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Procedia Engineering 119 (2015) 168 – 173
Procedia Engineering
www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

Water supply infrastructure cost modelling

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Abstract

The current paper presents the development and validation of cost functions for different types of assets of water supply systems based on known hydraulic (e.g., flow, pump head, pump power) and physical characteristics of the assets (e.g., volume, material, nominal diameter). The followed methodology is a five-step procedure: 1) database construction and analysis, 2) present cost value calculation, 3) cost function establishment, 4) model specification, and 5) model validation. Cost and infrastructure data from several Portuguese water utilities have been used. Regression models have been used for the cost modelling.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: Cost function, Asset management, Linear regression, Water supply;

1. Introduction

Effective decision-making in water supply and wastewater services requires a comprehensive approach that ensures the best performance at an acceptable risk level, taking into account the costs of construction, operating, maintaining, and disposing capital assets over their life cycle [1]. During the early stages of water resources studies, it is desirable to have reasonably accurate cost estimates of water supply projects without going through the effort of performing a detailed engineering design [2,3]. Cost functions represent important multipurpose tools for determining the fair value and the current replacement cost for water supply assets and, for estimating the capital cost of future infrastructures. Furthermore, they can be used in the water utility management for preparing long-term capital works program as part of water utility company strategic business plan [4].

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Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.868

To address this need, several investigators have developed cost models for different types of water supply infrastructures. Lindsay and Walski (1982) [5] and Walski (1980) [6] developed the Methodology for Areawide Planning Studies (MAPS), a computer program to simulate the water resource alternatives and to develop design and cost estimates at the planning level. Lencastre et al. (1995) [7] developed cost functions for several urban water assets based on construction costs of Portuguese projects. Clark et al. (2002) [8], using a cost database provide by U.S. EPA, have developed regression models to estimate the cost of construction, expansion, rehabilitation and repair of water distribution systems. Swamee and Sharma (2008) [9] have developed several cost functions for various assets of water distribution systems (e.g., pumping stations, pipes, tanks).

The current paper presents the development and the validation of an asset-based cost model, to assist engineers and asset managers in the estimation of the construction costs of water supply infrastructures. A five-step methodology and linear regressions for modelling capital costs of different types of water supply assets have been used. For this purpose, cost and infrastructure data from several Portuguese urban water utilities, located all over the country, were collected, processed, and analysed. Capital cost functions for different types of water supply assets (i.e., ground storage tanks, pumping stations, and pipes) were estimated, based on the assets' main physical (e.g., volume, material, nominal pressure, diameter) and hydraulic characteristics (e.g., flow, head, hydraulic power). Developed cost functions have been tested and validated with data randomly extracted from the original data sample. Conclusions are drawn and discussed.

This research has several key innovative features, namely, the development of an asset-based approach for cost estimation using real data, the presentation of a comprehensive and robust methodology for cost function estimation and the development of cost functions grounded on a set of terms associated to the interventions carried out in the system..

2. Methodology

This research follows a five-step methodology for the establishment of several water supply infrastructures cost functions, as described in the following sections.

2.1. Database construction and analysis

Urban water utilities from across Portugal were involved to collect infrastructure, equipment, and cost data associated to recently constructed water supply projects. Four classes of water assets were identified for the construction of the database: storage (*ground storage*), transport (*transmission mains*), pumping, and disposal (*distribution pipes*). Infrastructure and equipment data were selected; namely, the hydraulic parameters (e.g., flow, head, hydraulic power) or physical characteristics of each asset (e.g. volume, material, nominal pressure, diameter).

Each asset was related to key characteristics that justify costs (e.g. the volume is the key parameter for estimating ground storage tank construction cost). Data related to the construction costs of the asset were processed per cost item (e.g. civil works and equipment costs compose the total construction cost for tanks and pumping stations). Finally, database analysis were also necessary to identify and remove outliers and poor data sets to reduce the overall level of uncertainty associated to the relationships between costs and the key parameters.

2.2. Calculation of the present cost of cost-items

Costs collected in the database refer to construction dates between 2005 and 2014. The calculation of the respective present values, PC , in 2014 (ISO 15686-5: 2008) is calculated as follows:

$$PC = IC\prod_{i=0}^{n}(1+t_i) = IC \times IF_{0-n} \tag{1}$$

in which IC : the initial cost in the construction year; t_i: the inflation rate in year i ; n : the number of years between construction and 2014; IF_{0-n} : the cumulated inflation factor. The inflation rate for the capital costs of infrastructures in the public sector varies every year and is available in PORDATA website (http://www.pordata.pt/Portugal, 2015-04-16).

2.3. Key parameters and cost function establishment

Cost functions describe the relationship between costs and the key parameters associated with the asset and with the several operations necessary for the asset construction or installation.

