Water pollution in wastewater treatment plants: an efficiency analysis with undesirable output

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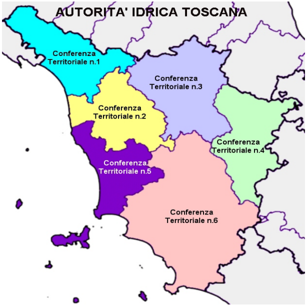
Institutional framework

- The present paper has been carried out with the collaboration of the water utility Acque Spa and the consulting company Ingegnerie Toscane
- Autorità Idrica Toscana (Tuscan Water Authority)

  Regional act 69, 2011 December 28
- Conferenze territoriali

  From 1994 to 2012, Autorità di Ambito territoriale ottimale (Local Water Authority)



- Conferenza Territoriale n. 2 "Basso Valdarno"

Aims and motivations

2030 Agenda for Sustainable Development
Goal 6, UN General Assembly (2015)

- Ensure access to water and sanitation for all
- By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally (Target 6.3)

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- It's almost impossible to completely remove all the dangerous elements
- Nitrogen is considered the most relevant one:
    - eutrophication
    - reduction of crop quality
    - pollution of groundwater
    - death of aquatic life

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We aim at

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1. assessing the environmental efficiency of wastewater treatment plants
   - the nitrogen concentration in outgoing water is treated as undesirable output
2. identifying the efficiency explanatory variables
   - population equivalent size
   - estimated dry weather flow
   - treatment technology

Related literature

- There is a huge amount of quantitative studies on water and sanitation services (WSS)
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- Undesirable output in the water framework

Authors - Years	Undesirable output
Picazo-Tadeo et al. (2008)	Unaccounted-for-water losses
De Witte and Marques (2010)	Water losses
Hernández-Sancho et al. (2012)	Water losses
Molinos-Senante et al. (2014)	CO_2 emission
Molinos-Senante et al. (2015) and (2016)	Lack of service quality

Modelling undesirable output

An undesirable output is characterized by null-jointness and weak disposability (Färe et al., 1989).

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There exist different approaches for handling undesirable outputs (Liu et al., 2016):

1. ignoring undesirable outputs;
2. adding a sufficiently large positive number $(-y_b + M)$ to the additive inverse of the undesirable outputs (Ali and Seiford, 1990; Seiford and Zhu, 2002). In our case, the natural choice for M is $M = 1$;
3. radial directional distance function approach (Chambers et al., 1996, 1998; Färe and Grosskopf, 2004);
4. non-radial directional distance function approach (Fukuyama and Weber, 2009; Zhou et al., 2012) (constant return to scale).

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Our approach

We perform an efficiency analysis with undesirable output by using a suitable AHP-non-radial directional function and by assuming variable return to scale (Kuosmanen, 2005).

The model

- $\beta = (\beta_x, \beta_y, \beta_b)$ is the directional vector function
- $g = (g_x, g_y, g_b)$ is the explicit directional vector

$$
\begin{aligned}
\max \quad & \beta = (\beta_x, \beta_y, \beta_b) \\
s.t. \quad & \sum_{k=1}^{K} (\lambda^k + \mu^k) x_n^k \le x_n + g_{x_n} \beta_{x_n}, \forall n \\
& \sum_{k=1}^{K} \lambda^k y_m^k \ge y_m + g_{y_m} \beta_{y_m}, \forall m \\
& \sum_{k=1}^{K} \lambda^k b_j^k = b_j + g_{b_j} \beta_{b_j}, \forall j \\
& \sum_{k=1}^{K} \lambda^k + \mu^k = 1 \\
& \lambda^k, \mu^k \ge 0, \forall k \\
& \beta_{x_n} \ge 0, \beta_{y_m} \ge 0, \beta_{b_j} \ge 0 \forall n, \forall m, \forall j
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Input model $\beta = (\beta_x)$ $g = (-x, 0, 0)$
No und. model $\beta = (\beta_x, \beta_y)$ $g = (-x, y, 0)$
All variable model $\beta = (\beta_x, \beta_y, \beta_b)$ $g = (-x, y, -b)$

