

COST-S: a new methodology and tools for sewerage asset management based on whole life costs

This paper discusses the development of a methodology and software tools aimed at assisting management decisions in order to provide acceptable performance at a minimum cost over the whole life of the sewerage system. Whole Life Costing (WLC) approaches have been shown to offer an ideal platform to provide investment and operational management tools that take account of the timing of interventions, system behaviour and performance all within a sensible economic and engineering framework. The need for such a methodology and the requirements for its useful implementation are introduced first. The paper then describes how research collaboration between the UK Water Industry and two UK research centres (Centre for Water Systems at Exeter University and Pennine Water Group at Universities of Sheffield and Bradford), and supported by the UK Engineering and Physical Sciences Research Council grant, resulted in an innovative, practical and auditable methodology with associated tools for better proactive management of ageing and rapidly deteriorating sewerage systems.

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Sewer performance, the maintenance of sewer assets, the flooding of properties by sewage and the costs associated with the provision of an acceptable level of sewerage services are matters of grave concern in the UK as well as in many other countries. Unlike many other infrastructure services the problems associated with their deterioration and the consequences of inadequate maintenance are far from obvious and it is often only when catastrophe strikes that such problems become manifest or visible – even to the service provider.

The case for sewerage service providers to demonstrate that their sewer asset management plans can deliver robust performance that meet regulatory requirements and that investments are sustainable as well as economically, socially and environmentally justifiable has never been stronger. Although significant

progress has been made in the integrated assessment of different aspects of water distribution network performance that may be used to decide replacement and management strategies, by contrast sewerage systems performance has not until now received the same attention and is not as well understood in terms of its interrelationship of physical and economic behaviour, modelling, and the impact of different management strategies. An acknowledged priority is the need for funding faster improvement in sewerage services to reduce the risks and consequences of sewer flooding. At the same time service providers must demonstrate that their plans for asset management will deliver the robust performance required to meet regulatory requirements, and that such investments are sustainable as well as economically, socially and environmentally justifiable (WaterVoice, 2003). Furthermore in the future service providers will have to respond to changing public

perceptions and expectations (Ofwat, 2003). Hence there is a need to develop tools that take account of system behaviour, performance and regulation within a sensible economic and engineering framework, tools that can be proven to be intellectually robust (Ofwat, 2000).

Whole Life Costing Approach

Whole Life Costing (WLC) is a tool to assist in assessing the performance of a system, aimed at facilitating choices where there are alternative means of achieving the objectives and where those alternatives differ, not only in their initial costs (CAPEX) and in their subsequent operational costs (OPEX), but also in the relative timing of the potential interventions. These tools have been shown to offer an ideal platform for delivering better investment decision making within a single framework for water distribution system management (Engelhardt et al. 2002, Skipworth et al. 2002). By taking a long-term, holistic approach WLC is able to

demonstrate the cost effectiveness of any regime of operation and intervention for a given set of internal and external constraints. Changes in performance, efficiency gains and regulatory goals over time can also be accommodated. The development of a WLC approach to sewer asset management that links system performance, cost and decision making is of particular interest for a number of reasons:

- The need to better understand performance using the available existing data and to model integrated performance such that changes in one aspect of performance can be tracked across all the other aspects.
- Socio-demographic changes across the urban landscape, which hold major implications for the usage, performance and fitness-for-purpose of existing sewer assets, must be included if investment and performance are to be optimised.
- The EU Water Framework Directive with its support for full-cost pricing (operational, capital and environmental) means that more holistic and comprehensive approaches are a necessity rather than a luxury.

However, there are several difficult questions that need resolving before implementing WLC, including:

- How to explicitly assign the costs at the appropriate decision level?
- How to define risk in monetary terms only?
- How to adequately predict the performance of the system over an extended time horizon?
- How to determine social and environmental costs and link them to an analysis of cost drivers.

The collaborative project between the UK Water Industry and two UK research centres (Centre for Water Systems at Exeter University and Pennine Water Group at Universities of Sheffield and Bradford), and funded by the UK Engineering and Physical Sciences Research Council, has answered those questions by developing the methodology and the tool for WLC management of sewer systems – COST-S.

