

## Modelling capital costs of sewer system assets

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### ABSTRACT

*The aim of this paper is the establishment of cost functions for the various assets of sewer systems, namely gravity and raising pipes, drainage and storm water pipes, service connections and pumping stations. Costs are defined as a function of the main physical characteristics of the assets, such as, pipe material and nominal diameter (for pipes and service connections) and flow rate, pump head and pump power (for pumping stations). A five-step methodology was followed: 1) data collection, processing and analysis, 2) present cost value calculation, 3) asset characterization and key parameters identification, 4) cost functions and prediction band estimation, and 5) cost functions validation. Cost and infrastructure data for construction contracts of wastewater systems managed by different Portuguese water and wastewater utilities were analysed. Cost functions were estimated based on multiple linear regression analysis.*

**Keywords:** Cost functions, wastewater systems, multiple linear regressions

## 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 consideration the costs of construction, operating, maintaining, and disposing capital assets over their life cycle [1]. Estimating costs of constructing wastewater systems is a crucial part of master planning these systems. Capital investments in wastewater systems represent a major challenge in all countries that often have inadequate financing capacity. Thus, in the preliminary stages of a project, it is of the utmost importance to have reliable cost functions for predicting infrastructure costs [2]. Cost functions represent important multipurpose tools for determining the fair value and current replacement cost for water and wastewater existing assets and, for estimating the capital cost of future works, where specific cost estimates are not available. 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 [3, 4].

To address this need, several investigators have developed cost functions for gravity, raising and drainage pipes as a function of pipe diameter and of excavation depth [5, 6, 7, 8]. A statistical approach to develop cost functions for sewer lines was proposed [9], aiming to define total pipelines construction cost as a function of capacity. Several cost functions have been proposed for sanitation systems for rural areas [10]. Other cost functions were presented [11] for various sewer elements in South-Africa. Several cost functions have been determined for Portuguese wastewater systems [3, 12, 13, 14, 15].

The current research aims at the establishment and validation of construction cost functions for different types of wastewater assets (pumping stations, gravity and raising pipes, drainage and storm water pipes and service connections), based on known main physical characteristics (*e.g.*, material, nominal diameter) and hydraulic parameters (*e.g.*, flow, pump hydraulic power). The

major contributions of this research are the presentation of a comprehensive and robust methodology for cost function estimation, using multiple linear regression analysis, and the development of cost functions for wastewater system grounded on a summation of terms with an associated physical meaning.

## 2 METHODOLOGY

The methodology followed for the establishment and validation of construction cost functions of different assets of wastewater system is a five-step procedure, as described in the following sections.

### 2.1 Data collection, processing and analysis

Portuguese water and wastewater utilities were involved to collect infrastructure, equipment, and cost data associated to recently constructed wastewater systems projects. Three classes of wastewater assets were identified for the construction of the database: transport (gravity and raising pipes), sewer (drainage and storm water pipes and service connections) and pumping. Infrastructure and equipment data were selected; namely, the hydraulic parameters (*e.g.*, flow, head, hydraulic power) or physical characteristics of each asset (*e.g.*, material, nominal diameter).

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

### 2.2 Present cost value calculation

Costs collected in the database refer to construction dates between 1998 and 2016. The calculation of the respective present values,  $PC$ , in 2016 is calculated as follows:

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

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 2016;  $IF_{0-n}$ : the cumulated inflation factor. Present cost value is calculated based on Harmonized Index of Consumer Prices, available in Portugal's Bank.

### 2.3 Asset characterization and key parameters identification

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 pumping stations: the cost of civil works to build 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),  $C_e$ . Cost functions for pumping stations can be determined assuming as the main key parameter the total hydraulic power,  $P = \gamma QH$  (kW), which is a function of the flow rate,  $Q$  ( $m^3/s$ ), the pump head,  $H$  (m) and the  $\gamma$  the water specific weight,  $9.81 \text{ kN/m}^3$ .

Regarding transport and drainage 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 Cost functions and prediction band estimation

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

$$Y = b_0 + b_1 X_1 \tag{2}$$

where  $y$  is the dependent variable (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 wastewater assets, as well as the variables involved and the type of statistical analysis performed.

Cost modelling also includes the estimation of prediction bands (percentiles 5-95%), where 90% of future data points were expected.