...the model

Scalar problem

$$\max \quad \sum_{n\in N} w_{x_n}\beta_{x_n} + \sum_{m\in M} w_{y_m}\beta_{y_m} + \sum_{b\in J} w_{b_j}\beta_{b_j}$$

$$s.t. \quad \sum_{k=1}^{K}(\lambda^k + \mu^k)x_n^k \leq x_n + g_{x_n}\beta_{x_n}, \forall n$$

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The choice of w

Two distinct levels of weights

- global weights: w_x, w_b, w_y, $w_x + w_b + w_y = 1$.
- weights for each group (inputs, good and bad outputs) $w_{x_n}, w_{y_m}, w_{b_j}$
  $$\sum_{n\in N} w_{x_n} = w_x, \sum_{m\in M} w_{y_m} = w_y,$$
  $$\sum_{b\in J} w_{b_j} = w_b$$

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  $$\sum_{n\in N} w_{x_n} = w_x, \quad \sum_{m\in M} w_{y_m} = w_y,$$

  $$\sum_{b\in J} w_{b_j} = w_b$$

Zhou et al. (2012)

- $w_x = w_b = w_y = 1/3$
- $w_{x_n} = \frac{w_x}{N}, \; w_{y_m} = \frac{w_y}{M} \; w_{b_j} = \frac{w_b}{J}$

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- $w_{x_n} = \frac{w_x}{N}$, $w_{y_m} = \frac{w_y}{M}$ $w_{b_j} = \frac{w_b}{J}$

In our model, weights are determined using the Analytic Hierarchy Process (AHP)

... the model

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Intensity	Definition
1	Equal Importance
3	Moderate importance
5	Strong importance
7	Very Strong importance
9	Extreme importance

Pairwise comparison matrix

$$\begin{array}{c} \\ x \\ y \\ b \end{array} \begin{array}{c} \begin{array}{ccc} x & y & b \end{array} \\ \begin{pmatrix} a_{xx} & a_{xy} & a_{xb} \\ a_{yx} & a_{yy} & a_{yb} \\ a_{bx} & a_{by} & a_{bb} \end{pmatrix} \end{array}$$

- $a_{ij} > 0$, $a_{ii} = 1$ and $a_{ij} = \frac{1}{a_{ji}}$ $\forall i, j$.

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- $a_{ij} > 0$, $a_{ii} = 1$ and $a_{ij} = \frac{1}{a_{ji}}$ $\forall i, j$.
- For each set of inputs, outputs and undesirable outputs, DM is asked to perform the analogous pairwise comparison
- Four comparison matrices: global comparison, inputs, outputs and undesirable outputs
- $w = (w_x, w_y, w_b)$ is the normalized eigenvector associated with the dominant eigenvalue

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- Two different sets of weights are considered:
  - the first one is constructed by assigning the same importance to the three groups of variables (inputs, good and bad outputs) and the same applies inside each group (Zhou et al. 2012: Non-radial model);
  - different pairwise comparison matrices are taken, following a discussion with the water utility staff (AHP-non-radial model).

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Efficient indexes

	Input model	Input/Good Out. model	Input/Good/Bad Out. model
β	$\beta = (\beta_x)$	$\beta = (\beta_x, \beta_y)$	$\beta = (\beta_x, \beta_y, \beta_b)$
g	$g = (-x, 0, 0)$	$g = (-x, y, 0)$	$g = (-x, y, -b)$
w	$w = (w_x, 0, 0)$	$w = (w_x, w_y, 0)$	$w = (w_x, w_y, w_b)$
Index	$WPI_1 = 1 - \sum_{n=1}^{N} w_{x_n}\beta_{x_n}$	$WPI_2 = \frac{1 - \sum_{n=1}^{N} w_{x_n}\beta_{x_n}}{1 + \sum_{m=1}^{M} w_{y_n}\beta_{y_n}}$	$WPI_3 = \frac{1 - \left(\sum_{n=1}^{N} w_{x_n}\beta_{x_n} + \sum_{j=1}^{J} w_{b_j}\beta_{b_j}\right)}{1 + \sum_{m=1}^{M} w_{y_n}\beta_{y_n}}$

Data choice

- 96 WWTPs from Acque SpA

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- Inputs and desirable outputs