The COST-S Methodology

A key feature of the methodology is how it incorporates the different aspects of system behaviour and performance, their inter-related nature, how they affect each other as well as how changes manifest themselves across the system's performance. The efficient and effective management of urban

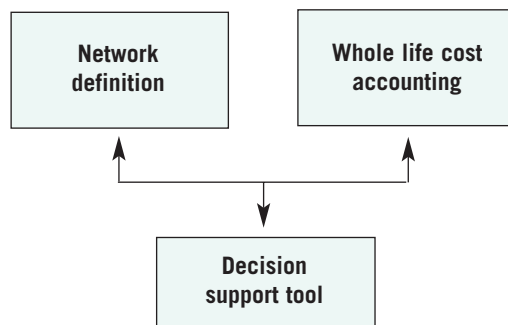


Figure 1 COST-S components.

drainage systems should be based on a number of prerequisites. These include a proper and adequate knowledge of the assets, and an understanding of their system performance, the level of service provided and required, the management intervention options available and their impacts, the costs associated with system performance, failure and interventions and, the consequences of service failure for the service provider, the environment and society.

A key element in the COST-S methodology is the integration of the hydraulic modelling platform with system performance models of collapse, blockage, sedimentation, CSO/storage and interventions as predictive tools. This allows the impact of different scenarios on hydraulic performance and flooding to be evaluated in terms of both performance and cost and couples system hydraulic inadequacy to the cost modelling of flooding impacts.

An important aspect of this work is the development of a specific set of Key Performance Indicators (KPIs) based on indicators that are either currently in use or have been suggested (IWA, 2003). The KPIs are generated by the modelling and that are used to both evaluate performance and act as a mechanism to initiate intervention options. This approach allows the impact of decisions on physical performance and performance indicators, through the hydraulic

platform and also the costs associated with performance to be investigated across the whole life of the system in terms of serviceability indicators and capital and operational expenditures. This must implicitly recognise the long lived nature of the assets and the fact that any fair and proper evaluation of performance must allow all the impacts arising from interventions to become manifest such that a proper trade-off between the short- and long-term effects of capital and maintenance strategies can be made. In this respect WLC approaches have been proven to offer an ideal platform for integrating such aspects within a single framework (Cashman et. al., 2004).

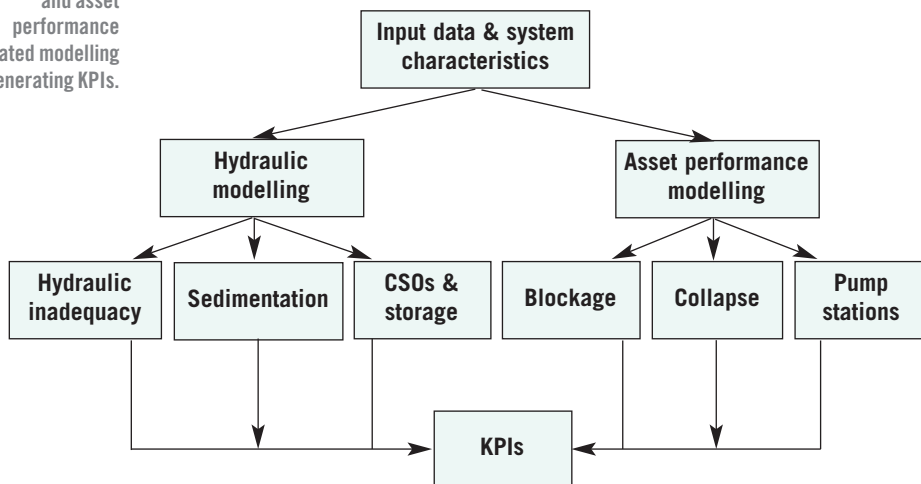
Architecture

The COST-S methodology has three components: network definition which includes modelling, whole life cost accounting, and a decision toolkit (Figure 1). This approach recognises that any urban drainage system comprises a network of assets which should provide an efficient service whilst meeting a variety of performance requirements. The complexity of dealing with these requirements leads to the need for a clear delineation of functions within the WLC framework.