Two major costs were identified for tanks and pumping stations: the cost of civil works to build the tank's structure and the pump house respectively (including earthworks, foundations and structures, architecture and civil works), C_{cw} , and the cost of the equipment (pipes, valves, electromechanical and mechanical components, and electrical facilities), C_e . Regarding ground storage tanks, the cost varies with the tank capacity, V (m^3). Cost functions for pumping stations can be determined assuming as the main key parameter the total hydraulic power, P_h (kW), which is a function of the flow rate, Q (m^3/s), the pump head, H (m): $P_h = \gamma QH$, being □ is the water specific weight, 9.81 kN/m^3.

Regarding transmission mains and distribution pipes, taking into account the main dimensions of the trench cross-section, the construction cost is a function of the nominal diameter, ND , for different materials. Concerning service connections, the cost per connection is defined as a function of the nominal diameter and material.

2.4. Model specification

The estimation of the cost functions is based on linear regression models, whose general form is:

$$Y = b_0 + b_1 X_1 \quad (2)$$

where Y is the dependent variable (i.e. the estimated cost), X_i , are the independent variables and b_i are the estimated coefficients. Linear regressions can also be used with relationships, which are not inherently linear (e.g. power function), but can be linearized after a mathematical transformation. The least square method was used to obtain the linear parametrical equations (cost functions). Model equations are represented in Table 1 for several water supply assets, as well variables involved and the type of statistical analysis performed.

Table 1. Variables involved and type of statistical analysis performed.

Asset	Variables	Model equation (*)
Ground storage tank	Y_i : Civil works cost, C_{cw} (€/m^3) Y_i : Equipment cost, C_e (€/m^3) X_i: Volume, V (m^3)	$Y_i = \square_0 \cdot X_i^{\square_1} \rightarrow \ln Y_i = \ln \square_0 + \square_1 \ln X_i$
Pumping station	Y_i: Civil works cost, C_{cw} (€/kW) Y_i : Equipment cost, C_e (€/kW) X_i X_i: Total hydraulic power, P_h (kW)	$Y_i = \square_0 \cdot X_i^{\square_1} \rightarrow \ln Y_i = \ln \square_0 + \square_1 \ln X_i$
Transmission and Distribution Pipes	Y_i: Pipe construction cost, C_{Pipe} (€/m) X_i: Nominal diameter, ND (mm)	$Y_i = \square_0 + \square_1 X_i + \square_2 X_i^2$
Service connection	Y_i: Construction cost, C_{SC} (€/unit) X_i: Nominal diameter, ND (mm)	$Y_i = \square_0 + \square_1 X_i + \square_2 X_i^2$

(*) $\square_i, \square_i, \square_i, \square_i, \square_i$ are parameters of the models.

2.5. Model testing and validation

Model testing and validation are important steps to assign the reliability of the models before they can be used. Once regression models have been constructed, it is important to confirm the goodness-of-fit of the model, and the statistical significance of the model and of the estimated parameters. A set of assumptions must be tested for checking the goodness-of-fit, namely: (i) linearity and additivity of the relationship between dependent and independent variables, (ii) statistical independence of the errors, (iii) homoscedasticity of the errors, and (iv) normality of the error distribution. The residuals analysis was carried out.

Additionally to confirm the goodness-of-fit of the model, the *p-value* and the coefficient of determination, R^2, were calculated. The *p-value* of the model describes, for each result, its statistical significance; the *p-value* of estimated parameters describes the parameters significance (significant results with $p\text{-}value<0.05$).

The model validation takes also into account the application of the model to another data set to check the model's predictive performance. By definition, each model is mathematically optimized to best fit the data on which it is built. But it is important to evaluate how well the model can fit other data not included in the original sample. For this reason it is necessary randomly split the data sample into two separate samples using one for modeling (ca. 90% of the sample) and the other for testing the model and to assess the model's performance.

3. Results

3.1. Obtained cost functions

Several cost functions were obtained for each water asset. Table 2 shows an example of such results for the case of ground storage tanks and water transmission mains in which the cost functions, the R^2, the *p-value* and the application range are presented.

Table 2. Cost function obtained and their prediction bands equations.

Asset	Cost function	Range of parameters	R^2, *p-value*
Ground storage tank	$C_{cw.1} = 2388\ V^{-0.38}$	V = [40-5000]	0.6, 13.8×10^{-4}
	$C_{cw.2} = 2995\ V^{-0.38}$	V = [150-15000]	0.75, 2.2×10^{-16}
	$C_e = 11709\ V^{-0.7}$	V = [40-15000]	0.69, 2.2×10^{-16}
Transmission Main	$C_{DI} = 32.59 + 0.11ND + 0.00053ND^2$	D =[60, 700]	0.86, 2.2×10^{-16}
	$C_{HDPE} = 30.05 - 0.07ND + 0.00096ND^2$	D =[63, 315]	0.63, 1.23×10^{-12}
	$C_{Steel} = -885.8 + 2.05ND - 0.00053ND^2$	D = [600, 1200]	0.93, 0.0044

3.2. Ground storage tanks

Ground storage tank cost functions are power-functions of the total volume, V (m^3). As examples of obtained results obtained, Fig. 1a presents the regression curve of the equipment cost and Fig. 1b depicts the regression curves for civil works and equipment costs. Ground storage tanks can have either one or two-units, being civil works' cost functions calculated accordingly; however, the number of units does not affect the equipment cost. The maximum capacity of one-unit ground storage tanks analysed was 5000 m^3, whereas for two-units was 15 000 m^3, being these volumes the range limit of application. Results show that, on average, for ground storage tanks' volume lower than 5 000 m^3, civil works represent about 60-70% of the total cost and the equipment 30-40%, respectively for one-unit and two-units; for higher volumes, civil works represent a higher percentage of total costs, about 85%.