Input (costs - euros)	Desirable Output
Materials + Energy Staff + Maintenance Sludge transport + Sludge disposal	Treated water (m^3) Kg of sludge (wet matter)

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- Undesirable output
  Looking at data and at the wastewater treatment process:
  1. you have no pollutants only if you have no water to treat (null jointness)
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Undesirable output

$$\frac{\text{Average Nitrogen concentration of outgoing wastewater}}{\text{Average Nitrogen concentration of ingoing wastewater}}$$

... data choice

Non-radial set of weights

	Global comparison	Inputs	Good Outputs	Bad Output
Matrix	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$	
WPI_1 Weights	$(1, 0, 0)$	$(1/3, 1/3, 1/3)$		
WPI_2 Weights	$(1/2, 1/2, 0)$	$1/2 * (1/3, 1/3, 1/3)$	$1/2 * (1/2, 1/2)$	
WPI_3 Weights	$(1/3, 1/3, 1/3)$	$1/3 * (1/3, 1/3, 1/3)$	$1/3 * (1/2, 1/2)$	$1/3$

AHP-non-radial set of weights

	Global comparison	Inputs	Good Outputs	Bad Output
Matrix	$\begin{pmatrix} 1 & 3 & 1/7 \\ 1/3 & 1 & 1/9 \\ 7 & 9 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 1 & 5 \\ 1 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 7 \\ 1/7 & 1 \end{pmatrix}$	
WPI_1 Weights	$(1, 0, 0)$	$(0.455, 0.455, 0.09)$		
WPI_2 Weights	$(0.75, 0.25, 0)$	$0.75 * (0.455, 0.455, 0.09)$	$0.25 * (0.875, 0.125)$	
WPI_3 Weights	$(0.149, 0.066, 0.785)$	$0.149 * (0.455, 0.455, 0.09)$	$0.066 * (0.875, 0.125)$	0.785

Results

	WPI_0	WPI_1	WPI_2	WPI_3
Non-radial				
Mean	0.430	0.617	0.504	0.468
Std. Dev.	0.322	0.273	0.343	0.347
AHP-non-radial				
Mean	0.419	0.609	0.491	0.404
Std. Dev.	0.333	0.283	0.354	0.385
N^o efficient WWTPs	19	27	27	25

Investigating efficiency explanatory variables

- WPI_1, WPI_2, WPI_3 indices for 96 WWTPs

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- The following relevant operational variables are considered
  1. Age
  2. Size (Population equivalent)
  3. Sewage system
  4. Level of treatment
  5. Technologies
  6. Estimated Dry Weather Flow
  7. Wastewater discharged by industrial and agricultural activities

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  7. Wastewater discharged by industrial and agricultural activities
- Kruskal-Wallis test (0.05 level of significance) on WPI_1, WPI_2, WPI_3 for both non-radial model and AHP-non-radial model