Network definition

Network definition encompasses current and future network configuration and performance and the effect on performance of interventions at any given time horizon. The urban drainage network must be defined in a manner that is compatible with the accounting module over the selected period of analysis, which necessitates that all aspects of performance that have a cost impact should be considered holistically and be capable of being quantified. A distinction is made between hydraulic performance related features and asset performance related modelling. In the first instance

Figure 2 A distinction is made between hydraulic performance related features and asset performance related modelling in generating KPIs.



aspects such as sedimentation, hydraulic adequacy and CSOs are included and through them flooding behaviour whilst under asset performance modelling blockage, collapse and pump station failures are considered. Together these aspects are reflected in the generation of KPIs as indicated in Figure 2.

Performance modelling

Performance modelling involves computing of indicators based on hydraulic modelling and asset modelling.

Hydraulic KPI – wet weather flow Hydraulic modelling is used to assess system performance in terms of Dry Weather Flows (DWF), Wet Weather Flows (WWF) and sedimentation. A major operational concern for urban drainage systems is their performance under WWF and especially the onset of hydraulic incapacity in system and any resultant flooding. This issue is being approached by reference to a series of design events with a range of return periods with the ability to alter the duration of the events. The proposed performance measure for hydraulic incapacity under WWF is based on a modified performance assessment system (Cardoso et al, 2002) expressed either in terms of discharge (Q) or water level (H) (hydraulic head), Figure 3 shows this in terms of water level. The Hydraulic KPI (HKPI) is considered to be satisfactory (100%) for water levels up to a certain value H^* below pipe soffit (pipe nearly full) which corresponds to discharges up to Q^* (Q^* smaller than the full pipe flow), falling to X% at surcharging (full pipe flow), and further falling to 0% when hydraulic head reaches the ground level and flow rate reaches some Q_{flood} (start of flooding). This function represents different levels of performance of an asset under WWF: satisfactory / acceptable / non-acceptable, at a moment in time. The extent of incapacity or flooding is introduced by computing a 1-hour moving average of HKPI, i.e. by averaging over the ‘worst’ one hour, for a rainfall event – hence, flooding that took place for 15 minutes with a moderate flood volume would still result in some small positive KPI value, whereas only flooding longer than one hour would give zero KPI. For one return period, this is done for a series of design events so that critical storm duration (ie, the one which gives smallest KPI) is used for each pipe. Further aggregation is done by summing up thus obtained KPIs with their probabilities. The described procedure results in a set of KPIs values for every individual pipe, which comprehensively describe system

functioning under a wide range of relevant conditions. Values of H^*/Q^* and X^* are dependent on pipe size, category, condition grade and possibly other factors.

Sewage Available to Transport (SATT) – dry weather flow

Dry weather performance is determined by reference to the system’s ability to transport dry weather flows, referencing the total available capacity with the required capacity of the system. The derived indicator is akin to determining the available ‘headroom’ in the system, either at an individual asset level or system level. The SATT score (Figure 4) is calculated as a difference between the available (non-occupied) pipe volume and the total volume, divided by the total volume, based on 24-hour simulation with diurnal variation of dry weather flows

Sedimentation

The flow simulations are also used to determine ‘actual’ velocities in the system and to reference these against critical or self-cleaning velocities according to the CIRIA Design Manual Report 141 (Ackers et al, 1996). Sedimentation KPI is calculated as a percentage of time (during 24 hour simulation) during which the velocities in a pipe are smaller than self-cleansing velocity. This is then used as an indicator of likelihood of sedimentation problems in the system, with pinpointing the likely locations. Further details of definition of hydraulic based KPIs are described by Djordjevic et al (2005).

Asset Performance modelling

Asset performance modelling aims to describe the performance of assets over the whole life horizon. Currently the Cost-S asset performance models predict blockage, collapse and deterioration. These models are derived from historic data, thus the primary limitation is quantity and quality of data. It is planned to expand asset performance modelling to include other parts of the sewerage system, such as CSOs and Pumping stations.

Deterioration modelling

An important feature of the WLC approach is the ability to make predictions of future performance of the system. Over these longer periods of time, deterioration will become

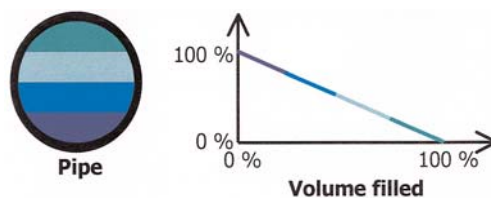


Figure 4
Dry weather flow - SATT.

