Instituto Superior Técnico

Data Envelopment Analysis

An approach to the Portuguese water sector

Extended Abstract

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Abstract

The present work consists of a first approach to the use of Data Envelopment Analysis (DEA) in the Portuguese water companies' sector. As bulk information regarding the performance of the water utilities increase due to regulation concerns, opportunities for a better knowledge of the water sector arise as well. DEA is therefore presented as a tool at the Regulator disposal in a sector characterised by market failures that prevent it to move towards an efficient (perfectly competitive) equilibrium.

DEA method is put forth as an instrument to assess how companies use their expenditure in order to provide the observed levels of service to their customers. Moreover, the evaluations made by DEA refer to the decision making units' efficiency in comparative terms, as they are compared between each other, creating a sort of artificial competition. The efficient units identified consist of those that lie in the boundary of a multidimensional space containing all the feasible input-output combinations. Such benchmark units are thoroughly examined, as well as the returns to scale philosophy that underpins the conducted assessment.

The evaluation undertaken gives a first account of how much companies can improve their performance regarding total expenditure and water losses, showing that the sector as a whole can also evolve significantly. DEA recommends very demanding target-values that are eventually related to the disparity of units' scale size and to the flagrant contrast between main ageing.

Keywords: DEA, performance measurement, expenditure efficiency, water loss efficiency

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1. Introduction

The present document describes an application of Data Envelopment Analysis (DEA) in the Portuguese water sector. As new data collections regarding the activity of the companies in the sector are now annually published by the regulatory authority, there is the opportunity to test new formulas to assess and improve their performance as water utilities.

DEA compares the efficiency of decision making units in a programming-based method that is deemed to recreate the circumstances under which all these units operate. This comparative environment brings a sort of artificial competition to the sector and can be used by the regulator to counter the monopolistic power of the Portuguese water companies.

2. Regulation in the water sector

According to FRIEDMAN [2002], market failures are present in almost every market, resulting that ordinary market coordination does not lead to an efficient equilibrium. Despite this fact, economies based on these *real* markets have shown significant economic growth and played major roles in the economic progress of the world in the last centuries. Therefore, it is of cumbersome importance to identify the weaknesses that keep these markets away from working efficiently. MARQUES [2011] states that the water utilities sector is characterised by market failures like natural monopolies, scale and scope economies, sunk costs, imperfect (asymmetric) information, externalities, *almost-public* goods, possible government failures, among others, and cannot run independently without avoiding inefficient situations that go against customers interests and expectations. The author sees these last difficulties as the major constraints to privatisation, in spite of the rising tendency towards the separation of responsibilities between private and public entities, which can be actually seen at many levels. MARQUES [2011] refers to three established and well-known models as the typical examples of private capital presence in the water sector: the English model, where companies management and water main are fully privatised; the French model, where although infrastructures belong to the state, both public and private bodies can do or share the water utilities administration under pre-agreed terms and conditions; and the Dutch model (or public management entity model), where public authorities own the infrastructures and are in charge of managerial issues, in a sort of auto-regulated market. Regardless of the implemented model, any of these three ways exhibits failures that can be either related to the existence of natural monopolies (as it is not suitable, for a given region or area, to have more than one distribution main) or to the lack of incentives to innovation that non-competitive markets tend to display, among other already mentioned market failures. In such circumstances, the presence of a regulatory body is required in order to [i] ensure that costumers interests are met, considering water supplying as a service of general economic interest, [ii] promote efficiency and innovation in the sector and [iii] secure that water supply systems remain trustful, sustainable and resilient.

The Regulator approach to the market depends upon the strategy of the economic regulation. In fact, regulation should aim not only at tariff controlling, but also at maximising social well-being by stimulating companies to deliver the best quality at minimum prices. MARQUES [2011] identifies two big regulation types. The first one consists of fixing companies rates of return, while the second is about creating incentives to performance. The first option reduces shareholders' risk dramatically, which, on one hand, does contribute to find new investors, but, on the other hand, does not give any kind of motivation to companies to improve their performance or invest in innovation, as shareholders' pay rate is assured. The second category has to do with regulatory mechanisms that urge companies to be more innovative, thus, more efficient. It can be done by establishing a price or revenue cap or simply by comparing performance between companies (although this last option is often combined with price or revenue caps). In fact, any savings arising from new and more efficient practices after the price review will be collected by the shareholders till the next prices are set. This allows companies to make profits during the time period between price reviews, but also increases business risk, driving investors away.

The Portuguese case is clearly closer to the first option where rates of return are secured. Nevertheless, this macro-scenario comes along with two other widely spread regulatory mechanisms: *benchmarking* and *sunshine regulation* which are nowadays employed by the Portuguese regulator *Entidade Reguladora dos Serviços de Águas e Resíduos* (ERSAR).