Kruskal-Wallis results - Non radial model

Non-radial		*WPI*$_1$				*WPI*$_2$				*WPI*$_3$			
Explanatory factor	Total WWTPs	% Eff.	Mean	Std. Dev.	Test	% Eff.	Mean	Std. Dev.	Test	% Eff.	Mean	Std. Dev.	Test
Year													
<1985	44	27%	0.627	0.267	0.6698	27%	0.543	0.310	0.084	25%	0.502	0.318	0.074
≥ 1985	52	29%	0.609	0.280		29%	0.471	0.368		27%	0.439	0.370	
PE													
<2,000	57	25%	0.612	0.260	**0.0176**	25%	0.451	0.349	**0.0077**	21%	0.386	0.339	**0.0005**
2,000 - 10,000	29	21%	0.547	0.269		21%	0.498	0.293		21%	0.509	0.301	
10,000 - 150,000	10	70%	0.849	0.250		70%	0.822	0.296		70%	0.814	0.305	
Sewage System													
Combined	39	18%	0.554	0.258	0.0659	18%	0.423	0.317	0.0682	15%	0.379	0.306	0.0752
Separate	57	35%	0.660	0.276		35%	0.559	0.351		33%	0.528	0.363	
Kind of Treatment													
Secondary treatment	92	25%	0.600	0.266	**0.0114**	25%	0.483	0.334	**0.0114**	23%	0.445	0.336	**0.0092**
Tertiary treatment	4	100%	1.000	0.000		100%	1.000	0.000		100%	1.000	0.000	
Technologies													
Others	6	50%	0.719	0.313	0.4312	50%	0.681	0.364	0.2146	50%	0.626	0.410	0.3034
Activated sludge	90	27%	0.610	0.270		27%	0.492	0.340		24%	0.457	0.342	
Dry Weather Flow													
<100,000	63	22%	0.592	0.257	**0.0294**	22%	0.439	0.336	**0.0022**	19%	0.380	0.326	**0.0002**
100,000 - 500,000	25	28%	0.594	0.290		28%	0.549	0.316		28%	0.563	0.319	
>500,000	8	75%	0.886	0.217		75%	0.873	0.237		75%	0.858	0.266	
% industrial WW													
No activity	60	22%	0.595	0.254	0.3927	22%	0.443	0.332	**0.0476**	20%	0.396	0.331	**0.0094**
≤ 10%	26	35%	0.620	0.307		35%	0.573	0.340		31%	0.546	0.340	
>10%	10	50%	0.742	0.281		50%	0.691	0.350		50%	0.698	0.347	

...Kruskal-Wallis results - AHP-Non radial model

AHP-non-radial Explanatory factor	Total WWTPs	WPI_1 % Eff.	Mean	Std. Dev.	Test	WPI_2 % Eff.	Mean	Std. Dev.	Test	WPI_3 % Eff.	Mean	Std. Dev.	Test
Year													
<1985	44	27%	0.640	0.268	0.2167	27%	0.540	0.324	**0.0488**	25%	0.440	0.363	**0.0479**
≥ 1985	52	29%	0.584	0.295		29%	0.449	0.375		27%	0.373	0.403	
PE													
<2,000	57	25%	0.605	0.274	**0.0408**	25%	0.428	0.363	**0.002**	21%	0.297	0.375	**0.0001**
2,000 - 10,000	29	21%	0.542	0.273		21%	0.500	0.293		21%	0.475	0.317	
10,000 - 150,000	10	70%	0.829	0.279		70%	0.826	0.285		70%	0.807	0.319	
Sewage System													
Combined	39	18%	0.526	0.267	**0.0137**	18%	0.419	0.318	0.1597	15%	0.316	0.325	0.1781
Separate	57	35%	0.667	0.282		35%	0.540	0.370		33%	0.464	0.413	
Kind of Treatment													
Secondary treatment	92	25%	0.593	0.277	**0.0114**	25%	0.469	0.344	**0.0114**	23%	0.378	0.372	**0.0092**
Tertiary treatment	4	100%	1.000	0.000		100%	1.000	0.000		100%	1.000	0.000	
Technologies													
Others	6	50%	0.702	0.339	0.4958	50%	0.642	0.395	0.3327	50%	0.562	0.481	0.3883
Activated sludge	90	27%	0.603	0.280		27%	0.481	0.351		24%	0.393	0.378	
Dry Weather Flow													
<100,000	63	22%	0.587	0.271	**0.0445**	22%	0.418	0.351	**0.0007**	19%	0.292	0.360	**0.0001**
100,000 - 500,000	25	28%	0.582	0.293		28%	0.555	0.307		28%	0.541	0.328	
>500,000	8	75%	0.870	0.242		75%	0.868	0.245		75%	0.853	0.280	
% industrial WW													
No activity	60	22%	0.588	0.268	0.2202	22%	0.426	0.346	**0.0326**	20%	0.307	0.367	**0.0002**
≤ 10%	26	35%	0.605	0.315		35%	0.575	0.335		31%	0.527	0.353	
>10%	10	50%	0.752	0.269		50%	0.660	0.379		50%	0.663	0.390	

Concluding remarks

- *The environmental efficiency of 96 Tuscan wastewater treatment plants is investigated*
- *A new integrated AHP/directional distance function model is proposed*
- *The nitrogen in the outgoing water is considered as undesirable output*
- *Efficiency determinants are identified among wastewater treatment plant features.*

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Thank you for your attention!

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