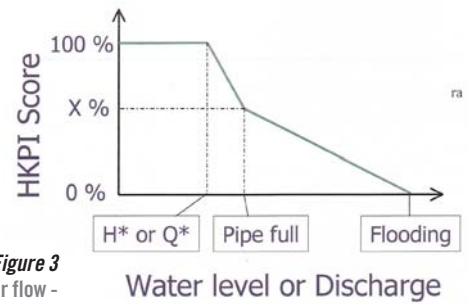


Figure 3
Wet weather flow - hydraulic KPI.

		ICG at t_{i+1}				
		1	2	3	4	5
ICG at t_i	1	$p_{1,1}$	$p_{1,2}$	$p_{1,3}$	$p_{1,4}$	$p_{1,5}$
	2	0	$p_{2,2}$	$p_{2,3}$	$p_{2,4}$	$p_{2,5}$
	3	0	0	$p_{3,3}$	$p_{3,4}$	$p_{3,5}$
	4	0	0	0	$p_{4,4}$	$p_{4,5}$
	5	0	0	0	0	$p_{5,5}$

Table 1
Transition probabilities for internal condition grade (ICG).

important. The deterioration model has been developed through the analysis of repeat CCTV data, such that the condition of a sewer is known at two fixed points in time. Following previously published work (Micevski et al (2002), Wirahadikusumah et al (2001)), deterioration is applied to the system based on a Markov transition at each timestep. Transition probabilities ($p_{j,k}$) in Table 1 have been derived from repeat CCTV data.

Blockage and collapse modelling

Blockage and collapse models have been developed from the analysis of incident records and sewer asset databases. The models have been developed to predict numbers of blockages and collapses within pipe sub-groups over the catchment, rather than actual locations of incidents.

To develop successful models, it was necessary to consider the various factors which affect the risk of blockage and collapse incidents occurring. These include the physical properties of the pipe, including condition and surrounding soil, as well as the properties of the sewage conveyed and location of the pipe. Further discussion on sewer blockage is reported in Shepherd et al (2005). Figure 5 illustrates the blockage model, which predicts the number of blockages per Km of sewer per year in each asset category. The categories are defined by the internal condition grade of the pipe, and the relative velocity (RV) multiplied by the pipe length. The relative velocity is a function of pipe diameter and gradient. It can be seen that blockage risk decreases with increasing RV x

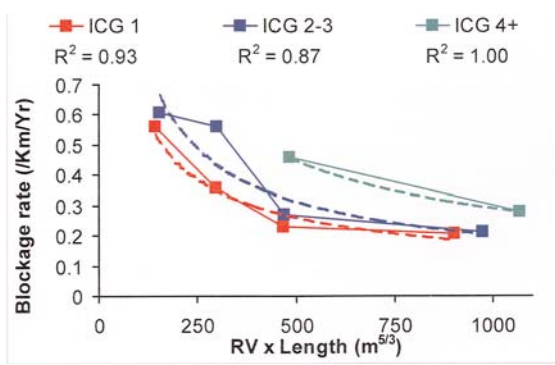


Figure 5
Blockage prediction model.

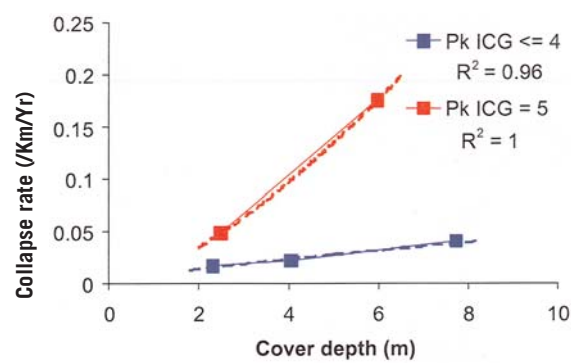


Figure 6
Collapse prediction model.

Length, and increases with ICG.

As collapses are far less frequent than blockages, there is a correspondingly smaller quantity of data from which to build a model. This has led to the collapse model, shown in Figure 6, considering a smaller number of contributory parameters. This model suggests that depth of cover is an important factor, with variation in ICG only becoming significant when sewers are in grade 5 (poorest condition). It might be expected that at very small depths, collapse rates would increase due to live loading becoming significant; this is not shown in the model as the dataset does not include a significant number of pipes with small depths of cover.