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

Asset	Variables	Model equation <sup>(*)</sup>
Pumping stations	$\gamma_i$ : Civil works cost, $C_{cw}$ (€/kW) $\gamma_i$ : Equipment cost, $C_e$ (€/kW) $X_i$ : Total hydraulic power, $P$ (kW)	$Y_i = \gamma_0 \cdot X_i^{\gamma_1} \rightarrow \ln Y_i = \ln \gamma_0 + \gamma_1 \ln X_i$
Transport, drainage and storm water pipes	$\gamma_i$ : Pipe construction cost, $C_{pipe}$ (€/m) $X_i$ : Nominal diameter, $ND$ (mm)	$Y_i = \delta_0 + \delta_1 X_i + \delta_2 X_i^2$
Service connections	$\gamma_i$ : Construction cost, $C_{sc}$ (€/unit) $X_i$ : Nominal diameter, $ND$ (mm)	$Y_i = \lambda_0 + \lambda_1 X_i + \lambda_2 X_i^2$

<sup>(\*)</sup>  $\alpha_i, \beta_i, \gamma_i, \delta_i, \lambda_i$  are parameters of the models.

### 2.5 Cost functions validation

Model validation is an important step 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 coefficient of determination,  $R^2$ , were calculated.

### 3 CASE-STUDY

The case-study used comprises wastewater system assets constructed between 1998 and 2016 from different Portuguese wastewater utilities. The asset characterization is presented in Table 2.

*Table 2. Asset characterization of wastewater system*

Asset	Number of available data	Construction date	Characteristics
Gravity pipe Raising pipe Drainage pipe Storm water pipe Service connections	370 205 155 42 99	[1998; 2016]	Material: PPc, DI, PVC, HDPE, concrete L (m): [10; 69 320] ND (mm): [80; 1 600]
Pumping stations	360	[2005; 2015]	Q (l/s): [3; 1 329] H (m.c.a.): [3; 83]

HDPE = high density polyethylene; DI = ductile iron; PVC = polyvinyl cholride; PPc = polypropylene carbonate; = flow rate (l/s); = pump head (m c.a.); = pipe length (m); = nominal diameter (mm).

### 4 RESULTS

The cost functions of transport, drainage and storm water pipes have been established as a function of the nominal diameter according to the pipe material. Ductile iron (DI) pipes, high-density polyethylene (HDPE) pipes, polyvinyl cholride (PVC) pipes and polypropylene carbonate (PPc) pipes were analysed. For each pipes category and for each material, correlation functions were obtained (Figure 1).

These cost functions show that: (i) unit costs increase with the nominal diameter for all pipes category, and (ii) obtained correlation coefficients are very good (between 0.68 and 0.99) 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.

Gravity pipes include DI, HDPE, PPc and PVC materials. The DI material was divided into two types: open-trench or bridge-crossing. In the case of PPc and PVC, these materials present very similar costs in the various cost items, allowing to group the elements together to obtain a single construction cost. DI material presents the highest construction cost up to diameters of 700 mm, value from which the HDPE becomes the most expensive gravity pipe material. In the DI, the cost is higher for gravity pipes installed in a trench, since DI installed in the crossing does not include the costs associated with the earthworks.

The raising pipes include DI, HDPE and PVC materials with nominal diameters between 80 and 1 000 mm. The DI presents the highest cost compared to other materials. HDPE and PVC have similar costs.

Drainage pipes include PPc, PVC and DI materials with nominal diameters between 200 and 400 mm. In the case of PPc and PVC, these materials present very similar costs in the various cost items, allowing to group the elements together to obtain a single construction cost. The DI has a smaller range of diameters (between 200 and 250 mm), however, construction costs are significantly higher compared to PPc/PVC pipes.

The analyzed storm water pipes include concrete and PPc materials with diameters ranging from 300 to 800 mm. The concrete covers the widest range of diameters, while the PPc is used for pipes up to 630 mm. PPc pipes have a higher construction cost compared to concrete pipes.