Sunshine regulation takes advantage of the fact that utilities' performance is publically exposed, compared and discussed. It attempts to persuade companies to improve their behaviour in the market in front of their customers (and their groups of representation), media, government, political parties and other NGOs. The companies with poor results, either publicly or privately owned, are prompt to go after their benchmarks, which appears to lead to a gradual improvement in the sector as a whole (peer pressure effect).

This last mechanism tends to be more effective when the performance of the companies in the market is compared with values of reference. In fact, identifying benchmark units not only contributes for this peer pressure effect, but also consists of a workaround method in order to introduce some artificial competition in the market.

At the end of the day, the regulation policies described are generally combined, ending up in hybrid mechanisms. Even when truly economic regulation is not put into practice with serious price or revenue limits imposed by regulators, it is rather usual to have at least some supervision over the water sector accomplished by extensive collection of information that is eventually spread amongst the stakeholders.

3. The Data Envelopment Analysis method

3.1 Measuring efficiency

DEA sees a decision making unit (DMU) as an assessment unit that simply converts inputs in outputs as depicted in Figure 1. DMUs can be companies in the same sector or market, hospitals, schools, police stations, bank branches, etc. The identification of inputs and outputs that should be picked up in each assessment is difficult and has critical importance on the values of efficiency that are returned for each DMU. As an example, if one bank branch is to be considered a DMU, then *Capital Assets* and *Human Resources* would possibly be converted in *Loans*, *Sales of Financial Products* and *Banking Transactions*, in order to capture business efficiency in each branch. In these terms, DEA will be examining whether one unit could have secured more output given its input levels or could have used less input for the observed output levels.

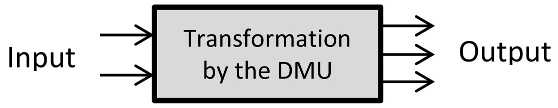

Fig. 1 - Input-Output transformation (Thanassoulis [2001]).

According to Thanassoulis [2001], the two approaches lead to the two following definitions of Pareto-optimality where a DMU uses $m \geq 1$ inputs to secure $s \geq 1$ outputs:

TIE - **Technical Input Efficiency**: *The technical input efficiency of a DMU is the maximum factor by which its input levels could be jointly contracted while its output levels do not fall.*

TOE - **Technical Output Efficiency**: *The technical output efficiency is the inverse of the maximum factor by which its output levels could be jointly expanded while its input levels do not rise.*

The two measures put forward relate to *radial* contraction of input levels or *radial* expansion of output levels and are so called because both changes are equiproportional in all input or output variables in the assessed DMU. Besides, the prefix *technical* refers to technical transformation of inputs into outputs without taking into account the prices that may be related to them. Price effect and its influence in the mix of variables are beyond the scope of the present document and would rather be considered in *allocative* or *price efficiency*.

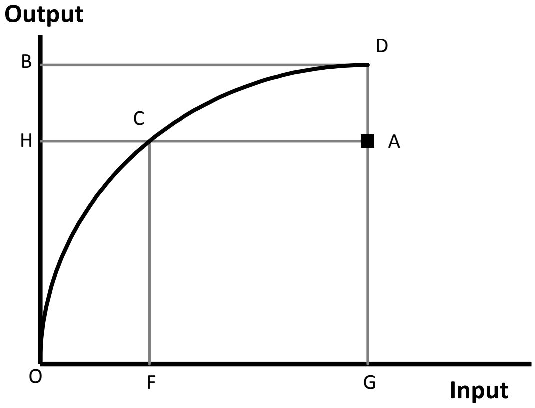

Fig. 2 - Graphical efficiency measure (Thanassoulis [2001]).

The foregoing definitions can be graphically seen in Figure 2, where one single input is supposed to secure one single output. The curve OD is the locus of maximum output levels attainable for given input levels, thus, the *efficient boundary* of the production space between itself and the horizontal axis. This space is the set of all feasible input-output combinations and is generally called the *production possibly set*. In fact, if points on OD are deemed to be feasible, so will be any other points below that curve, as they either use more input for given output level or produce less output for given input level (*free disposal* assumption). It is now graphically evident that DMU A could expand its output without increasing its input level and so, in the light of the definitions previously stated, DMU A shall not be considered Pareto-efficient. Instead, its technical output efficiency can be calculated by doing $1/_{(OB/OH)} = {}^{OH}/_{OB}$. Likewise, its technical input efficiency is represented by ${}^{OF}/_{OG}$.