The models are based on the available data and the factors which were shown to most significantly affect blockage and collapse risk. It is anticipated that as data quality and availability improves, these models will be improved upon, however they do present a good starting point.

Cost accounting

The accounting module provides a methodology whereby the costs arising from the operation, maintenance and management of a network are identified and coupled with the performance of the network. Cost identification utilises an activity-based costing approach (Innes and Mitchell, 1990) in order to relate activities to their contingent costs rather than

simple measures of output. Sewerage networks may be regarded as systems transforming external inputs into outputs that also have unintentional discharges and emissions (flooding) – system losses. The results of which add to the cost of operating the network and in fact represent a significant source of operational expenditure. An objective should therefore be to reduce to a minimum such waste of resources.

However, there is not a simple relationship between a particular cause, such as a blockage, and the actions needed to address it. The approach adopted is that for each particular causal loss, eg, blockage, collapse, equipment failure or hydraulic inadequacy, a probabilistic approach to the range of available responses, impact and consequential costs is adopted in order to determine the range of expected costs associated with a range of incidents. These are based on actual practice and analysis of incident data in order to derive realistic probability-consequence models. Costs are broadly associated with one of three cost categories: planned, unplanned-reactive and, planned-proactive, that reflect the level of activity occurring in the drainage system. The characterisation of the distribution of activities and costs has been based on both analysis of incidents and expenditure and institutional knowledge to provide a methodology for the redistribution of costs that is able to trace consequent costs back through an organisational hierarchy.

Decision support tool

The COST-S decision support tool (DST) represents the integration of the accounting and network definition modules onto a software platform. This consolidates the network data required

for physical representation, in order that its performance can be modelled, and cost data as identified by the accounting module. The tool's Graphical User Interface (GUI) has two modules: DST Builder and Policies Explorer. A feature of the approach is the inclusion of performance based cost drivers linked to the KPIs as well as the cost of rule based management intervention strategies that can be adjusted over different time periods. Interventions, whether reactive or proactive, represent actions that can be undertaken that will have an effect on the performance of the system, eg, structural relining. The performance effects impact on the cost drivers over the period of analysis and the updated values of the cost drivers are picked up by the cost relationships identified in the accounting module. The updated cost values ultimately accrue to the WLC account. Different scenarios and strategies can be investigated through the decision support tool.

A comprehensive mathematical framework for a generalised modular DST for assets management has been developed and implemented within a software tool. This framework consists on four units:

1. A discrete-time dynamic system unit
2. Space and time aggregation and selection unit
3. Interventions selection unit
4. Multi-criteria decision analysis unit

The purpose of each unit is to embed standard interfaces for certain types of services, eg, modelling, optimisation and multi-criteria decision analysis.

The first unit encompasses all the performance models discussed above. The structure is developed as a discrete-time dynamic system, which evolves through a sequence of stages. At each stage the system is in a particular state and a set of interventions is specified. Based on available information the models then compute the state at the next stage and generate a set of indices that quantifies impact of the interventions taken over the assets (generally in terms of cost or KPIs). The integration of various models is implemented in such a way that allows easy replacement of each of them, for example if one wanted to replace the built-in hydraulic model it would be easy to replace it with another model and produce the same set of KPIs.

The purpose of the second unit is to provide the user with a GIS-based tool for the analysis of simulation results. Such a unit is embedded within the DST builder (Figure 7). The indices (cost or KPIs) can then be viewed, selected and aggregated in space and/or in time.

The third unit allows the selection

Figure 7
The DST builder.

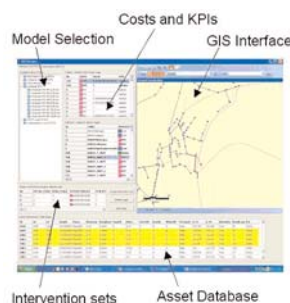


Figure 8
The policies explorer.



of suitable intervention solutions for local problems (eg, selection of pipe replacements and/or relining for improving hydraulic performance, or selection of pipes to be cleaned to reduce cost of repeated blockages) through the DST builder. Selection of assets for a particular intervention is performed through the GUI by the user. Intervention parameters (eg, new pipe diameters for pipe replacement or new storage volumes in providing new storage) are set manually, allowing the user to run the models and select interventions of interest. However, the software is designed so that, such operation can be performed automatically by any optimisation technique, such as genetic algorithms. The selected interventions for each sub-problem are saved as an options set thus allowing further analysis of each of the sets.

