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Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis

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ABSTRACT

To overcome the difficulties of strategic asset management of water distribution networks, a pipe failure and a rehabilitation model are combined to predict the long-term performance of rehabilitation strategies. Bayesian parameter estimation is performed to calibrate the failure and replacement model based on a prior distribution inferred from three large water utilities in Switzerland. Multi-criteria decision analysis (MCDA) and scenario planning build the framework for evaluating 18 strategic rehabilitation alternatives under future uncertainty. Outcomes for three fundamental objectives (low costs, high reliability, and high intergenerational equity) are assessed. Exploitation of stochastic dominance concepts helps to identify twelve non-dominated alternatives and local sensitivity analysis of stakeholder preferences is used to rank them under four scenarios. Strategies with annual replacement of 1.5–2% of the network perform reasonably well under all scenarios. In contrast, the commonly used reactive replacement is not recommendable unless cost is the only relevant objective. Exemplified for a small Swiss water utility, this approach can readily be adapted to support strategic asset management for any utility size and based on objectives and preferences that matter to the respective decision makers.

1. Introduction

1.1. *Strategic asset management (SAM)*

Awareness about the need for long-term rehabilitation planning of our aging water infrastructure has risen globally during the past two decades (AWWA, 2001; Burns et al., 1999; Herz, 1998; Kleiner and Rajani, 1999; Sægrov, 2005; Selvakumar and Tafuri, 2012; Vanier, 2001). Infrastructure asset management (IAM) is increasingly applied to rehabilitation planning on the strategic, tactical, and operational levels (Cardoso et al., 2012; Christodoulou et al., 2008; Fuchs-Hanusch et al., 2008; Haffejee and Brent, 2008; Heather and Bridgeman, 2007; Marlow et al., 2010; Ugarelli et al., 2010).

Recently, the CARE-W (Sægrov, 2005) and AWARE-P (Cardoso et al., 2012) research projects have greatly contributed to the development and implementation of structured

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IAM approaches, including strategic asset management (SAM). Both rely on (i) knowledge about the expected useable lifetime and condition of assets over time (failure models), (ii) knowledge about the consequences of rehabilitation alternatives (rehabilitation models), but are weak in (iii) systematic and transparent decision support, and (iv) thorough accounting for planning uncertainty.

Application of the available SAM approaches in the water sector is still limited, given the high need for human, informational, and data resources (Alegre, 2010). In Switzerland, SAM is a specific challenge due to the sector's high fragmentation (Lienert et al., 2013a) and prevalence of mostly small water providers, the majority with <10'000 beneficiaries (SVGW, 2006).

1.2. *Failure models*

To compare water network rehabilitation options, knowledge about the expected useable lifetime and condition of pipe assets is crucial (Selvakumar and Tafuri, 2012). Probabilistic water pipe failure models to predict age-dependent pipe deterioration abound (reviewed in Kleiner et al., 2009; Kleiner and Rajani, 2001; Liu et al., 2012). Whereas their practical value has been shown especially in connection to larger water networks (e.g. Alvisi and Franchini, 2010; Eisenbeis et al., 1999; Poulton et al., 2007; Renaud et al., 2012), their calibration to the local conditions is usually infeasible in small to medium-sized water networks because of their high data demand. Hence, there is a lack of failure models that support rehabilitation planning in the very common small to medium-sized networks in Switzerland, but also in other European countries such as Austria, Germany, and France. Additionally, common data particularities, namely left-truncation, right-censoring, and selective survival bias, are usually not explicitly considered in model parameter inference, which may lead to biased predictions of failures (Le Gat, 2009; Mailhot et al., 2000; Renaud et al., 2012; Scheidegger et al., 2011). A general approach as well as a specific model to avoid biases in pipe failure models due to these particularities were recently proposed by Scheidegger et al. (2013). The problem of short networks (small sample size) and limited failure records in pipe failure model calibration can be overcome by Bayesian parameter inference (Dridi et al., 2009; Watson et al., 2004).

1.3. *Comparing rehabilitation alternatives*

The available rehabilitation models are mostly used to support operational and tactical (i.e. short to mid-term) pipe repair and replacement planning (for a review see Engelhardt et al., 2000). Nonetheless, software to support strategic (long-term) rehabilitation decisions exists, usually combining pipe deterioration and evaluation models with decision support features (e.g. KANEW (Kropp and Baur, 2005), PiReM (Fuchs-Hanusch et al., 2008), D-WARP (Kleiner and Rajani, 2004), Aware-P (Cardoso et al., 2012), Casses (Renaud et al., 2012), WilCO (Engelhardt et al., 2003), PARMS Planning (Burn et al., 2003)). From the information available, and examining four software products in detail, we judged none suitable to simultaneously meet core requirements of our approach: a) combinability with our failure model, b) flexible implementation of rehabilitation strategies and performance measures, and c) propagation of parameter uncertainty. We therefore selected the sector-independent asset management software FAST (Fichtner Asset Services and Technologies, 2013) which is based on a set of interacting differential equations as used in system dynamic modeling.E.g. Rehan et al. (2011) follow a system dynamic approach for the long-term planning of water and wastewater systems and studying the financial sustainability of different rehabilitation strategies.

1.4. *Decision support*

As noted by others, e.g. (Alegre, 2010; Giustolisi et al., 2006; Selvakumar and Tafuri, 2012), the evaluation and prioritization of water system rehabilitation alternatives should be supported by robust and feasible decision support tools. In water engineering, single- or multi-objective optimization and cost-benefit analysis are commonly used to support decisions (Engelhardt et al., 2000; Giustolisi et al., 2006) although they often ignore subjective stakeholder preferences. In a long-term and multi-stakeholder context like strategic rehabilitation planning, the integration of stakeholder preferences by multi-criteria decision analysis (MCDA) seems more appropriate (Keeney, 1982).

MCDA has been applied to water infrastructure asset management at least twice (Baur et al., 2003; Carriço et al., 2012); both using ELECTRE of the outranking family of MCDA methods (Roy, 1991). Many other MCDA approaches are available, see e.g. Belton and Stewart (2002) and Figueira et al. (2005) for an overview. Another well-established MCDA approach is multi-attribute value and utility theory (MAVT/MAUT). Four important reasons for choosing MAVT/MAUT to support asset management decisions (further explained in Schuwirth et al., 2012) are: 1) foundation on axioms of rational choice, 2) explicit handling of prediction uncertainty and stakeholder risk attitudes, 3) ability to process many alternatives without increased elicitation effort, and 4) possibility to include new alternatives at any stage of the decision procedure.

1.5. *Uncertainty assessment*

A major concern for long-term planning is the consideration of uncertainty about future developments, the probabilistic description of which is difficult due to high ambiguity (Rinderknecht et al., 2012). Scenario planning has been proposed to handle these uncertainties (Schnaars, 1987) and mitigate under- and over- prediction of change (Schoemaker, 1995). It is increasingly incorporated into both IAM and MCDA to evaluate the robustness of decision alternatives to future change (Cardoso et al., 2012; Goodwin and Wright, 2001; Karvetski et al., 2009; Montibeller et al., 2006; Stewart et al., 2013). While scenario thinking can be interpreted as a way to cover in-between uncertainties of a range of possible futures, uncertainty quantification and propagation of model outputs combined with sensitivity analysis allows the consideration of uncertainty within future scenarios (Stewart et al., 2013).