The present example shows that DMUs operate in a variable returns to scale environment (VRS), as these two last measures of efficiency are clearly not equal. If constant returns to scale (CRS) were held, the measures would be equivalent and the efficient boundary would be a ray starting at the origin O (section «*3.5 Returns to Scale*» further details the relevance of both options of analysis).

According to Thanassoulis [2001], the construction of the PPS takes into account the following basic assumptions:

Assumption [i] *Interpolation between observed input-output correspondences leads to observable input-output correspondences;*

Assumption [ii] *Inefficient transformation of inputs to outputs is possible;*

Assumption [iii] *The efficient transformation of inputs to outputs is characterised by constant returns to scale;*

Assumption [iv] *The PPS is the smallest set meeting the foregoing assumptions and containing all input-output correspondences observed at the DMUs.*

Tab. 1 – Multi-input case where 2 inputs secure a single output.

DMU	X_1	X_2	Y
DMU_1	$x_{1,1}$	$x_{2,1}$	y_1
DMU_2	$x_{1,2}$	$x_{2,2}$	y_2
…	…	…	…
DMU_N	$x_{1,N}$	$x_{2,N}$	y_N

The next example shows how to graphically build the PPS from the prior assumptions. Table 1 lists N fictitious DMUs where two inputs (X_1 and X_2) secure one single output (Y). If one of the variables is standardised, say Y, the 2D display of the PPS is possible by dividing the input values by their corresponding output values, so that both inputs are normalised to X_1/Y and X_2/Y, respectively. Figure 3 depicts the 2D dispersion of the N fictitious DMUs of Table 1 for the $Y = 1$ cross section.

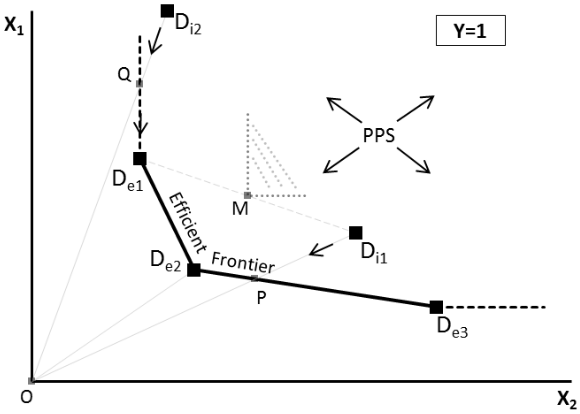

Fig. 3 – PPS built from the fictitious DMUs in Table 1.

Interpolation between DMUs makes it possible to have the fictitious DMU M that results from a 50%-weighted combination of the units D_{e1} and D_{i1} (Assumption [i]). If inefficient transformation of inputs to outputs is allowed, it is therefore possible to find DMUs that show higher levels of X_1 and X_2 than fictitious DMU M does for the same output level. These points lie above and to the right of DMU M and, according to Assumption [ii], they also represent feasible correspondences.

In order to capture TIE of D_{i1} it is required to apply a radial contraction to the input levels of the DMUs. This is to say that the ratio between X_1 and X_2 will remain constant while both levels decrease proportionally till the values observed at point P. The TIE of DMU D_{i1} is then equivalent to $OP/_{OD_{i1}}$ and its benchmark peers are D_{e2} and D_{e3}.

On the contrary, units located on the efficient boundary cannot have X_1 and X_2 reduced simultaneously and so their radial efficiency is 1. However, any DMUs lying on the vertical extension from D_{e1} or on the horizontal extension from D_{e3}, in spite of being radially efficient, do not meet Pareto-optimality criteria and shall not be considered as benchmark units, nor as DEA-efficient, because there is still opportunity for input disposal.

The capture of TIE of D_{i2} can be illustrative of the previous remark. As input levels reduction is initiated, the DMU will experience a proportional contraction in both input levels until point Q is attained. From this point on, it is no longer possible to have a simultaneous contraction, as the feasible production set frontier would be crossed. This residual amount of X_1 consists of a *slack* of input that turns any DMU lying on this extension of the boundary not Pareto-efficient.

3.2 Envelopment Model

The graphical approach can be computed in order to obtain the technical input efficiency of each DMU under assessment. The following linear-programming model can be used when N DMUs ($j = 1, \dots, N$) use m inputs to secure s outputs.

$$\text{Min} \quad k_0 - \varepsilon\left(\sum_{i=1}^{m} F_i^- + \sum_{r=1}^{s} F_r^+\right)$$

$$\begin{array}{lll} \text{S. t.} & \sum_{j=1}^{N} \lambda_j x_{ij} = k_0 x_{ij_0} - F_i^-, & i = 1, \dots m \\ & \sum_{j=1}^{N} \lambda_j y_{rj} = y_{rj_0} + F_r^+, & r = 1, \dots s \\ & \Lambda_j \geq 0, & j = 1, \dots N \\ & F_i^-, F_r^+ \geq 0, & \forall i, r \\ & k_0 \; livre & \\ & 0 < \varepsilon \ll 1 & \end{array}$$

Model 1 – Envelopment Model (assessing TIE).

