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The rise, current position and future direction of asset management in utility industries

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Ensuring the fitness for purpose of the UK's utility networks is vital to both the country and the network owners. Replacing these networks would cost many hundreds if not thousands of billions of pounds. As these assets age, high levels of investment are now required to maintain a satisfactory performance level. For example, the annual investment needed for the UK's electricity distribution network is over £1 billion. Hence, efficiently managing these assets is extremely important and 'asset management' is the core of the infrastructure companies' businesses. This paper reviews what is meant by the term 'asset management' and why it has risen in importance over the last few decades. The current position of asset management modelling is then described before the likely key future developments are considered.

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Introduction

Utility companies such as the water, electricity and gas companies can be differentiated from many other industries by the value of their asset base compared to company turnover (Banyard and Bostock, 1998). For instance, the replacement value of the English and Welsh water companies' assets has been estimated at £200 billion by the regulator (Parsons, 2006a). The large amounts of expenditure needed to renew, renovate and enhance this asset base means that asset management is now and has been for a number of years, a core business component for owners of infrastructure systems in the UK and many other developed countries. For example, the proposed investment in the UK electricity distribution system over the years 2005–2010 is £5.7 billion (OFGEM, 2004), while the American Water Works Association has estimated that $250 billion might be required for the replacement of water distribution pipes and valves over the next 30 years in the USA (Marlow and Burn, 2008).

The term 'asset management' first arose in the finance sector with its core component being the trade-off between risk and return (Brown and Humphrey, 2005). The approaches, techniques and tools developed there have been adapted to suit asset management practices in other industries, such as electricity, gas and water. Brown and Humphrey (2005) chose to define asset management as 'the art of balancing performance, cost and risk. Achieving this balance requires the support from three pillars of competence: management, engineering and information'; this stresses that asset management is not a straightforward scientific discipline but a corporate strategy that involves many decisions (Figure 1). In contrast, IAM/BSI (2004) defines asset management as 'systematic and coordinated activities and practices through which an organization optimally manages its assets, and their associated performance, risks and expenditures over their lifecycle for the purpose of achieving its organizational strategic plan'. Drawing upon several different definitions, Alegre (2007) suggests that 'Asset Management is a multidimensional approach that may be defined as the corporate strategy and the corresponding planning and systematic and coordinated activities and practices through which an organization optimally manages its assets, and their associated performance, risks and expenditures over their lifecycle' (Figure 2).

Considering Australian local government's responsibility for roads, drainage and sometimes water supply and sewerage, Howard (2001) defines asset management as

> Simply the way we look after the assets around us, both day to day in maintenance and operations, and medium to long term in strategic asset planning.

In the context of Yorkshire Electricity's distribution network, Hammond and Jones (2000) regard asset management as

> Ensuring that the distribution asset performs its required function safely, within the law and at a minimum lifetime cost.

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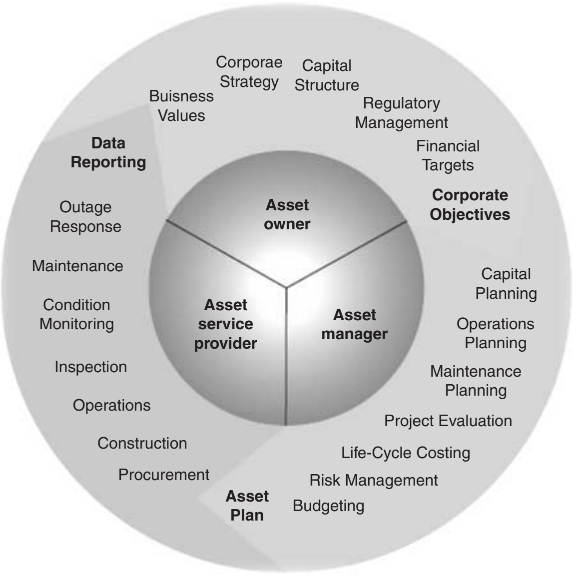

Figure 1 Asset management is based on three functions and many decisions (from Brown and Humphrey, 2005).

