of a system (OREDA 2009). Reliability analysis involves building a model to represent the impact of equipment failures on the performance metric of interest, typically plant availability (i.e. the proportion of time the system is operational and capable of performing as intended).

A reliability block diagram is typically used to represent the impact of failures with blocks arranged in series and in parallel. If a simple two component system is considered, a series arrangement indicates that the failure of either results in system unavailability whereas a parallel arrangement indicates that both items have to fail for the system to become unavailable. By using multiple nested series and parallel groups the reliability of complex systems can be represented.

![Figure 1 | Components in series and parallel.](image)

When considering the performance of production systems (typically in the oil and gas industry) there are often complexities that require a different approach to traditional reliability techniques. Such complexities are non-simple failure and repair processes, partial levels of operation, deferred impact of failures, system configuration changes and capacity variations. Monte Carlo techniques
can be applied to capture the impact of these random events. The approach consists of developing a model of the system (normally in the form of a reliability block type representation) and subjecting it to events (typically failures and repairs) that can occur during the lifetime of the system. Such events are generated stochastically, through the use of random numbers. The nature of the model means that it is possible to include a wide variety of complex component and system behaviours. By using this technique a simulation of a system's lifetime can be undertaken by stepping through events as they occur. However, an individual simulation is not necessarily a reasonable indication of average performance as it might have been subjected to events that were more, or less, favourable than the average. To obtain an indication of average performance and the likely range of performance, it is necessary to undertake multiple simulations (as many as 10,000 simulations are commonly used).

The Optagon software from DNV GL has been developed over a number of years to utilise this approach; moreover the software extends this concept by associating a capacity, or flow, with each component. Key inputs to such modelling are the impact of equipment failures on system performance and reliability data (in terms of mean time between failures and mean down-time) for the failures and repairs. Logistic delays to undertake repairs can also be included as part of the downtime. An example of this use in the gas industry was reported by Rogers (Rogers 2000).

By using a Monte Carlo package a range of performance statistics can be obtained about the reliability and availability of a system. These include

- shortfall (the proportion of capacity that is not supplied);
- unavailability (the proportion of time when output is below the required system capacity level); and
- component criticality (contribution to loss of output).

In applying this approach in the water industry a further step has been taken beyond reliability analysis for production systems and this is termed ‘Resilience’. This additional step involves taking into account compliance. The resilience of a wastewater treatment facility, as an example, is a fundamental factor in maintaining continuous compliance with its environmental discharge consent. Resilience is defined as the ability of a system to perform and maintain its function in routine, as well as unexpected circumstances. The overall resilience of a given facility combines the performance of the treatment process with the availability of the associated critical equipment. Process performance relates to the dynamics of the facility – tools such as BioWin can be used to define how many equipment items need to fail before an impact on quality might be realised as well as how long until a breach in consent is expected (this is also referred to as ‘deferred effect’). The availability of equipment items is dependent on the number of critical failures that occur and how long it takes to address those failures.

**USE IN OTHER INDUSTRIES**

Reliability analysis in the form of reliability, availability and maintainability (RAM) studies has been used in the Aeronautical and Defence industries for many years. More recently, it has also been used in the oil and gas industries.

Different industries have different drivers. The aeronautical and defence industries are typically driven by availability of equipment (eg maximising the amount of time a military or commercial aircraft is in a serviceable condition and available for operations). In the oil and gas industry, key reasons for carrying out RAM studies are to maximise revenues through increased production, benchmark performance and quantify ‘lost’ production potential, reduce CAPEX and OPEX expenditure, optimise design and operation, target investment and maintenance activity, and reduce contractual penalties by optimising commercial strategies. RAM studies are applicable through
the full lifecycle of a facility, from concept to front end engineering design, Detailed Design through to Maintenance and Operation, and can provide information for key decisions at all of these different stages.

Such use of RAM studies in these industries is very much accepted practice as it is seen to add significant value during all stages of the lifecycle of a system or facility. Recent examples include

- $435M CAPEX + $25M/annum OPEX savings through optimisation of storage and shipping requirements for a LNG supply chain.
- $300M CAPEX saving for a major oil and gas operator through optimisation of installed equipment redundancy.
- 10% increase in throughput through optimised maintenance for an offshore gas platform.

**APPLYING RESILIENCE MODELLING TO THE WATER INDUSTRY**

Resilience of a desalination plant – throughput based

The Authors have recently applied the techniques of resilience modelling to a desalination plant. There were significant concerns on the initial reliability of the facility and the owner wished to establish the reliable output of the plant and to determine if cost effective options were available to improve this.