In Model 1, x_{ij} and y_{rj} stand for the observed level of the i^{th} input and r^{th} output, respectively, at DMU j. The values F_i^- and F_r^+ represent the input and output slacks and ε is a non-Archimedean infinitesimal ($0 < \varepsilon \ll 1$). As seen before in the graphical approach to DEA, the model not only makes it possible to the decision maker to ascertain whether DMU j_0 is DEA-efficient, but also measures its input efficiency. The latter happens as follows. For a given set of feasible λ

values, the left-hand-sides of the constraints related to i and r specify a production point within the PPS. The model then seeks a PPS point which offers at least the output levels of DMU j_0 while using as low a proportion of its input levels as possible (THANASSOULIS [2001]). DMUs are considered DEA-efficient if and only if the next three conditions are true (let the * superscript denote optimal values):

[i] $k_0^* = 1$ (radial *DEA input efficiency* of DMU j_0);

[ii] $F_i^{-*} = 0,\ i = 1, \dots, m$;

[iii] $F_r^{+*} = 0,\ r = 1, \dots, s$.

3.3 Super-efficiency

Model 1 can be modified so that super-efficiency can be assessed. This consists of evaluating the same DMU j_0 in a slightly different PPS, where all DMUs except the one under assessment are involved. As a result, Pareto-efficient units can have their efficiency greater than or equal to 100%. This alternative method is particularly useful to set comparisons between DEA-efficient units. Among other possible interpretations, it enhances the decision maker visibility on how much a Pareto-efficient DMU is responsible for the PPS expansion, giving an account of how easy it will be to other DMUs to emulate its levels.

3.4 Value-based Model

While Model 1 is used to evaluate efficiency in a production context, its dual (Model 2) assesses efficiency in a value-based perspective. The variables u_r and v_i are dual to the constraints that are respectively related to the r^{th} output and i^{th} input and, due to duality, Model 1 and Model 2 yield the same efficiency rating (k_0) in respect of DMU j_0 (THANASSOULIS [2001]).

The optimal value u_r^* can be seen as the imputed value per unit of output r. In the same way, the optimal value v_i^* can be seen as the imputed value per unit of input i. By comparing the optimal values for the input and outputs variables, the decision maker is given an insight into the rates of substitution and transformation between the factors of production, thus, into each variable contribution to the attained efficiency at unit j_0. Nevertheless, the weights of the variables should be examined in comparative terms rather than standing alone. Indeed, although optimal input and output weights are DMU-specific (derived in order to maximise the efficiency rating of the respective DMU), there are infinite combinations of optimal values for the same DMU rating (see THANASSOULIS [2001] for more detail on value-based models interpretation).

$$\text{Max} \quad k_0 = \textstyle\sum_{r=1}^{s} u_r y_{rj_0}$$

$$\begin{aligned} \text{S.t.} \quad & \textstyle\sum_{i=1}^{m} v_i\, x_{ij_0} = 1 & \\ & \textstyle\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i\, x_{ij} \leq 0, & j = 1, \dots j_0, \dots N \\ & u_r \geq \varepsilon, & r = 1, \dots s \\ & v_i \geq \varepsilon, & i = 1, \dots m \end{aligned}$$

Model 2 –Value-based Model (assessing TIE).

3.5 Returns to scale

According to THANASSOULIS [2000b], the assumption that input-output transformation is characterised by constant returns to scale does not take into consideration scale effects on productivity. In fact, under local CRS, if DMU A is efficient and its input levels are scaled by $(1 + a)$, where $|a| \ll 1$, then its output levels will also be scaled by $(1 + a)$. Figure 4 illustrates the differences between CRS and VRS PPS boundaries for 4 fictitious DMUs.

Under CRS conditions, DMU D_i technical input efficiency is calculated in respect to point B and equals $^{AB}/_{AD_i}$. TIE is actually considered in relation to the points on the «CRS Frontier» which result from contracting or expanding the levels observed at the unique DEA-efficient DMU D_{e2}.

If VRS is deemed to be possible, the CRS assumption is no longer taken into account in the PPS construction. This is to say that the convexity constraint that had been relaxed is now recalled («$\sum_{j=1}^{N} \lambda_j = 1$», related to Assumption [i]). As a result, extrapolations to units' levels are no longer available and all the PPS is generated through interpolations between the observed DMUs. In these circumstances, the efficient boundary is transformed and DMUs D_{e1} and D_{e3} are now DEA-efficient like DMU D_{e2} (still) is. The TIE captured for DMU D_i is therefore related to the «VRS Frontier» emphasised at Figure 4 and shall now be calculated $^{AC}/_{AD_i}$. This last value corresponds to the *pure technical input efficiency* (PTIE) and is always greater than or equal to the TIE. The ratio between the CRS and the VRS values is termed *scale efficiency* and measures how far from its *most productive scale size* each DMU is operating.

