Article

Development of an asset lifetime model for distribution network management

Patricia Gómez-Martínez [1]* and Francisco Cubillo [2]

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[1] Canal de Isabel II Gestión S.A.; pgomezmartinez@canalgestion.es
[2] Canal de Isabel II Gestión S.A.; fcubillo@ canalgestion.es
* Correspondence: pgomezmartinez@canalgestion.es; Tel.: +915451000

Abstract: Aging infrastructures maintenance results in increasing asset investment in order to provide and maintain a specific level of service to consumers. In this regard, efficient replacement polices are needed. This paper proposes a method for improving renewal efficiency in water supply systems through a reliable asset lifetime model that will lead investments to those elements with greater impact in service provision to the end user. As uncertainties are minimized, the likelihood of failure will be more accurate and renewal investments will become more efficient. Therefore, the failure predictor model has been built in a reliable manner through collected data from Madrid distribution network which comprises more than 17.000 km with over 400.000 water pipes. It is based on the statistical analysis of historical data from over 55.000 system failures gathered during four complete years. Additionally, detailed information from more than 4.400 disturbance events was recorded through field visits and laboratory essays of soil and pipe materials when failures were repaired. Examination of such large series of data recorded allows a better understanding of explanatory factors of failures. It is an essential step for building a consistent asset lifetime model. According to this model, a renewal strategy is proposed. It based on the risk of service disturbance and involved costs. It supports planning and operation decisions reaching failures reduction and system resiliency improvement.

Keywords: Asset lifetime model, system Failure, service disturbance, asset management.

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1. Introduction

Providing an appropriate level of service is the primary goal for water suppliers in urban water distribution systems. Even though a certain level of service is defined by regulatory standards, service responsible agents use to set their own commitments of service with thresholds that go beyond such specifications for improving customer satisfaction level. In this regard, the level of service, considered as the guarantee of supply at every property, can be measured in terms of continuity of service, pressure and quality provided to the end user.

On the other hand, service suppliers make remarkable efforts to establish suitable asset management policies. Aging infrastructures require increasing asset investment for maintaining the level of service. So that, developing a cost effective asset renewal and replacement strategy is essential. Two different strategies for replacement optimization have been analyzed in the literature [1]. One of them is focused the optimal replacement time for a pipe while the other is based on prioritizing the pipes in the network for replacement under a certain budget.

Actually, water suppliers are focused on improving efficiency in CAPEX & OPEX for some horizons and scenarios but all issues involved in asset management are linked to uncertainty. The key for a better asset management is to set criteria, methods and systems to facilitate that improvement of efficiency at the decision making process through uncertainties minimization. So that, managing uncertainty becomes a primary goal that would probably result in a better asset management for providing the desired level of service.

In addition, main constraints and targets are linked to the fulfillment of standard of service under normal demands, normal operation and normal operability of infrastructures. However, since normal conditions are a never happened scenario, resilience of supply system turns into a key concept to incorporate in asset management. So, it must be properly defined as a component of standard of service.

Water suppliers use different systems to take decisions assuming values that manage uncertainty: demand evolution, asset real capacity, operation feasibility, events resolution time, etc. Efficiency can be assessed by analysing the combination of total costs and their link to network's vulnerability rate [2]. It involves a deep understanding of system performance, system resiliency and network deterioration process. Additionally, when costs are analysed a Multi-Criteria method based on risk aspects and effects for consumers is needed [3].

This way, an effective asset management requires condition assessment. It includes the collection of information about assets condition, analysis of this information, and ultimately transformation of this information into knowledge, leading to effective decision about likelihood of failure and renewal [4]. Hunaidi [5] classifies condition assessment methods into direct and indirect methods. Direct methods include automated/manual visual inspection, non destructive testing and pipe sampling. Indirect methods include water audit, flow testing, and measurement of soil resistivity to determine the risk of deterioration. But uncertainties are still substantial.