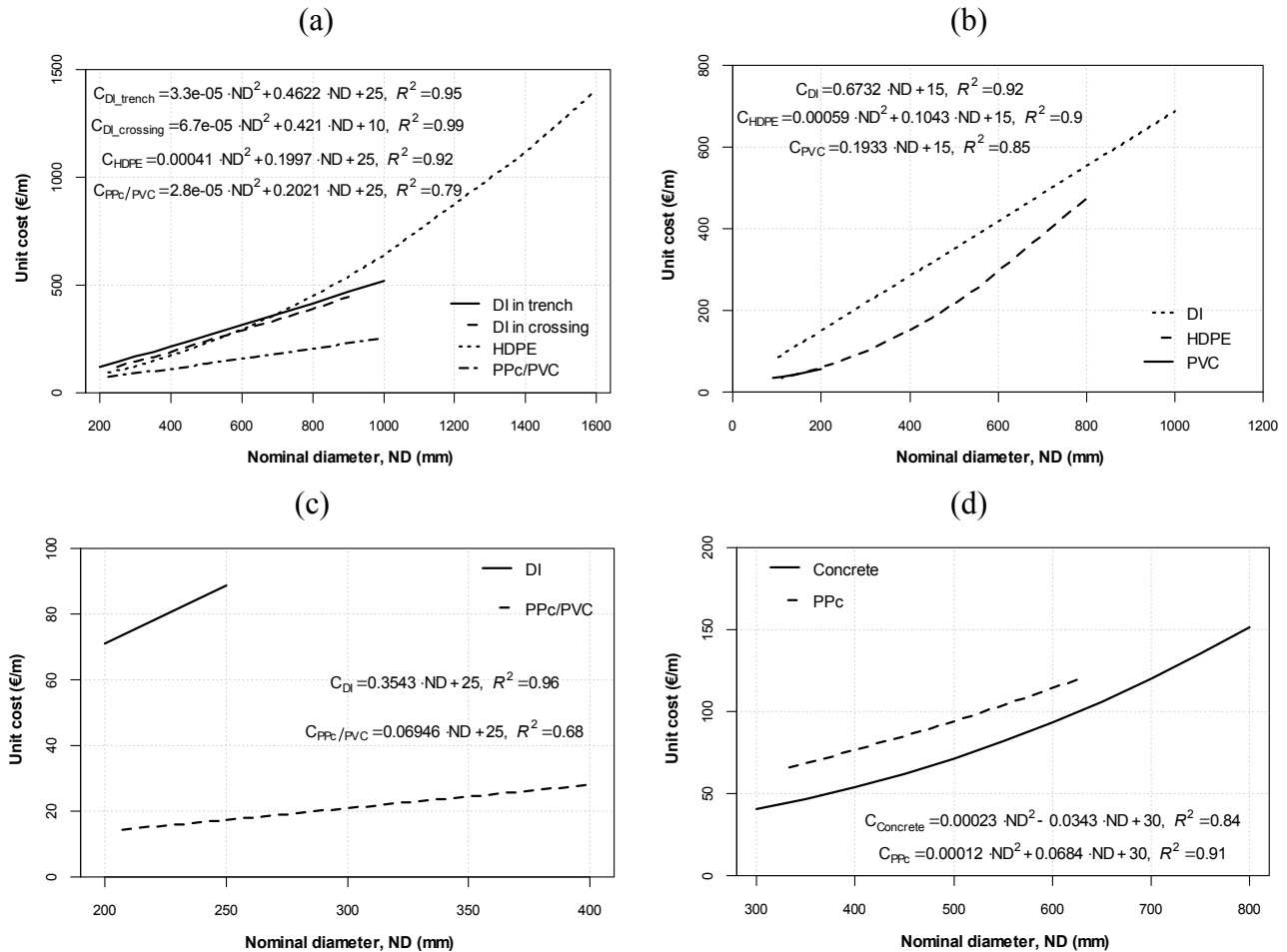


Figure 1. Pipe cost functions: a) gravity; b) raising; c) drainage; c) storm water

Service connections studied include PPc and PVC materials, which, as the drainage pipes, these materials have been grouped for a single cost. Characteristic parameters used were the nominal diameter, the density and the number of service connections. The cost of the service connections is calculated according to the respective diameter (€/unit), and it must be added to the cost of the drainage pipes as a function of the density of service connections and of the average diameter (Figure 2).

Pumping stations of wastewater systems were divided into three types, according to the number of pump groups and the type of building: Type I - compact and conventional pumps without building; Type II - conventional pumps with building (number of groups 1 + 1); and Type III – conventional pumps with building (number of groups 2 + 1 or 3 + 1). There is an increase in the construction cost from Type I to Type II, and from Type II to Type III (Figure 3). This increase is explained, in the first case, by the increase in the cost of civil works resulting from the construction of the building and, in the second case, by the increase in the cost of electromechanical equipment and civil works due to the increase in the number of pump groups installed.