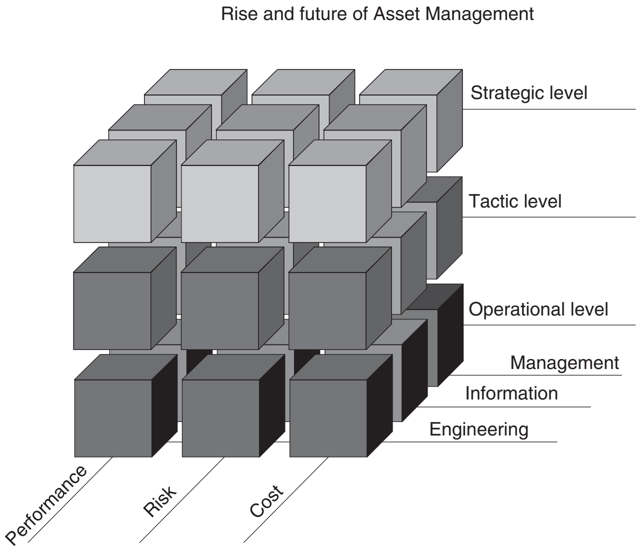

Figure 2 Dimensions of structured asset management (from Alegre, 2007).

While in the UK water industry, asset management is generally categorized under one of the two headings: asset maintenance to ensure continuity of existing service level provision (known as ‘capital maintenance’), or planning for future change.

Hence asset management is the integration of among other things, maintenance and replacement analyses, finance, economics and systems engineering. Although these components were around 50 years ago, it has only been in the last 20 or so years that there has been the drive to integrate them together under the label of asset management. This rise in importance of asset management has been driven by three factors:

The ageing of infrastructure systems

In the water industry, heavy reliance has been placed on sewerage and distribution systems for over 100 years in many cases. However, it is only recently that the legacy of under-investment in these ageing assets and the resulting levels of leakage, bursts and reduction in quality are being addressed.

In the electricity industry, the large expansion of the networks that took place in the early and middle 20th century had markedly decreased by the last quarter of the century as the natural limits to expansion were approached. Figure 3 shows the age profile of one asset class for one of the UK’s electricity network operators. Similarly the majority of the HV transmission assets in England and Wales were installed in the 1960s and are now approaching the end of their design life (Clutterbuck *et al*, 2005). At the same time as the networks have been ageing, often the service quality required from them has been increasing (Dekker and Scarf, 1998). Hence the emphasis has become on maintaining and enhancing the existing, ageing networks.

The advent of new technology

Fifty years ago the asset registers and network diagrams of asset-intensive industries were paper based. Computer-based asset registers generally came in during the 1980s with network diagrams following in the 1990s. However, it was only in the second half of the 1990s that the various computer-based systems started to be integrated together (Banyard and Bostock, 1998; Banyard, 2001). This was a major task consuming significant resources and taking a number of years. For example, Severn Trent Water, one of the 10 water and sewerage undertakers in England and Wales, owns and operates in excess of 1000 sewage treatment works, over 220 water treatment works, more than 1500 water supply and sewerage pumping stations, 45 600 km of water mains and 53 300 km of sewers. Hammond and Jones (2000) report that the size of this data capture task was often greatly underestimated as it could involve an electricity company entering 130 000 detailed sheets of asset information which needed linking to geographical and schematic diagrams. However, these comprehensive asset data systems enable far better analysis and prediction of asset performance provided, of course, that the underpinning data are robust and fit for purpose. Examples of the benefits that have followed from computerized maintenance management systems in other industries are given by Labib (1998) and Kobbacy (2004).

Complementing this move to asset data systems have been the advances in condition measurement technology such as the development of less invasive approaches for estimating condition.

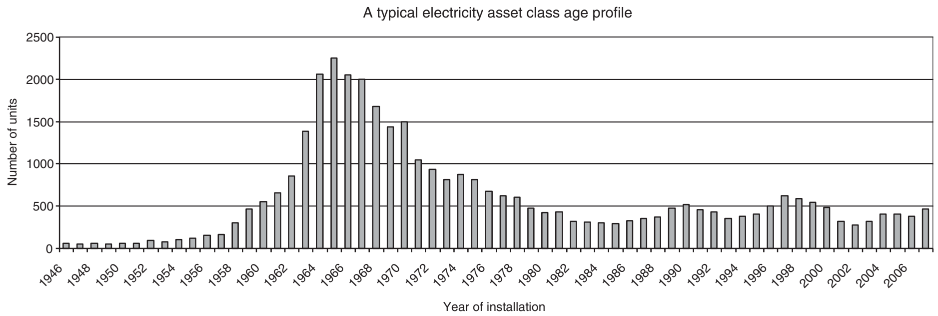

Figure 3 Ages of a class of assets for one of the UK's electricity distribution network owners.