Some solutions are focused on the development of water networks models to foresee the system possible behavior. However, when defining assets lifetime models, uncertainty has also to be faced. Failures in pipelines depend on many factors that are difficult to characterize quantitatively [6]. So that, some research projects are being developed for a better understanding of the explanatory factors of bursts and failures. Additionally, different asset lifetime models have been developed. Kleiner and Rajani [7] grouped them as physically based models and statistical models. While the first group aims to discover the physical mechanisms behind pipe breaks, statistical models are based on historical break data to identify break patterns in the water mains [8].

As Xu et al. [9] affirms, in the absence of deterministic physical models for pipe break, data-driven techniques provide a promising approach to investigate the principles underlying pipe break. However the uncertainties associated with the recorded failure data provides imprecise results of the methodologies or models used [10]. In this regard, a model able to calculate the residual and economic assets lifetime should be built from reliable data in a robust manner.

Therefore, the presented method proposes a statistical failure prediction model which is built from a complete database of failures. It is developed from two complementary databases: in the first one, every failure at each element has been carefully registered along 4 years period (2010-2014); in the second one, additional information from field visits to failures repair has been included for improving this approach. In such way, assets renewal policies can be led efficiently through a strategy for replacement based on the risk of service disturbance. The paper also presents results from the case study of Madrid water supply system, where Investment Plans are issued every year for minimizing the likelihood of bursts while improving system resilience. It shows how renewal policies efficiency can be improved from different hypothesis in the decision process.

2. Materials and Methods

In this paper, a method for improving renewal efficiency in water supply systems through a reliable asset lifetime model is presented. The priority of investment is defined according to the concept of possible service disturbance events which are linked to the likelihood of failure at each element of the system and its impact in the level of service provided. Thus, the risk of service disturbance is defined as follows (1):

$$\text{Risk of service disturbance} = \text{Likelihood of failure} \cdot \text{Consequences} \qquad (1)$$

This way, the proposed method is based on the minimization of uncertainty linked to the prediction of system disturbances while analysing its consequences and system resilience. In this context, a reliable model of failure prediction for defining assets lifetime is needed to minimize uncertainty. Through this model a more accurate diagnoses of system condition can be obtained in order to lead renewal and replacement policies.

Renewal efficiency is considered as the investment option that reduces disturbances impact as well as optimizes investment costs. Therefore, this approach also includes the evaluation of costs by considering the trade-off between replacement cost and the cost related to failures. The cost of failures includes not only service disturbance impact to end users as a cost but also repair costs. From this approach, assets lifetime is governed by an age threshold where renewal cost is below the cost related to failures.

Developed methodology can be explained in two steps. First of all, a failure prediction model is proposed. Then, renewal strategy is defined according to the risk of service disturbance and involved costs.

2.1. Failure prediction model

It has been built from the historical data of system failures gathered during four years, between 2010 and 2014. Along this period, more than 55.000 pipe failures were recorded and repaired. These episodes correspond to bursts and leakages in water pipes and connections. Likewise, more than 4.400 out of the total mentioned disturbance events have been analyzed in detail through field visits and laboratory essays of soil and pipe materials, where further information of failure causes have been identified accurately.

Figure 1. Field visits to water network failures.

According to this information, every element in the supply system has been characterized by the attributes that could have more relevance in failures. Assets deterioration process is influenced by different parameters; some of them are physical factors but others depend on operational circumstances. Therefore, a reliable analysis should include data from both pipe characteristics and hydraulic analysis. From a complete study of all failure variables identified they have been classified as: factors linked to external agents, intrinsic element factors, operational factors and installation factors.