The first part of the study consisted of establishing a model of the plant that identified the various plant components, their interconnections and the reduction in output that occurred if one or more of each component was unavailable. This information together with reliability data was used to create the resilience model. The model was loaded into the Optagon software to allow analysis to be performed.

As mean-time-to-failure (MTTF) and mean-time-to-repair (MTTR) is not readily available for the Water industry the – Offshore Reliability Data Handbook (OREDA) (OREDA 2009) data from the offshore oil and gas industry was used as a basis. Examination of this data suggested that the repair times given were unrealistic in an environment without 24-hour working by maintenance personnel, and so this data was multiplied by a factor of 3 and then rounded up to the nearest day to give a more representative value for this application.

This model was then run as described above. A typical throughput simulation at the 50th Percentile (P50) condition is shown in Figure 2 below.

The Monte Carlo Analysis described above looked at many thousands of flow profiles, similar to that shown in Figure 2, to determine the probability of production availability. These profiles were randomly generated largely using the MTTF and MTTR data. This is shown in graphical form in Figure 3 below and the P5, P50 and P95 values are given in Table 1. P50 represents the availability which 50% of all simulations exceed. A production availability of 100% represents the case with no shortfall expected and therefore would require everything to work perfectly – in reality, this is not achievable. Over the life of a facility there will be periods where production is operating at 100% expected throughput level, however there will be certain periods of time where reduced or no throughput is experienced.

Further analysis of this data allowed an evaluation of the contribution of the different system components to the production shortfall. The results of this analysis grouped by type are shown in Figure 4.

One surprising outcome from this analysis was the contribution of the motor control centres (MCCs) to the reduction in plant throughput. The plant uses active front ends (AFE) for the large drives on the plant. Each of these are water cooled with primary and secondary cooling loops and heat exchangers. In the secondary loops there is a single pump for each AFE with no redundancy.
in the system. This cooling system introduced a reduction in reliability into the design that had not been appreciated until this analysis was done.

Following the identification of the Base Case condition, a number of different scenarios were investigated to identify their potential impact on the Plant. These ranged from relatively low cost options such as increasing the redundancy of the MCC cooling to the high cost option of adding an additional RO train. The model was rerun for each of these scenarios to establish the impact on production availability.

As can be seen in Figure 5 the largest impact on the production availability was not enabled by the addition of additional plant but by the change in the time to repairs. While 24 hour maintenance is not a practical option in most cases this information provides information to target maintenance contracts.
with guaranteed response times and repair times for the equipment which is identified as critical. It also highlights the importance of generating water industry specific information on MTTR.

**Resilience of a wastewater treatment works facility – quality based**

A decision support tool was developed to assess the resilience of a wastewater treatment plant. Performance was measured by non-compliant events based on breaches in environmental discharge.

**Table 1** | Percentile production availability for a desalination plant

<table>
<thead>
<tr>
<th>Base case result</th>
<th>Production availability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P5 (5th percentile)</td>
<td>91</td>
</tr>
<tr>
<td>P50 (50th percentile)</td>
<td>86</td>
</tr>
<tr>
<td>P95 (95th percentile)</td>
<td>79</td>
</tr>
</tbody>
</table>

**Figure 4** | System component contribution to production shortfall.

**Figure 5** | Probability of production availability scenarios.
consent of the final effluent. The tool considered historical equipment reliability data, equipment configuration and criticality and insights from site personnel including aspects relating to maintenance, spares, equipment reliability and impacts of equipment failure. In order to define criticality Biowin modelling of the system was carried out with equipment in a failed condition. This allowed input to the model of data on the plant capacity with equipment failed and the time delays between equipment failure and deterioration of plant effluent.

Key results included a prediction of the number of non-compliant events and identification of the key contributors to non-compliant events. A number of sensitivity cases were developed to highlight ways that would improve or reduce plant resilience including consideration of critical spares availability, equipment failure frequency, additional impacts identified by the project team and equipment criticality.