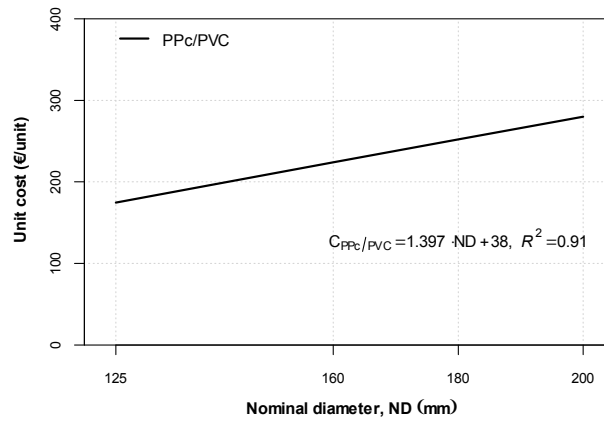


Figure 2. Cost functions of service connections

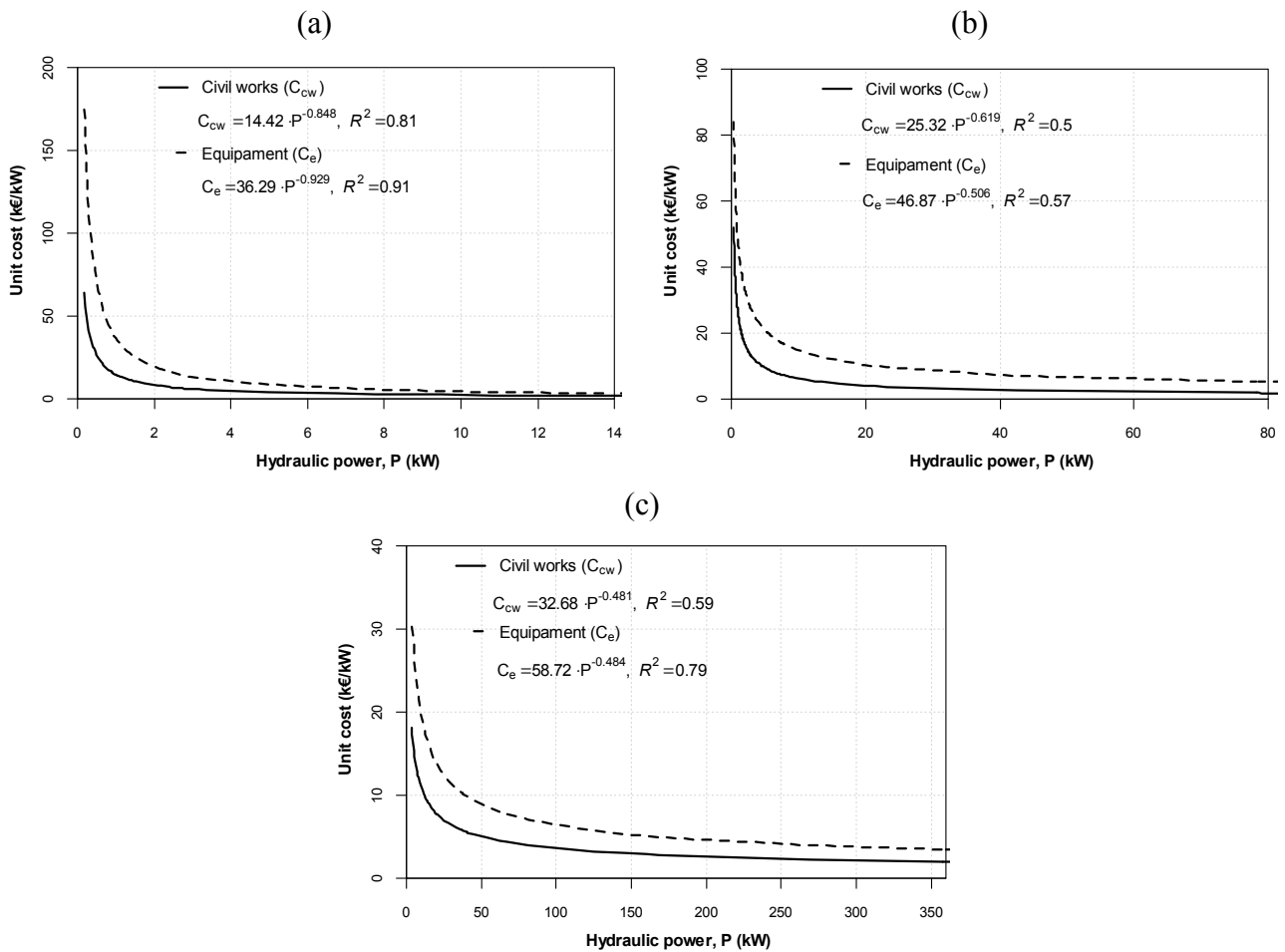


Figure 3. Cost functions of pumping stations: a) Type I; b) Type II; c) Type III

## 5 CONCLUSIONS

A comprehensive and robust methodology for cost function estimation, using multiple linear regression analysis, has been systematized. Cost functions have been determined for different types of assets of wastewater systems (sewer lines and pumping stations) as a summation of cost items described by a combination of variables.

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.

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