Changes in the structure of the industries

Asset-intensive industries and, in particular, utilities have seen a major change in structure and operation in the last 30 years. Between 1974 and 1989, water in England was supplied either by relatively small water-only companies, or much larger water and sewerage authorities, which had been established under the Water Act, 1973, with charges levied according to rateable value of properties. In 1989, the 10 water and sewerage authorities were privatized and public companies formed. While their operational areas coincided with those of the predecessor authorities, the companies now fell under the auspices of the newly formed Office of Water Services (OFWAT), now known as the Water Services Regulation Authority, whose role is to protect the customer from inappropriate pricing and to improve efficiency among the companies. Using a method of price-cap regulation, OFWAT introduced the requirement for water companies to submit an Asset Management Plan (Lindley, 1992) as part of a five-yearly Periodic Review cycle, within which the performance and investment needs of each company were to be identified. This then raises a further incentive for robust asset planning on behalf of the companies—the need to satisfy a regulator and justify funding for future investment. These changes in the water industry have been paralleled in the electricity industry with its privatization in 1990 and the setting up of the regulator OFFER with a similar remit of requiring future investment expenditure to be justified. In both cases, the regulatory approach has been to challenge the industries rather than to manage them (Parsons, 2006a).

Modelling asset management strategies

Analysing refurbishment and replacement projects involves criteria such as (Grigg, 2005)

- *Technical*—The change in performance in terms of the service quality and the level of risk.
- *Financial*—The amount of investment required and the return on this investment through lower operating costs.
- *Regulation*—How any investment fits within the regulatory framework.
- Environmental considerations.

An indication of these different viewpoints can be seen with the term 'asset life'. Clutterbuck *et al* (2005) define the technical asset life as the 'technical state requiring replacement', the commercial asset life as the 'legal agreement for charging purposes (usually 40 years)' and the financial asset life as the 'period over which assets are financially depreciated over their useful economic life.' Clearly the ultimate decision as to which refurbishment and replacement projects to carry out is likely to be a trade off. However, although asset modelling is not the be all and end all in this decision-making process, it is an important and needed component (Parsons, 2006a).

We will follow the splitting into sections on component condition, maintenance strategies and asset simulation used in Schneider *et al* (2006).

Current condition and performance

As Marlow and Burn (2008) point out, stakeholders are not directly interested in an asset's condition as customers are interested in the service quality that they receive while shareholders are concerned with the predicted financial returns and the likely future expenditure that will be required. However, asset condition is a key input into these measures.

Generally infrastructure assets age at different rates due to differences in their construction material, the operating duty that they experience, their environments and the way they were installed (Morton, 1999). Therefore a simple age to failure model such as the Weibull described in Freeman (1996) is usually not appropriate. Rather there is a need to determine the physical condition of an asset and then to use this condition to predict current and future performance. One difficulty is that although 'condition assessment ... is often portrayed as a cornerstone of effective Asset Management' (Marlow and Burn, 2008), there is often a lack of standardized guidelines for assessing condition. Although there are many asset models, too often poor quality input data lead to poor quality outputs (Parsons, 2006a). A major part of this problem with condition assessment stems from the difficulty of identifying reliable measures of the 'ageing' that can be relatively easily measured and which can then be used to predict future performance.

Clearly condition assessment is easier for some classes of assets than others as they are more accessible. Grigg (2005) notes that road assessment is more well developed than the assessment of water pipes and sewers as the visibility of roads helps in both measuring their condition and allowing the lay person to identify and complain about those in a poor condition. Additionally inspecting all items can be expensive and is usually unnecessary as sufficient information can be gained from inspecting a sample. Where the goal is to estimate the proportion of items in different conditions, stratified random sampling is an obvious candidate. However, O'Hagan (1995) argues that where the target is more complex such as estimating the cost of the required maintenance and refurbishment work in a number of zones in order to provide an estimate for the whole network, then a Bayesian approach may be more appropriate because of the prior information about zone costs.