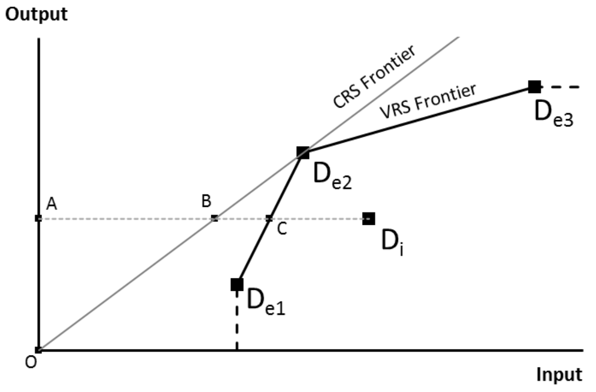

Fig. 4 - CRS and VRS frontiers.

Finally, assessments under VRS can estimate whether *increasing returns to scale* (IRS) or *decreasing returns to scale* are locally held. These are respectively the cases of DMUs D_{e1} and D_{e3} where, in spite of the PTIE of 1, operational scale size is responsible for the existence of economies and diseconomies of scale.

The identification of the most productive scale size is directly related to the admission of variable returns to scale. This possibility reflects the fact that operational scale size might affect comparative performance, which is not always obvious, according to THANASSOULIS [2000a and 2000b]. On one hand, the introduction of VRS accounts for the inheritance of the infrastructures and the area that is deemed to be supplied, as companies cannot change these circumstances. On the other hand, the sector as a whole sooner or later will have to tackle inefficiencies due to unproductive scale size that blocks greater productivity. This last aspect is particularly evident when scale efficiency is to be calculated.

4. Building the model

4.1 Adapting to the Portuguese water sector

According to ERSAR [2014], the Portuguese water supply systems can be divided into two main groups. The first group is in charge of water abstraction, treatment and conveyance to the local water companies (upstream or bulk services). The second group consists of generally smaller companies that are responsible for the fresh water distribution directly to household and business clients (downstream or retail services). The regulator further believes that companies in the sector experience different operational environments regarding the number of inhabitants and their dispersion in the supplied area. For that reason, the benchmarking metrics are published in its reports along with the following typification, so companies are more reasonably compared:

[i] APU (predominantly urban area);
[ii] AMU (medium urban area);
[iii] APR (predominantly rural area).

Besides, it is of general knowledge that some water utilities are more recent than others and use fairly modern infrastructures with no signs of damage comparing with some other peers. Although it is natural that the impact of rehabilitation on budgeting is bigger for aged companies, since there is no data regarding total expenditure breakdown, it becomes impossible to explicitly internalise this reality in the present assessment. Nevertheless, DEA is applied using 3 different combos of variables, so that the approach to the sector is done through more than one perspective. The first combo evaluates how efficiently DMUs expend their money on providing the best service possible to their clients. The second assesses the efficiency concerning the water loss, as this is one of the main symptoms of pipe aging and consists as well of a crucial financial cost. Finally, the third combo attempts to create a PPS where multi-inputs secure multi-outputs, in order to combine varied factors that can simultaneously impact the general efficiency of the water companies.

As stated in *«2. Regulation in the water sector»*, for a given region it is only suitable to have a single supplier (presence of natural monopolies). This creates a sort of a primary tendency for companies to keep increasing their size, since growth costs seem to become easier and easier to leverage as companies' area of influence keeps being expanded. By giving an account of the scale efficiency of each DMU, DEA can help decision makers to understand if there is any limit to growth. In fact, the Portuguese water sector shows a great disparity in terms of the companies' scales of activity, making it rather pertinent to assess how these different sizes influence the efficiency of each DMU regarding total expenditure and water loss.

4.2 Choosing the input-output variables

Input and output variables have a major role to play in the definition of the type of efficiency that is being captured. According to THANASSOULIS [2001], the chosen variables should be those, and only those, that influence output levels regarding the sort of efficiency of the transformation process. They should further reflect an exhaustive search of those potential factors and should also include any attributes that are supposed to impact efficiency although they might be exogenous to the units' management.

Tab. 2 – Short-list of potential input-output variables.