In order to analyze relations between elements and failures, some data such as age, material, diameter, and depth has been obtained from the geographic information system (GIS). Other factors related to operation like average operation pressure, pressure oscillation and water velocity among others have been calculated by calibrated models of system perform. Pressure transients have been also included in this study analysing the relationship between system manoeuvres at special network elements and its incidence in the rest of system's components. For that, information from a database where operational manoeuvres are recorded has been examined. Some other specific factors, gathered from failures visits in situ, provide information about causes of bursts to confirm if the failure has been produced by a particular event or if it is the consequence of element deterioration. Some of such field and laboratory observed factors have been the type of surrounding soil, the soil temperature measured, field pressure registered, deficiencies on elements materials, deficient installation conditions related to bedding and level of compacting of the embedment soil, the occurrence of external factors like constructions works in the area closed to the failure, external loads from traffic or walls or presence of roots, and maintenance conditions, including the level of internal and external corrosion and section thickness reduction.

All these explanatory factors have been studied for each failure element in order to characterize them. A statistical analysis has been developed considering uniform groups of components in the water system: Strategic water mains, distribution water mains, service connections and special network elements such as manoeuvre valves, air valves, or drainage pipes among others.

		Service connections	Distribution pipes	Strategis pipes	Network Elements
Geographic Information System (GIS)	Diameter	◉	◉	◉	◉
	Age	◉	◉	◉	◉
	Material	●	◉	◉	●
	Depth	◉	●	●	◉
	Location (buried, chambers...)	●	●	●	◉
Geological, urban and regional Planning Maps	Type of soil	◉	●	◉	●
	Soil cover	●	●	●	●
	Traffic loads	●	●	●	●
Bursts and leakages records	Failures' date and location	●	●	●	
	Spatial failures distribution	●	●	●	
	Temporal failures distribution	●	●	●	
Field visits to bursts and laboratory tests	Soil temperature	●	●	●	
	Soil agresiviness	●	●	●	
	Isolated conductive zones	●	●	●	●
	Pipe bedding condition	●	●	●	●
	Compaction of embedment soil	●	●	●	●
	Deficiencies on elements materials	●	●	●	●
	Field pressure registered	●	●	●	●
	External loads from traffic or walls	●	●	●	●
	Presence of roots	●	●	●	●
	Corrosion (internal and external)	●	●	●	●
	Section thickness reduction	●	●	●	
Calibrated hydraulic models of system perform	Max. Pressure	●	●	●	
	Av. Pressure	●	◉	●	
	Min. Pressure	●	●	●	
	Max. Velocity		●	●	
	Av. Velocity		●	●	
	Min. Velocity		●	●	
Monitoring records (SCADA)	Max. Pressure at sectors' entrance		●	●	
	Min. pressure at sectors' entrance		●	●	
	Pressure oscilation at sectors' entrance		●	●	
Operation and works records	Operational manoeuvres		◉	●	●

Figure 2. Burst observed factors and most relevant explanatory factors selected.

In order to built an asset lifetime model, the likelihood of failure is related to the cumulative distribution function of the time F(t) for each group of components. It is defined as follows (2) for a period [t, t+Δt]:

$$p_f(t\,,t+\Delta t)=\int_t^{t+\Delta t} f(\tau)d\tau = F(t+\Delta t)-F(t) \qquad (2)$$

The analysis of all explanatory factors for every group of components minimizes the error in the prediction of the expected number of failures for each validation scope. The correlation between registered episodes and the characterization of the involved element at each event results in the determination of the likelihood of failure for every system element. The expected number of failures is obtained through the probability density function given by the studied factors which is defined as the likelihood of failure for service connections and special elements and the likelihood of failure per unit length in case of strategic and distribution pipes.

For exporting results to every element at each group of system's components, the final model considers the explanatory factors with higher relevance in failures by multiplying the failure predictor model dependent to the time and the corrective coefficients proposed for the other selected factors (3). The corrective coefficients are obtained through the quotient between the distribution function linked to failures and the generic distribution function for each factor.

$$p = p_1(t)\cdot f_2\cdot f_3\cdot f_4 \qquad (3)$$

Where p1(t) is the likelihood of failure given by the time and f2, f3 y f4 are the corrective coefficients for selected explanatory factors 2, 3 and 4.