The flexible tool enables the operator to update the model and use it to support cost effective asset management decisions in the following areas:

- Installing spare equipment: By highlighting key contributors to non-compliant events, the benefit to plant resilience can be quantified by considering additional equipment redundancy.
- Maintenance and Repair Strategy: By changing either the frequency of equipment failures and/or how long repairs take, the most sensitive equipment to plant performance can be identified.
- Spares Holding: Having boxed and stored spares available on-site could significantly reduce the number of non-compliant events.
- Plant Load: Impacts can be changed depending on the flow through the facilities. For example, plant load may need to increase due to population growth. The model will predict the expected increase in non-compliant events.
- Additional Impacts: Any known or expected issues (e.g., extreme weather events, blockages during winter) can be included to quantify their impact on plant resilience.
- Removal of old and installation of new equipment: comparative assessments between different options can be performed by changing the model parameters.

**Resilience research project of a typical water re-use facility**

The approach has also been taken a step further in the Australian Water Recycling Centre of Excellence National Demonstration Education and Engagement Program project. The project seeks to address concerns regarding the use of recycled water as a potential source of potable water. The project is multi-faceted having many streams of work. One sub-stream is focused on trying to quantify and provide credible evidence that the mechanical reliability of water recycling plants are robust and pose no more
risk to public health than those of a more typical water treatment process – in essence determining the resilience of the water recycling process. The project is ongoing, however the approach being taken is to create a representative Reference Plant (with several configuration options) to represent a typical water recycling process, and then to use industry data to inform the model from plants around the world that have been operating for a long period. The requirements around the data are complex owing to the multiplicitous nature of the data collected from the different operators. It has been vital to develop a robust data standard to streamline the collection, analysis and storage of the supplied data. The focus of the resilience modelling for this project is the quality of its performance as opposed to its production throughput. The results aim to quantify the risk to public health by predicting likely frequency of non-compliance over a set time period. The vital data for the modelling, in addition to the reliability data, is the equipment set redundancy and its critical number, and the likely deferred impact time. The critical number refers to the point at which the number of equipment items would lead to a quality breach. It is expected that the Reference Plant and the supporting data will be a great source of information and support for asset management planning in the future (eg optimizing maintenance strategies in plants, better targeting of critical equipment for renewal planning purposes).

**THE CHALLENGES OF AVAILABILITY DATA**

The need for good quality data that is representative of critical outages of equipment is important for ensuring meaningful results, so that any outputs can be used with an acceptable level of confidence. Ideally equipment performance should be based on actual operating records where these are available. However, historical operational data is usually limited in its use since the main purpose of these records is typically for detailing personnel working hours and providing an overview of maintenance tasks performed and not primarily for the purpose of recording critical equipment outages that would feed into resilience modelling. It is therefore important that if equipment performance is to be based on historical records there are good maintenance management systems (eg Maximo, SAP) in place so that relevant information is recorded.

Where historical records are deemed to be unsuitable, data from generic industry sources may be used. For example, the oil and gas industry has a commonly used data source, OREDA, that has been developed through contributions from operators across the entire industry – this handbook includes failure frequencies and repair times for different equipment types at both the equipment and the component level. Such data is very useful for representing facilities that are yet to be built, but it is not currently widely available in the water industry. Vendor data may be used but normally is not representative of expected performance since equipment behaviour will be process and operation specific, and vendors may present optimistic views of the reliability of their equipment. As noted above, a project is currently in progress that assesses the resilience of a typical water re-use facility with equipment reliability data based on historical data from several sites from around the world.

In terms of data handling, general rules should be applied to the data set, where possible, in order to filter out any events which are not relevant for modelling purposes (i.e. events that have not resulted in a critical outage of equipment should be excluded). For example, work order priority may be an indicator of event criticality. Depending on the data recorded, a line-by-line review may be the only option in order to determine whether an event is deemed to be critical and how long the critical outage lasted – however, this may be a time consuming exercise that requires significant further investigation.

Previous resilience modelling experience highlighted the following challenges with using historical data:

- Recording of information may be inconsistent. For example, a higher work order priority may be assigned that would indicate that a critical outage has occurred, whereas in reality it was not a critical event.
• Outage durations may not necessarily indicate how long equipment has been unavailable for – typically an overestimation is provided since the work order may include diagnosis of problems, delays in administrative procedures and times awaiting a spare component. In reality, during such activities the equipment may actually be operating. There is also the possibility for double-counting when more than one person has worked on the maintenance activity – for example, 30 maintenance hours might be recorded when in reality 2 maintenance crew attended to the repair and therefore the equipment was unavailable for 15 hours.