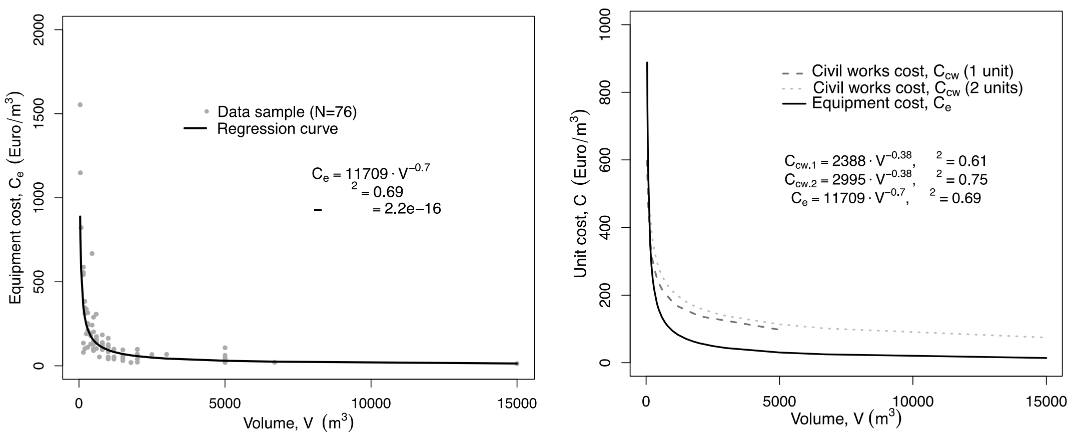

Fig. 1. Ground storage tank: (a) regression curve for equipment cost; (b) obtained functions for civil works and equipment.

3.3. Transmission mains

The cost functions of transmission mains have been established as a function of the nominal diameter according to the pipe material. Steel pipes, ductile iron (DI) pipes, and high-density polyethylene (HDPE) pipes of nominal pressure (NP) 10 and 16 bar were analysed. For each pipes category and for each material, correlation functions were obtained (Fig. 2). These cost functions show that: (i) HDPE is used for lower diameters (≤ 315 mm), ductile iron for diameters between 60 and 700 mm and steel above 600 mm (up to 1200 mm); (ii) unit costs increase with the nominal diameter; (iii) for the same diameter, HDPE (NP10-16) pipes have a lower cost that DI pipes (60-300 mm) and DI is more expensive then steel pipe (600-700 mm); (iv) obtained correlation coefficients are quite good (between 0.63 and 0.93) despite the dispersion of the data. The dispersion is due to the pipes costs depending also on soil material (% of rock), the location in the country, the total length of the pipe (the longer the pipe, the lower the unit cost), the economic situation of the country, among other parameters.

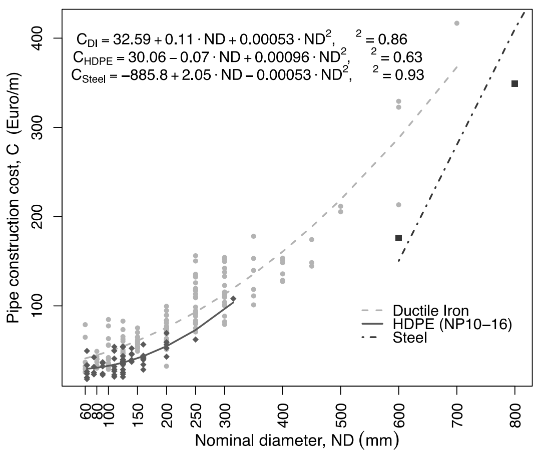

Fig. 2. Transmission mains: cost functions for all categories of pipes.

4. Conclusion

The contribution of this research is twofold. First, it provides a comprehensive and robust methodology for cost function estimation. Second, it develops cost functions that are grounded on a set of terms with an associated physical meaning. It should be highlighted that obtained cost functions are a step-forward in cost analysis, as these provide useful information to use in design of new systems and in the management of existing systems, contributing for a more sustainable management in the short, medium and long terms. Although these cost functions have been obtained for the Portuguese reality, the methodology followed herein can be used by utilities from other countries to determine their own cost functions.

Acknowledgements

The authors would like to thank to the AdP group, especially Nuno Lopes and Luis Mamouros, that have provided data and supported this research project. We would like also to thank to Susana Lopes and David Figueiredo for the helping in data collection, processing and analysis.

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