The underlying goal of assessing an item's physical condition is to estimate its current and future performance. Hence the performance of an item can be combined with condition measurements to give an overall score for the item, and performance and condition (P&C) grading criteria formed the basis of investment decision-making in early periodic reviews in the water industry (Banyard and Bostock, 1998). More recently, however, the water industry has seen a move away from standard P&C grading following the introduction of the robust Common Framework approach, developed for capital maintenance planning wherein 'capital maintenance should normally be justified on the basis of current and forecast probability and consequence of asset failure with or without investment' (Lumbers and Kirby, 2003). That is, accepting that inadequate capital maintenance will lead to failure, the Common Framework requires capital maintenance to be justified on the basis of anticipated impact of failure on both service and cost (operational and capital).

The concept of serviceability forms the cornerstone of the Common Framework approach. Defined as the capability of a system of assets to deliver a reference level of service to customers and to the environment now and into the future (Parsons, 2006b), serviceability is a function of both asset capability and Asset Management, and OFWAT uses a suite of appropriate serviceability indicators to assess companies' performance on an annual basis. Examples of indicators include the number of properties subject to sewer flooding incidents, sewer collapses, interruptions to supply and poor mains pressure. The Common Framework requires that companies must identify the cost of failure, by assessing failure and its consequences in the absence of investment, and they must also identify appropriate investment needs by selecting appropriate intervention options for mitigating the risk of failure. It is important that such interventions should include operational change options in addition to capital maintenance requirements.

In the electricity industry, the performance metrics that the companies are judged on are more failure related such as the number of customer interruptions, the number of customer minutes lost or the number of customers off supply for more than 1 h. Hence there has been less emphasis on combining performance quality with physical condition to get an overall score. Instead the number of failures experienced by an asset type or an area often gets used with condition information.

Intervention strategies

The risk of asset or system failure may be defined as the product of the probability of an event occurring and the consequences arising from that event. Thus, mitigation measures may be taken to address either, both or none of these two components of risk. The decision making can be broken down into the following categories.

Intervene only on failure If the consequences of a failure are low in terms of system performance and safety issues, and the failed item is relatively inexpensive, then minimal or no maintenance may be appropriate. For example, the failure of pole mounted transformers has relatively little impact (Freeman, 1996) and so the most cost-effective policy may be to just replace on failure. However, modelling of the expected failure rate is still useful as it predicts the future expenditure on replacement.

Intervene using time This has been the main approach for assets whose failure could be costly or dangerous. For example, safety concerns when oil-filled switches failed meant that major refurbishment was carried out at fixed intervals. The water industry has also based its asset renewal rates for surface (ie above ground) assets on nominal book lives (Heather and Bridgeman, 2006). The major problem with time-based intervention is how to choose the intervention interval, especially in situations where failures are rare.

Intervene using the condition Recently intervention has been increasingly carried out based on an asset's condition. The simplest incorporation of condition into the problem of deciding when to replace is to use the observed number of failures. The idea is that the failure rate increases as an item, for example, an underground cable, reaches the end of its life. However, Morton (1999) reports that this is a simplification of the situation and that in practice the faults are analysed to see whether there are generic factors causing them that will lead to further failures in the future, for example, carrying out direct current pressure tests on high voltage cables. Furthermore, bearing in mind the general definition of risk as the product of probability and consequence (IAM/BSI, 2004), replacing an asset before failure may reduce the likelihood of failure, but will not affect the consequence of failure should it happen.

Asset simulation

It is important to gain an understanding of how condition and performance are likely to change over the next few years if no remedial action is taken. Indeed, this is imperative in the water industry where the Common Framework requires asset managers to discern either a change in the rate of deterioration, or a change in the volume of assets requiring renewal (Parsons, 2006b). A natural approach is to model how the condition will change and then to predict how an asset's condition will affect performance. Unfortunately, this two-stage modelling process is difficult for many infrastructure items as often little or no time series data about how the item's condition is changing is available and the relationship between condition and performance is poorly understood. This partly stems from the long asset lives compared with the relatively recent emphasis (and capability) to record condition information in an asset database.