Inputs	**TOTEX**	Total expenditure [€/year]
	WLOSS	Water loss [m^3/year]
	MALFUNC	Malfunctions [no./year]
Outputs	**PROPS**	Properties [no.]
	WCONS	Water consumed [m^3/year]
	LENGTH	Length of mains[km]
	CONNECTS	Connections [no.]

Table 2 presents the outcome of a careful data screening from all the information that the Regulator annually demands and collects from water supply companies in the sector (*vide* ERSAR [2014]). This short-list consists of the final attributes that potentially interfere in the capture of efficiency for the 3 combos:

[C1] Total expenditure efficiency
[C2] Water loss efficiency
[C3] General efficiency (multi-input/multi-output)

Due to the nature of DEA as a linear-programming method, while capturing TIE, inputs are going to be radially contracted till the efficient frontier or its extensions. Thus, they should rather be perceived as attributes that should be reduced, given that the less they are needed, the more efficient the DMU under assessment will be. On the other hand, in a TOE oriented analysis, outputs are seen by the DEA as variables to expand and the larger they are, the more efficient the assessed unit will be. The variables presented in Table 2 are distinguished as inputs and outputs taking these last observations into consideration (their relevance in each combo in particular will be discussed ahead); nonetheless, THANASSOULIS [2001] sets forth that there might be cases where depending on the sort of efficiency to capture the same variable can feature an input or an output.

4.3 Screening DMUs

Companies with missing data on the required fields are automatically excluded from the analysis as they cannot be compared with their peers. The 15 bulk water supply companies in the sector fit the requirements, offering a reliability of 86% on the accuracy of the collected data (ERSAR [2014] gives an account of data consistency). On the other hand, just 206 out of 260 companies that provide retail water supply services are suitable for this exam. This number is still far from the ideal 100% of eligibility, but increases the reliability of retail service companies to 76% (the remaining 54 non-eligible companies show a poorer reliability average of 47%).

5. Results

5.1 Total expenditure efficiency

Picking variables from the short-list. The Total expenditure (TOTEX) is the only variable that reflects the amount of money DMUs spend in their activity. Therefore, it is adopted as the only input variable either for bulk and retail systems. The selection of the outputs, however, should take into consideration some differences between these two types of systems.

For bulk suppliers, according to Table 3, the number of properties (PROPS) is 93% correlated with water consumption (WCONS), what suggests that one of these two output variables could be abandoned in presence of the other. And taking into account that the number of properties (reflecting indirectly the number of inhabitants) is not likely to influence the conveyance through large distances in the territory, PROPS is dismissed from the analysis of bulk systems. As the number of connections (CONNECTS) is not known for bulk companies, the length of mains (LENGTH) and the WCONS are the only variables left. They are, in fact, adopted as the only output variables, since both impact DMUs' efficiency. TOTEX and WCONS are 96% correlated (*vide* Table 3) and, in spite of its poor correlation with TOTEX, the geographical dispersion of mains reflected by LENGTH not only surges maintenance and rehabilitation costs but also contributes for a better characterisation of the operational environment.

For retail suppliers, the correlations between TOTEX and the outputs PROPS and WCONS are very expressive, which is to say that they interfere significantly in incurred spending (see Table 3). The other two output variables – LENGTH and CONNECTS - are not as highly correlated with TOTEX, nonetheless, all the four variables are adopted, since the combinations between them, once again, favour the characterisation of the units' operational environment. Thus, PROPS is readmitted as a variable and, despite its high correlation with WCONS (89%), both are kept in the assessment bearing in mind that, regarding the retail water supply, the presence of ratios like *density of properties* or *consumption per property* will create the opportunity to figure out more accurate and more legitimate benchmark peers for inefficient companies. However, should the number of available DMUs be smaller, the addition of new variables might not be as suitable (THANASSOULIS [2001]).

Tab. 3 – Correlations between variables for bulk/retail services (%).

Bulk Retail	TOTEX	WLOSS	MALFUNC	PROPS	WCONS	LENGTH
TOTEX		86	-18	**94**	**96**	27
WLOSS	74		-9	78	**93**	17
MALFUNC	38	61		-24	-25	70
PROPS	**96**	83	44		**93**	18
WCONS	**94**	65	31	89		11
LENGTH	61	76	67	70	48	
CONNECTS	75	83	61	83	63	**93**

CRS and VRS bulk analysis. Just one bulk unit is considered Pareto-efficient under CRS: ICOVI. It operates in a predominantly rural area and, despite of being fairly well evaluated by the regulator in terms of the key performance indicators (KPI) concerning the quality of the service, it attains a super-efficiency of 221% that makes it an unreasonable benchmark peer.