• The level of detail provided in the outage durations is typically limited. The resilience model can represent a breakdown of times including logistic delays, spares lead times, actual repair duration and restart times – however, this level of information is not typically recorded hence a single overall outage duration is usually considered.

Key benefits in using historical operating data include:

• Not having to rely on expert knowledge or judgement – hard recorded data that can be audited will provide a consistent approach in data handling. Benchmarking is also possible against actual performance experienced.

• Provided that the level of data recording allows it, a detailed representation beneath the equipment level (i.e. component level) can be represented including consideration of critical spares holding arrangements.

• Regular updates of models are possible to account for newly recorded events.

One area of interest would be to determine the impact on facilities performance with different maintenance strategies. It would be expected that with increased and improved preventative (planned) maintenance, equipment failures would be less frequent. This could be achieved by performing sensitivity analysis and comparing predicted performance with various changes to equipment reliability and planned maintenance activities. It should be noted that resilience modelling will not directly quantify how much equipment reliability changes if a certain maintenance regime is applied – expert input will be required to allow sensitivity analysis to be undertaken. Improved data gathering on the benefits of preventative maintenance would therefore be valuable.

In order to take into account uncertainty in equipment performance, sensitivity cases can be developed to quantify the change in resilience if equipment reliability varied (i.e. increased or reduced outage times, more or less frequent critical failures).

The following improvements to collecting historical performance data could be made:

• Clear distinguishing of critical from non-critical outages in order to take into account the correct events.

• A more detailed breakdown of event durations could be provided in order to separate critical outage durations from other activities when equipment may still be operational.

• As more resilience analysis is undertaken it would be beneficial to compile data from various assets to create a water industry ‘typical’ performance data set that is similar to the oil and gas industry generic data.

A VISION OF THE FUTURE

Since the financial downturn of 2008, utilities have found themselves in a situation where, despite the need to invest in rehabilitation or replacement of critical infrastructure to maintain serviceability, the regulatory appetite to raise prices to fund this investment has not been favourable. The result has been an increasing focus on extending the useful life of the asset base, deferring investment and ‘sweating’
the assets. Good practice asset management approaches are being adopted to better target the funding that is available. Associated with these approaches, utilities are seeking to better understand and manage the asset lifecycle, increasingly using risk-based approaches that balance the criticality of the assets and their likelihood of failure. This is a trend that is likely to increase in the future.

Adopting a lifecycle asset management approach will necessitate a greater understanding of asset resilience as utilities use risk to target investment. At each stage of the lifecycle, from planning, through design, construction, operations, maintenance and replacement, the effects of asset resilience on funding decision making will need to be considered. As an example, resilience will likely become a key design factor, being built into rehabilitation and replacement projects, as well as new-build and expansion projects.

As well as being optimised for performance and cost, the designs of the future will be required to perform in terms of resilience having to meet set targets. Life cycle costing, using resilience as a key determinant will become the norm. Resilience will be an equally important consideration from the viewpoint of operations and maintenance optimization, and the types of models described above will need to be enhanced to enable scenario testing as resilience becomes a core of lifecycle optimization. In the future, design approaches and their supporting tools within the utilities corporate environment will need to integrate or incorporate resilience functionality, making it a business-as-usual process.

As utilities install enterprise asset management decision support systems, especially computerised maintenance management systems, the improvement in data, analysis and decision making around maintenance optimization will change exponentially. The financial drivers mentioned above will encourage the optimization of maintenance, which in turn will likely reduce the margins for error. Understanding and modelling the effects of the resilience of the asset base on maintenance expenditure will also become business-as-usual.

The lack of good quality data is likely to be a key issue in the short to medium timeframe. Water operators will need to share their data, like the oil and gas industry has in creating and maintaining OREDA, to make available a common industry source of good quality equipment performance related data. This data will be very useful for operators during design (i.e. for equipment not yet built) and generally where past practices have meant historic performance data at equipment level is limited or of poor quality.

As described above, the key to understanding resilience is to evaluate whether the asset base can perform and maintain its desired function under both routine and unexpected circumstances. As part of vulnerability assessments, utilities need to consider a broader range of potential threats than ever, including cyber security and terrorism. The resilience modelling of the future will need to enable utilities to build such considerations into their assessments, considering the broader range of factors that can cause the asset system to be performing under ‘unexpected circumstances’. The mitigation measures for these new threats will involve new assets, processes and procedures and the effectiveness of these measures will need to be assessed in cost benefit terms. This is the key challenge for the resilience models of the future.

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REFERENCES