2.1. Renewal strategy

In a second step, consequences of failures are measured. The renewal strategy is based on an economical analysis between benefits of a minor service disturbance ratio over the total replacement cost. So that, consequences are evaluated in terms of service interruption impact and costs. The variables in this analysis are: replacement cost, which depends on element material and its environmental conditions such as soil type, land uses and loads and pipe trench depth; element failure impact that depends on the duration of service disturbance, the number of properties involved by each failure, the time of disturbance needed for failure detection and its repair, and its monetary conversion; repair cost which varies according to elements physical characteristics and its location.

This way, every element in the system has new attributes related to the impact of its potential failure that is defined as 'properties x hour' with service interruption, its repair cost and its replacement cost. The concept of 'properties x hour' includes not only the number of customers affected by each failure but also the duration time of their affection. For calculating replacement cost, some simplifications in renewal policies have been introduced, assuming that every element is replaced by an identical one.

The benefit of replacing an element depends on the likelihood of failure of both, the old and the new element. It can be measured by the cost linked to each failure c_r and the reduction in the likelihood of failure which varies with the time. Thus, the analysis should include a corrective coefficient which considers a reduction in expected costs for future failures. In order to assess the convenience of replacing a certain element, renewal costs c_s must be compared to obtained benefit C_R. For a proper analysis, benefit must be discounted back to its present value which depends on the discount rate selected r.

Therefore, benefit of replacement C_R for a horizon of N years can be calculated by the following formula (4), where A is the old element with an age of k years, and R is the new element. While p_i is the likelihood of failure for the year i obtained from the lifetime model, pi+k is the corresponding likelihood of failure for an element of k years.

$$C_R = c_r \sum_1^N \frac{p^A_{i+k}-p^R_i}{(1+r)^i} \qquad (4)$$

Finally, according to its service perturbation and costs, a priority list of elements that should be replaced can be obtained. In such way, renewal investments will be led in an efficient manner to those elements with greater impact in service provision to the end user while optimizing investments.

2. Results and Discussion

The water utility Canal de Isabel II Gestión, which supplies water to more than six million people in the Madrid area (Spain), applies asset management system for Investment Plans (enlargement and replacement) and for Operational Resilience improvement. The key points of this system are infrastructures lifetime and resilience assessment. With the main goal of improving service provision linked to aging infrastructures, the most efficient distribution of annual investment budget is required.

The proposed method has been applied in the network in order to assess how the efficiency of investment changes with different hypothesis of the failure predictor model. It has been applied to Madrid Region where the network comprises more than 17.000 km with over 400.000 water pipes.

Figure 3 presents the main characteristics of the proposed case study for every group of components. Strategic water mains, distribution water mains, service connections and special network elements are graphically characterized in relation to its age and diameter. For each of them the generic cumulative distribution function (generic FDA) and the failure conditioned distribution function are illustrated (conditioned FDA). They have been built according to historical available data until 2014. Graphics related to age begins at the year when information is reliable so they start with a specific value of cumulative distribution functions (20% -35%).