Time-based modelling Time-based policies are often appropriate for long-term planning as age information is often the richest source of information in terms of coverage of the largest proportion of the asset base. For example, the condition of a large network of buried low voltage cables for distributing electricity may be harder to determine than which parts of the network were built and replaced when. There is also hesitancy in using forecasts of condition degradation too far into the future. Long-term planning is concerned with trends and surprises going forward such as whether investment requirements are likely to increase sharply or decrease, rather than exact values. It also involves scenario comparisons and a simple age-based model can be used for benchmarking and risk assessing different investment options against a common base profile.

As mentioned earlier, time can also be used to decide when to refurbish or replace an asset by estimating a time period below which the condition and performance are acceptable and above which they are not. The difficulty is in deciding the time period value to use. Whereas historically there was a tendency to use the manufacturer's guidance, there is now more emphasis on estimating the technical asset lives with concepts from Reliability Centred Maintenance (RCM) (Moubray, 1999) being very widely employed to assist with this task. RCM involves Failure Modes and Effects Analysis or a similar procedure being used to identify the different ways items can fail and assessing the criticality of each of these failures. Then a combination of engineering experience and failure data are used in reliability formulae to determine the probability of failure. Where there have been a significant number of failures due to age-related deterioration, then it is reasonably straightforward to carry out this process. However, often the items have been managed so as to keep the failure rate very low, for example, if failures are potentially dangerous or would give rise to a major operational or serviceability issue. Usually in these situations, decay is assumed to be a cumulative stochastic process and a value is defined for an item's condition such that items having a worse value are regarded as being in a 'state requiring replacement' (Figure 4). Clutterbuck *et al* (2005) report that this state is often defined in terms of an asset's capability to perform its duty rather than in terms of its probability of failure, for example, is an overhead conductor likely to fail if there are high winds. In the absence of sufficient failure data, engineering knowledge is used to define this replacement state.

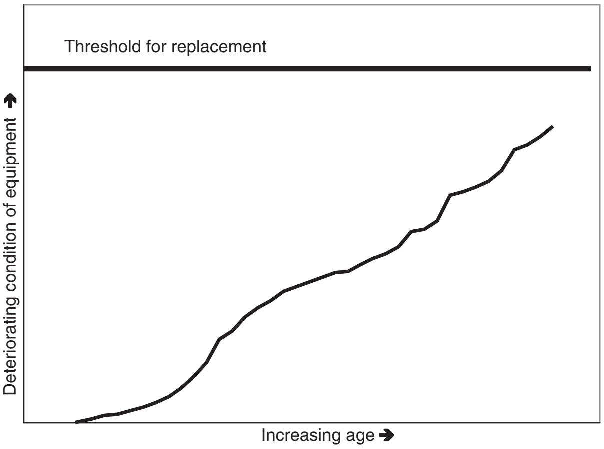

Figure 4 Deciding on a replacement age by modelling an item's stochastic deterioration and then considering the probability that the asset condition is worse than a threshold value. The age when this probability becomes too large is taken as the replacement age (based on Ansell *et al*, 1998).

Once the state requiring replacement has been defined, curves can be fitted to the condition information collected from inspected, replaced and decommissioned assets, and a replacement time is chosen that ensures that only a very small fraction of the assets will deteriorate to a worse state than the state requiring replacement. However, the replacement time or book life of an asset is usually only a guide to when a particular asset should be replaced. In practice, if an asset is believed to be operationally sound, then its replacement may very often be delayed. This approach does, of course, carry additional inherent risks, as the potential exists for unplanned and emergency replacement work in the event of asset failure.

Detecting potential failures This approach assumes that there are three condition states: good condition, defect detectable (potential failure, P), failed (function failure, F). Items are inspected periodically and when a defect is detected, the item is refurbished or replaced.