The assessment under VRS brings two new emulation units: Águas do Zêzere e Coa and EPAL, both operating in regions considered to be mainly rural and mainly urban, respectively. According to the Regulator, these last two DMUs' classification regarding service interruptions is not exceptional and EPAL also exhibits an especially bad classification in water losses KPI. Both DMUs operate holding decreasing returns to scale (DRS), as well as all other units except DMU Águas de Santo André, which means that the vast majority of the companies would be better off if they reduce their scale size.

Finally, under VRS, the three efficient DMUs (ICOVI, Águas do Zêzere e Coa and EPAL) arise as benchmark peers for respectively 13, 11 and 12 other units out of 15, which certifies them as benchmark peers, along with the tolerable results in the regulator KPIs. The adoption of VRS might be arguable, but it is undeniable that DEA returns very demanding target-values when CRS are held. The potential savings obtained with DEA vary depending on the returns to scale philosophy of analysis. Results under CRS conditions require a reduction of 51% in companies' expenditure, while those under VRS impose a softer, yet quite demanding, 20% reduction (approximately 275 k€).

CRS and VRS retail analysis. The analysis of the retail water suppliers under CRS returns 4 Pareto-efficient DMUs: CM de Alcochete (in a moderately urban region), CM de Castro Daire (rural region), CM de Moita (urban region) and CM de Ponte da Barca (rural region). This analysis returns at least one benchmark unit for each typification put forth by the regulator: rural, moderately urban and urban areas. In fact, 98% of the DMUs in rural areas and 95% of the DMUs in urban areas can find at least one benchmark peer according to their typification. Although DEA is less accurate for the moderately urban typification (58%), the assessment shows how successful DEA can be on providing the right benchmark units regarding these demographic concerns and also corroborates its capacity of finding different emulation units for DMUs with different input-output mixes.

When VRS are held, DEA returns 12 more efficient units in addition to the previous 4. This time, the set of DEA-efficient DMUs ends up being too broad as some of these units are supposed to be emulated by very few companies (just 1 DMU in the worst situation). In fact, scale efficiencies are often low for the DEA-efficient DMUs (close to or less than 50%) and it also indicates that the majority of these peers tend to hold DRS.

Finally, DEA gives an account of the potential savings in the retail subsector. Once again, results under VRS are less demanding, although they still indicate savings of 35%, representing 1 286 k€ approximately.

5.2 Water loss efficiency

Picking variables from the short-list. Water loss (WLOSS) is chosen as the only input variable for bulk and retail systems simply because it is the only option from the short-list of variables that reflects the water losses in the infrastructures of the DMUs. Although it might not look like an input or a resource of a typical industrial process, it is impossible to detach water loss from water distribution. The water loss has therefore to be managed and it should be minimised while the inherent savings can compensate the costs associated to the operations of maintenance and rehabilitation.

The water loss analysis for bulk companies makes use of the same two output variables that are used for the previous combo: LENGTH and WCONS. On one hand, physically, the chances for water loss to occur should be higher for bigger extensions of mains; and, on the other hand, although losses are rather related to water pressure inside the pipes than to the water flow, the water consumption (WCONS) gives an important account of DMUs scale size.

In the analysis of retail companies, the presence of the variable WCONS favours DMUs that supply big consumers (with activities related to agriculture or industry) rather than regular household clients. WCONS is dismissed from the analysis as this fact is considered to be illegitimate when it comes to the assessment of water loss efficiency, not being directly related to the physical phenomena itself. The remaining variables (PROPS, LENGTH and CONNECTS) are preserved as they give an insight into the *density of properties* and the *dispersion of connections* when combined between each other. The latter seriously characterise the circumstances under which retail services companies happen to operate (this is especially evident in water losses records; *vide* ERSAR [2013] and ALEGRE *et al.* [2005]).

CRS and VRS bulk analysis. The water loss analysis of bulk companies under CRS returns three Pareto-efficient DMUs: Águas do Centro, Águas do Noroeste and Águas do Vouga. The three of them can be presented as fair winners in this assessment since they stand out as benchmark peers for respectively 7, 8 and 7 other DMUs and also attain the best evaluation in the regulator KPIs regarding water losses. These good results are obtained with remarkably low values of rehabilitation what can be seen as a sign that their structures are still in an early period of their economic lifecycle. Águas do Vouga presents a significantly higher super-efficiency of 216% comparing with the other two Pareto-efficient DMUs that remain close to 100%. This eventually leads to the very demanding 72% of water loss reduction and shakes this unit's suitability as an emulating peer, since this provocative value is hard to be worthy of consideration.

If VRS are to be allowed, five new companies join the DEA-efficient group and the projected water saving for the sector decrease to a much more reasonable 13%. However, just one of these 5 companies presents itself as benchmark peer to any other DMU and two of them (Águas do Douro e Paiva and EPAL) even score very badly at ERSAR's KPIs on water loss. Lastly, although IRS and DRS can be found among the 15 bulk water suppliers, all the identified peers hold DRS, revealing that, according to DEA, such companies would be better off by decreasing their scale size.