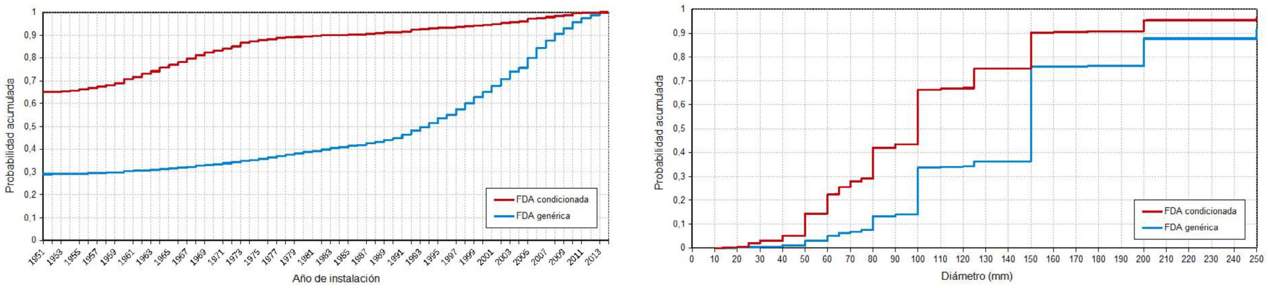

Figure 3.a Distribution water mains

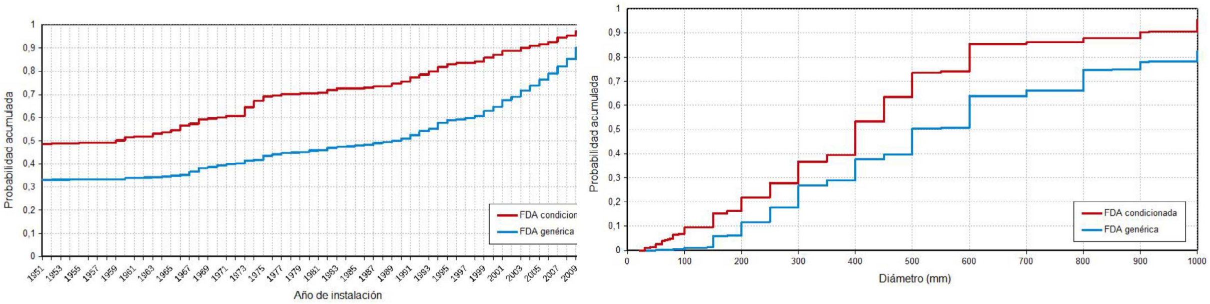

Figure 3.b Strategic water mains

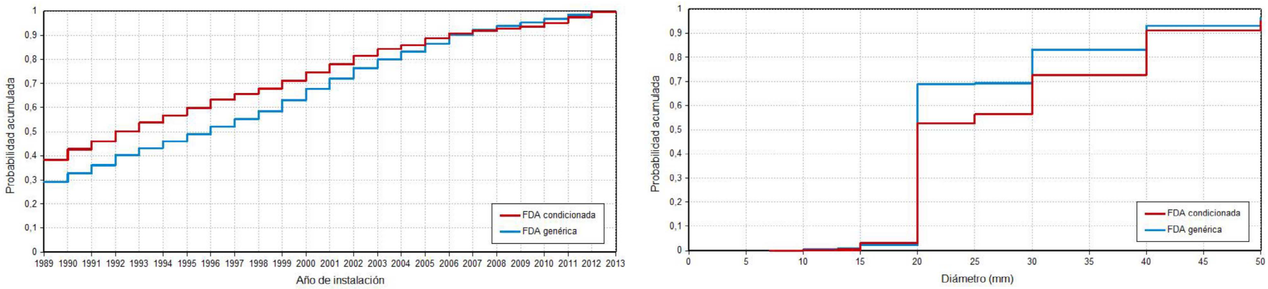

Figure 3.c Service connections

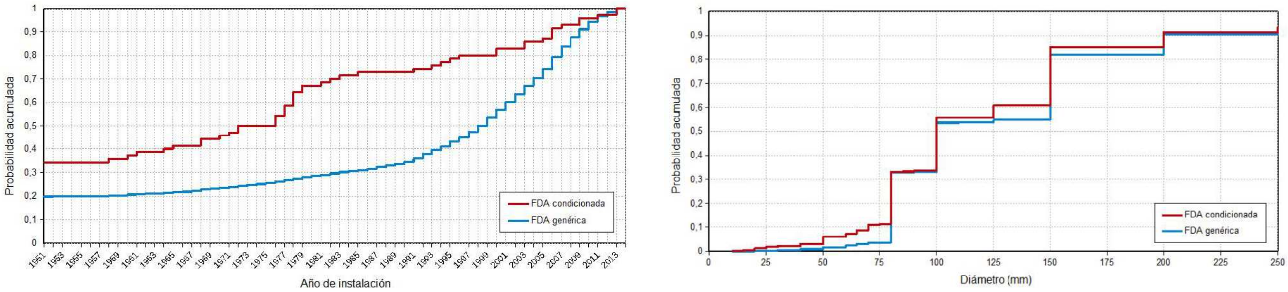

Figure 3.d Special network elements

Figure 3. Group of components characterized in relation to its age and diameter.