A difficult question in implementing such an approach is in deciding the length of the intervals between inspections. Clearly this is very dependent on how long it is from when a defect is first detectable to a failure occurring, but even if the

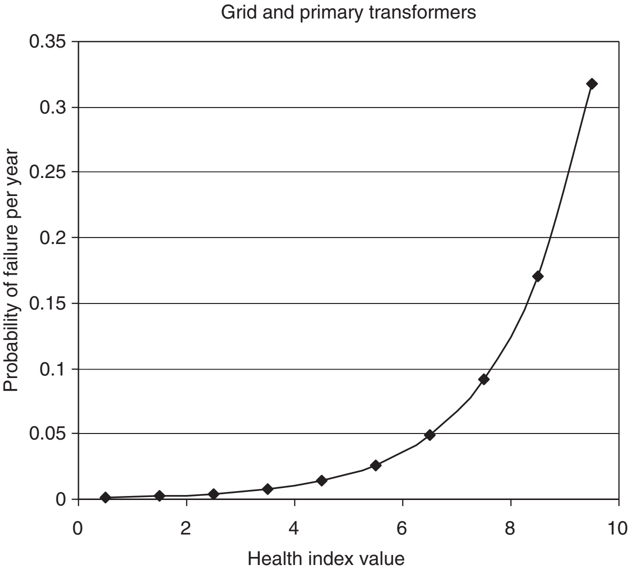

Figure 5 Estimating the probability of failure for a given condition or health index (based on Hughes, 2003).

average length of time for this can be estimated, there will still be a distribution of times about this average. Moubray (1999) uses $P-F$ curves and the resulting $P-F$ interval as part of the process of choosing the inspection interval. However, Dekker and Scarf (1998) point out that 'in RCM it is just stated that inspections should be carried out more frequently than the estimate of the $P-F$ interval'. Therefore, Christer (1999) models the distribution of the 'delay time' from a defect being detectable to failure, and then employs this distribution in the task of choosing the inspection interval.

Condition and performance: deterioration curves For many asset categories, the situation is more complicated than simply detecting whether a defect is present or not, as the relationship between condition and failure is more continuous, that is, as the condition deteriorates, the probability of failure increases but it is not a single-step process. Modelling this situation entails handling two aspects: what condition an asset whose condition is known now, is likely to be in at a future time, and how condition is related to the probability of failure.

Given the condition of assets of different ages, a simple function can be fitted to the data so as to predict the future condition of an asset. If there are explanatory factors such as whether the asset is near to the coast, then a regression model can be employed. Silva *et al* (2000) report that a logistic growth model performed well at predicting their deterioration index that started at zero for new assets and whose worst possible value was 100.

The condition-based risk management (CBRM) approach described in Hughes (2003) has an ageing algorithm that relates overall condition to time, and a curve that relates overall condition to the probability of failure (Figure 5). Given an item in a certain condition, its future condition is estimated taking into account factors such as loading and environment, and then its predicted probability of failure is found from Figure 5. By restricting the family of curves that are fitted to the data, for example, to exponential curves, the approach can be applied to situations where there is limited information about the assets such as their individual ages not being known. A similar two-stage model is reported by Jiang and Jardine (2008). Here a continuous degradation model is applied to individual condition measures. These condition measures then form the covariates in proportional hazard and accelerated life models of failure.

Closely related to the CBRM model with the (continuous) condition changing exponentially with time is having a number of condition states and modelling the transitions between them as a Markov chain. The idea is that given the current distribution of items between the condition states, the future distribution can be predicted by multiplying the current distribution by the Markov transition matrix once for every year the prediction is into the future. This approach has formed the core of a number of pavement and bridge management systems in the USA with Golabi *et al* (1982) reporting annual savings of \$14 million in 1980 from the application of the model to the refurbishment of Arizona's roads. A weakness of the model is that the probability of an asset's condition deteriorating to the next state is independent of the time already spent in the current state. Extensions to this method are described in Kleiner (2001); Black *et al* (2005) and Kleiner *et al* (2006).

Condition and performance: relating condition to performance There is often a significant gap in knowledge in how an asset's condition relates to its performance, particularly with regard to its failure rate and this is partly why the water industry has moved away from performance and condition grading. If failures are rare, then there is little data to go on and engineering knowledge becomes pre-eminent, an example being the CBRM approach of Figure 5 mentioned above.

It is easier to link condition to performance for pavements (roads), and this is probably a major factor behind the development of models such as the Markov Decision Process model of Golabi *et al* (1982) many years before their consideration by, say, the electricity industry.