The Policies Explorer includes units three and four and allows the user to assess the cost and performance associated with different intervention sets over both a single and multiple stages (Figure 8).

For each stage interventions over a period of time can be selected from the created options sets and then the behaviour of the system simulated and compared with other interventions in terms of costs and KPIs. This allows sequences of decision to be made and compared. Similarly to operations within unit three, this operation is performed manually by the user, but it can be easily automated, by including dynamic-simulation-based optimisation techniques.

Since interventions or intervention sequences are generally compared on the basis of more than one criterion, multi-criteria decision analysis techniques are needed and the software includes a generic interface for a variety of such technique to be plugged-in.

Conclusions

Sewerage service providers need to demonstrate that their sewer asset management plans will deliver robust performance that meet regulatory requirements and that investments are sustainable as well as economically, socially and environmentally justifiable. The development of the COST-S methodologies and tools demonstrates that sewerage systems performance has finally received the same attention as the integrated assessment of different aspects of water distribution network performance that may be used to decide replacement and management strategies. The new tools improves understanding of sewer system interrelationships, of physical and economic behaviour, modelling,

and the impact of different management strategies. ●

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References

Ackers, J.C., Butler, D., May, R. *WP (1996) Design of sewers to control sediment problems Report 141. CIRIA.*

Cardoso, M.A., Coelho, A. C., Praça, P., Brito, R. S. and Matos, J. (2002). *Technical performance assessment of urban sewer systems, 9th International Conference on Urban Drainage, Portland.*

Cashman, A., Savic, D., Saul, A., Ashley, R., Walters, G., Blanksby, J., Djordjevic, S., Unwin, D. and Kapelan, Z. (2004) *Whole life costing of sewers (Cost-S): Developing a sustainable approach to sewer network management, 5th International Conference on Sustainable Technologies and Strategies in Urban Water Management, Lyon.*

Djordjevic, S., Cashman, A., Kapelan, Z., Shepherd, W., Dorini, G., Saul, A. J., Savic D. and Walters, G. A. (2005) *Hydraulic based performance indicators within a whole life costing approach to sewerage, submitted to Water Resources Planning and Management, ASCE.*

Engelhardt, M.O., Skipworth, P.J., Savic, D.A., Cashman, A., Walters, G.A. and Saul, A.J. (2002) *Determining maintenance requirements of a water distribution network using whole life costing. Journal of Quality in Maintenance Engineering Vol. 8, No. 2, pp. 152-164.*

Innes, J. and Mitchell, F. (1990) *Activity Based Costing: A Review with Case Studies, Chartered Institute of Management Accountants, London.*

IWA (2003). *Operations & maintenance committee. Performance indicators for wastewater services. Draft March.*

Micevski, T., Kuczera, G. and Coombes, P., 2002. *Markov Model for Storm Water Pipe Deterioration. Journal of Infrastructure Systems, 8 (2), 49-56.*

Ofwat (2003) *High service levels meeting customers' expectations. PN33/03, Birmingham.*

Ofwat (2000) *MD161: Maintaining serviceability to customers.*

<http://www.ofwat.gov.uk/lettersmd/md161.htm> Birmingham.

Shepherd, W.J., Cashman, A., Djordjevic, S., Dorini, G., Saul, A., Savic, D. and Lewis, L., 2005. *Investigation of blockage relationships and the cost implications for sewerage network management. In: Proceedings of 10th International Conference on Urban Drainage, Copenhagen, Denmark, 21-26 August 2005.*

Skipworth, P.J., Engelhardt, M.O., Cashman, A., Savic, D.A., Saul, A.J. and Walters, G.A. (2002) *Whole life costing for water distribution network management. Thomas Telford, London.*

WaterVoice (2003). *Customers matter most in government's policies on review of water prices. WV5/03, Birmingham.*

Wirahadikusumah, R., Abraham, D. and Iseley, T., 2001. *Challenging Issues In Modeling Deterioration Of Combined Sewers. Journal of Infrastructure Systems, 7 (2), 77-84.*