As can be observed in the figures for distribution water mains the gradient of the failure conditioned distribution function is greater than the generic one along the 25 first years, what means that the likelihood of failure is higher for pipes installed in those years. The performance is similar in the case of strategic pipes for those installed in the 15 first years represented and for service connections for those elements installed along the 10 first years considered in the graphic. For special elements the likelihood of failure is higher for those installed in the 35 first years considered.

Regarding system's diameter, almost the 90% of distribution water mains present diameters smaller than 250 mm, and the likelihood of failure is greater for pipes with diameters lower than 150 mm. In the case of strategic water mains, the 80% of pipes present diameters smaller than 1000 mm and the likelihood of failure is greater for pipes with diameters below 500 mm. Besides, more than 90% of service connections present diameters inferior to 50 mm and while the more frequently installed diameter in the recent year is 20 mm, the greater gradient of failures is presented for diameter 40 mm which was installed in the past. The 90% of special elements got diameters below 250 mm and failure is more frequent for those where diameter is smaller than 80 mm.

Described methodology has been applied to this case study. Firstly assets lifetime has been calculated through the failure prediction model, defining the likelihood of failure for every element. Then, a second module calculates for each of them its potential failure impact in service provision as the risk of service disturbance measured by 'properties x hour' and the repair cost. Then, it is compared with the renewal cost as it is presented in Figure 4 for distribution water mains and in Figure 5 for strategic water mains. The point cloud for each case represents every element. It allows identifying the priority list for replacement by defining a red line as a threshold. The elements in the left side of the red line should be selected for renewal strategy because the relevance of the risk of service disturbance or, because the cost of renewal is not too high in relation to the impact of failure.