CRS and VRS retail analysis. The CRS analysis of the retail suppliers returns one single Pareto-efficient DMU: CM Boticas (in a predominantly rural area). This unit is the only reference for the other 205 retail companies and performs extremely well in the regulator evaluations concerning water losses. Nonetheless, the estimated water loss reduction calculated under CRS for the retail DMUs reaches a very unlikely to happen value of 94%.

Under VRS, DEA returns 11 efficient companies more. The three different typifications (rural, moderately urban and urban) are now covered with these new efficient DMUs, although all of them operate holding DRS. Moreover, apart from EPAL and Águas da Região de Aveiro that could just reach an average classification, all the remaining DMUs proved to have good levels of water loss according to the regulator. Finally, the estimated reduction of water loss under VRS is still 67% for retail systems. Such value remains quite unsound to be required at once by the regulator, but the described scenario for retail companies presents benchmark peers that seem to be reasonably solid. There might be the case that some companies are, indeed, too far away from what would be desirable in terms of water losses. But it may also happen that DEA is not covering the disparity of mains aging or any other aspect that may impact the water loss efficiency.

5.3 General efficiency (multi-input/multi-output)

Picking variables from the short-list. The multi-input/multi-output analysis main objective is to understand DEA limitations when more than one input is used to secure more than one output. This proves to be rather unmanageable when different input variables (or different output variables) cannot be combined between them in order to provide any precise physical meaning or measure (for instance, the usual TOTEX split between OPEX and CAPEX).

In order to get different variables involved, all the input variables from Table 2 are included in this analysis, either when it comes to bulk or retail assessments: TOTEX, WLOSS, MALFUNC.

The output variables selected for the bulk evaluation are the same that were used before, as the arguments put forth in the two previous combos can be extended to this one: LENGTH and WCONS. For the retail units' analysis, however, all the output variables are used: PROPS, WCONS, LENGTH and CONNECTS.

CRS and VRS bulk analysis. The multi-input/multi-output analysis returns 9 Pareto-efficient DMUs under CRS and 10 under VRS. Independently of the returns to scale that are deemed to be held, the number of DEA-efficient DMUs is excessive when it is compared with the total number of bulk water companies (14 units, since one is excluded due to missing data). This clearly indicates that there are too many variables for the few available DMUs and that DEA comparative worth is ruined.

CRS and VRS retail analysis. The analysis of the retail companies using multi-inputs and multi-outputs returns 19 Pareto-efficient DMUs under CRS and other 17 more when VRS are held. Although the ratio between the DEA-efficient peers and the total number of units is not as dramatic as it is for bulk systems, the number of DMUs supposed to be efficient is still too large. Firstly, many of those peers are supposed to be emulated for very few DMUs, what makes them not suitable for benchmark units. Secondly, just three of the 36 efficient DMUs prove to be consistent when their target-values are compared across the 3 combos. In fact, this comparison shows how unprepared some of these DMUs are in order to be considered as benchmark peers, as they just conquer DEA-efficiency due to the presence of the new input: Malfunctions.

6. Conclusion

The use of the DEA method shows some limitations when water companies' age seems to be so different. In fact, older units tend to display worse records concerning water losses, failures and service interruptions, even when maintenance levels are fair. On the other hand, some companies with alarming water losses records still avoid rehabilitation or do it insufficiently. The introduction of variables concerning *mains age* and *flow pressure* could help to balance these situations, but these sort of information is still not available. Nevertheless, age discrepancy tends to be eliminated across the years as, theoretically, the average age of infrastructures is likely to converge to the duration of their components lifecycle. This will make DEA more appropriated and more valid through time, being able to provide asset management feedback. In fact, when all DMUs have a similar average age, if some benchmark companies do not show any signs of good asset management, that probably means that companies with worse performance neither will show.

None the less, DEA proves to be able to segregate operational environments, especially those concerning *rural*, *moderately urban* and *urban* areas. This is done by the linear combination between the output variables that were thoroughly chosen. At the same time, VRS analysis gives a useful insight into companies' scale size disparity in the sector and consists of a valuable way to find new benchmark peers and new relations between DMUs, providing less demanding target-values for inefficient units.

Finally, it is desirable that this first approach to the use of DEA in the Portuguese water sector can lead to forthcoming research on issues like [i] sale price allocation; [ii] fairness of VRS analysis; [iii] companies' most productive scale size regarding possible mergers or spinoffs; [iv] companies' performance through time (use of the Malmquist Indexes); [v] water losses negligence and economic impact of late interventions.

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