The future

The regulation of the utilities will continue to evolve; however, the consequences of any changes are likely to be tactical, such as altering the relative merits of refurbishment and replacement, but are highly unlikely to lessen the importance of asset management. If anything, the importance of asset management is likely to continue to increase.

The capability to collect condition information and other asset observations will continue to increase both in terms of

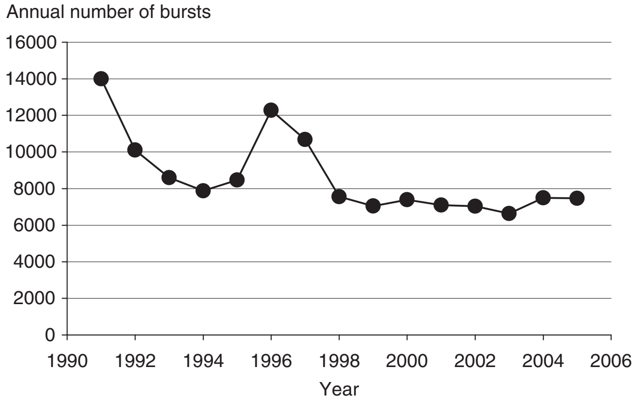

Figure 6 Although the level of bursts levels off at a reference value of around 7000, this may well not be the best economic level for it (based on Parsons, 2006a).

new measurement techniques and the wireless retrieval and storage of this information. This influx of data will mean that the modelling will need to be robust to the presence of incorrect and missing data. OFWAT (Parsons, 2006a) has identified the specification of the data quality that existing models require as being a major concern with regard to their validity. Other challenges that are identified are the need for the models to be understandable and peer reviewed, and for sensitivity analyses to be carried out on their outputs.

Time series data will become more readily available as the age of the asset databases grow. This will impact on the deterioration models in that there is likely to be a rise in deterioration curve fitting to individual asset data such as that reported in Brint and Black (2007).

One of the key problems in formulating asset management plans is the lack of knowledge about how the physical condition of the asset relates to the asset's performance and its failure rate (Parsons, 2006a). The increased collection and storage of asset condition will allow better models to be developed, but the natural variation in the operating circumstances will make this a difficult task, for example, many failures are caused by short-term stresses on the network.

Water companies are expected to maintain a stable serviceability in line with a reference level of service (Parsons, 2006a). This reference level is normally taken 'as the best historic levels achieved by the company'. However, although Figure 6 shows that a reference level of bursts is being achieved at around the 7000 mark, it is not clear that this is the best economic level. In the future, economic modelling in this area will be increasingly needed to set the target levels of service.

Finally, there is the question of whether a large increase in asset management expenditure will be needed in the future due to the ongoing deterioration of existing infrastructure. This has been a concern for at least the last 15 years with a typical example being the American Water Works Association's estimate that $250 billion might be required over the next 30 years in the USA (Marlow and Burn, 2008). Part of the problem is that the assets involved have very long lives; for example, Grigg (2005) reports that pipe replacement in the USA has slowed to below once every 200 years. In the UK the situation is similar; for example, Severn Trent Water is currently replacing 0.7% of its asset stock per annum, with plans to raise this to 1% in future years (Severn Trent Water, 2007). However, the House of Lords Science and Technology Committee report on water management expressed serious concern 'that the network replacement rate may still be far too slow and could be storing up problems for the future' and strongly recommended that OFWAT gave serious consideration to working with the companies to increase the replacement rate (House of Lords, 2006). In its response, OFWAT accepted the seriousness of the situation, while also confirming that there had been a 22% increase in maintenance expenditure for the period 2005–2010 compared to 2000–2005 (OFWAT, 2006). A fundamental issue for effective asset management is the need for cost-effective decision making to manage the potentially significant levels of expenditure that may be needed.

Concluding remarks

The cost of the wholesale replacement of the UK's infrastructure networks is crippling. Even the annual refurbishment budget is many billions of pounds. Therefore, good asset management of these networks is vital. The past 20 years has seen the development of comprehensive asset registers. However, collecting quality data about asset condition and performance for these asset databases is still an issue. The challenge for the future will be to use these databases for the multiple decisions required in asset management (Figure 1).

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