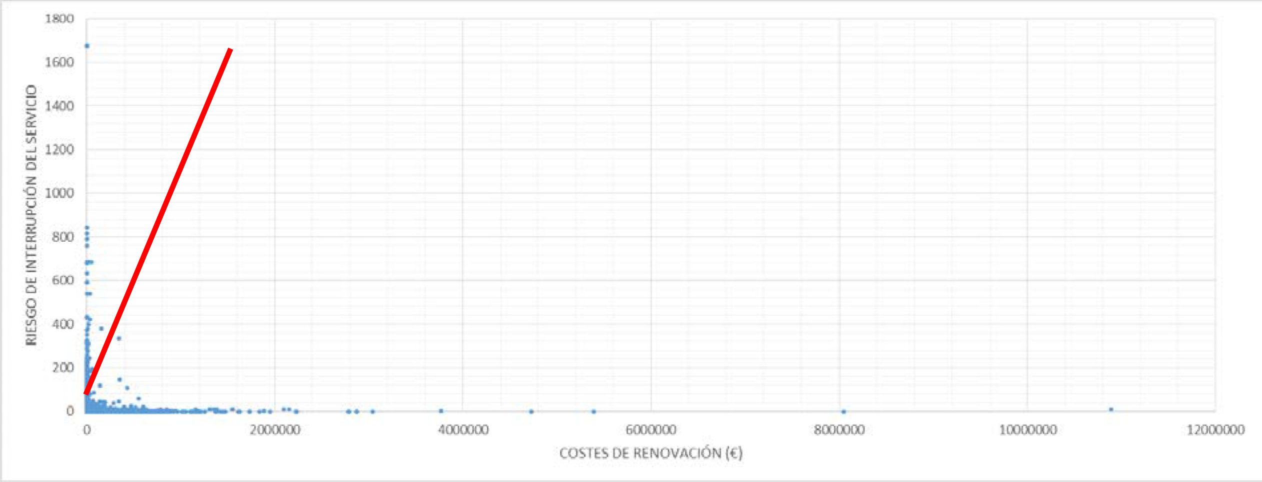

Figure 4. Results for renewal strategy in distribution water mains**.**

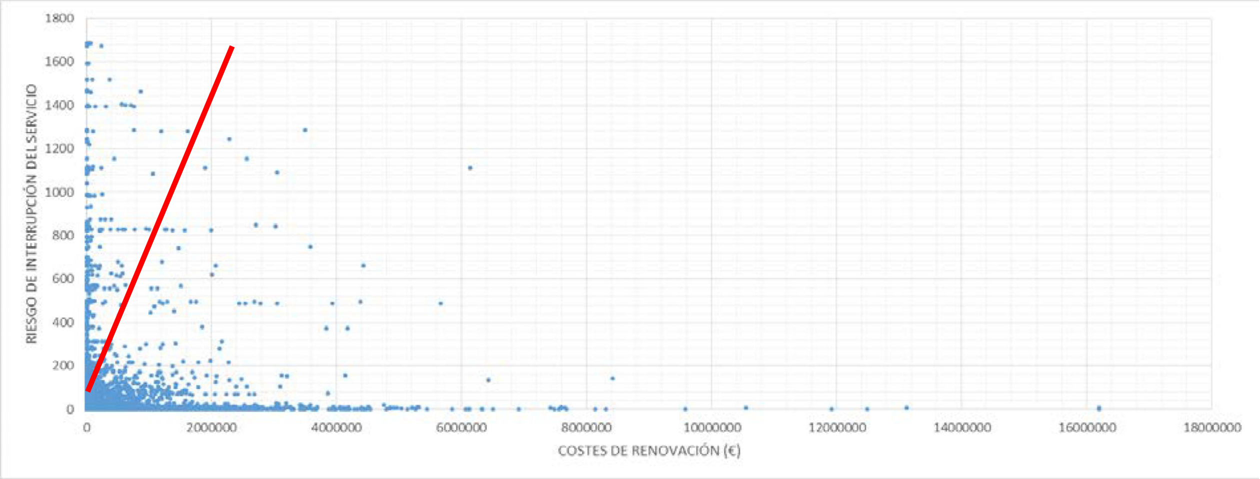

Figure 5. Results for renewal strategy in distribution water mains**.**

Moreover, elements located in the right side of the threshold proposed include some cases that preventive replacement implies great disturbances. It is the case of critical pipes for providing service where assuming the risk of failure is recommended.

As replacement priorities change according to system conditions and previous investments, the proposed method forecasts annually the set of pipes that should be renewed to minimize service disturbance.

5. Conclusions

As conclusion, asset lifetime models reliability is a relevant factor to consider for leading water replacement investments and giving support in water utilities decision making process.

In that process the lifetime model provides useful information in terms of planning as well as operation. Planning is improved because pipes which should be renewed (depending on investment availability) are clearly identified. That decision is made based on the risk of service disturbance as well as the cost-benefit analysis of renewal. Operating decisions are improved by reducing the likelihood of failures, improving system resiliency and economic analysis of repairing or replacing designated assets.

Building a robust failure prediction model based on detailed databases of failures is essential to minimize uncertainties in the likelihood of service disturbance events calculation. Different models based on Madrid's network data are proposed for service connections, distribution pipes, transport mains & elements. Results confirmed that models with more than 4 variables do not add predictability.

As replacement priorities change according to system conditions and previous investments, the model of residual useful life forecasts annually the set of pipes that should be renewed to minimize service disturbance. The new renewal strategy based on the proposed useful life model will provide an improvement of investment efficiency for water companies but also it will increase customers' satisfaction from reductions on service disturbance events.

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