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A novel methodology based on LCA + DEA to detect eco-efficiency shifts in wastewater treatment plants

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ABSTRACT

The high-frequency on-line measurements coming from sensors installed in wastewater treatment plants (WWTPs) can be used for alert systems and decision support tools. Given the complexity of WWTPs, many authors developed efficient techniques for plant assessment. By contrast, few contributions are focussed on the identification of regime shifts in WWTPs on short-term, even if the early detection of occurring inefficiencies is a relevant information for plant managers. In order to fill this gap, the present paper uses a daily LCA + DEA analysis in order to monitor the potential deterioration of the eco-efficiency.

This approach consists of an original combination of environmental life cycle assessment (LCA), data envelopment analysis (DEA), time series analysis and statistical tests. The main innovation in DEA algorithm consists of the set of decision-making units (DMUs), here composed of the 1-day operation datasets of a single WWTP. The results show a good performance in the regime shifts classification, for which the receiving operating characteristic (ROC) analysis returned a score of 0.8 (in a range 0–1).

1. Introduction and state of the art

Waste water treatment plants (WWTPs) are complex facilities, in which the set of physical, chemical and biological processes treat the waste water produced by human activities before the delivery to receiving water bodies. Many plant layouts are possible depending on the quality and the quantity of treated wastewater; a common feature of WWTPs is the use of many inputs such as chemicals and electricity. Extensive dissertations about WWTP processes are provided by Spellman (2003) and Metcalf and Eddy (2014).

WWTPs are generally considered resource-intensive facilities with a large room for efficiency improvements (Castellet and Molinos-Senante, 2016; Castellet-Viciano et al., 2018). Several applications have been presented in the literature to identify directions for improvements and suggest operational solutions, using different techniques. Recently, the larger and larger availability of on-line measurements coming from sensors should theoretically enable daily benchmarking, ultimately allowing faster correction actions, when needed (Torregrossa et al., 2017a). In fact, each device installed in a WWTP (such as pumps, blowers and stirrers) can be equipped with sensors capable of delivering high-frequency data (up to several values per second, Torregrossa et al. (2016)). Nevertheless, WWTP high frequency data is often simply stored and average values are calculated and assessed only a few times per year (Torregrossa et al., 2017b).

1.1. WWTP performance optimization

In the waste water treatment domain, several authors proposed methodologies to improve the performance of the plants at the design stage or during the operational stage.

Some authors proposed *decision support tools*. For example, Flores-Alsina et al. (2008) proposed a model-based multi-criteria decision analysis of WWTP control strategies. They evaluated the influence of activated sludge input uncertainty in the decision making process during the multi-criteria evaluation of control strategies in a WWTP. Poch et al. (2004) and Poch et al. (2014) proposed the use of environmental decision support systems to optimize the WWTP performances. Both approaches are based on scenario analysis, performed on scenarios pre-defined by the operator. Torregrossa et al. (2017b) proposed a cooperative decision support system for the energy management of WWTPs with a specific application to reduce the energy consumption of the aeration system in the biological stage. The proposed decision support system (DSS) relies on the calculation of a number of key performance indicators (KPIs) and, most interestingly, is not tailor-made for any specific plant structure, but is able to work simultaneously with multiple WWTPs. In Torregrossa et al. (2017c), a methodology for the monitoring of pump performance was proposed, based on the analysis of time series that enables to separately analyse the trend and the fluctuations in the efficiency performance.

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Another common approach consists of the use of KPIs. For example, Quadros et al. (2010) proposed a portfolio of performance indicators which covers eight aspects of WWTP performance, such as the treated waste water quality, the management of by-products and the use of financial resources. Shao et al. (2014) proposed a multi-parameter framework to analyse and compare the environmental performances of different wastewater treatment technologies and support the decision making process. Buonocore et al. (2016) used Life Cycle Assessment (LCA) to assess different operational scenarios in a WWTP in Southern Italy. Gu et al. (2016) used a new 'gray water footprint reduction' to evaluate the environmental impacts of nine WWTPs in China. Doherty et al. (2017) proposed a KPI-based performance assessment evaluation that takes into account also the changes in energy performance over time. Longo et al. (2016) analysed three main benchmarking approaches (normalization, statistical techniques and programming techniques), showing advantages and disadvantages for each of them in the selection of the correct performance parameters. A common approach in the applications outlined above is the practice of benchmarking the performance of WWTPs against reference values taken from literature which refer to an average performance over time, and are therefore not temporally differentiated. A specific benchmarking approach is based on the Data Envelopment Analysis (DEA). Given the importance of this approach for the present paper, this topic is deeply discussed in Section 1.1.1.

Other approaches are based on *LCA* to include environmental criteria. For example, Yago Lorenzo-Toja et al. (2016) combined LCA and Life Cycle Costing (LCC) to classify the WWTPs under an eco-efficiency perspective. Arnell et al. (2017) proposed a method combining dynamic process models (including dynamic greenhouse gases calculation, detailed energy models and operational cost evaluation) and LCA. In the context of waste-water treatment, this approach is particularly promising especially considering the new frontiers opened to LCA by the current era of data abundance, which poses old (data storage) and new (data mining, computational speed) challenges (Heijungs et al., 2015). The deep integration of Internet of Things (IoT) in product and service oriented manufacturing systems has in fact enabled a Big Data support for life cycle modelling along the entire value chain (Cooper et al., 2013).

1.1.1. DEA approaches in WWTP domain

According to Bogetoft et al. (2011), DEA is a methodology that "provides a mathematical programming method of estimating best practice production frontiers and evaluating the relative efficiency of different entities." Cooper et al., 2007 provided a clear and extensive explanation of the main concepts of DEA, while a short introduction to DEA is provided in A.

Essentially DEA:

- can produce an efficiency index processing several inputs and several outputs;
- does not require specific hypotheses such as weight attribution;
- imposes no restrictions on the measurement units of inputs and outputs;
- allows the calculation of a relative efficiency of the points compared to the given dataset.

As mentioned above, the use of DEA methods in WWTPs is frequent, and generally aims to compare the performances of several WWTPs. Hernández-Sancho and Sala-Garrido (2009) and Hernández-Sancho et al. (2011) used DEA on plants located in the region of Valencia in order to assess their performances and identify the main factors affecting it. With a similar approach, Sala-Garrido et al. (2012a) investigated the impact of seasonality on WWTP efficiency in Spain. Sala-Garrido et al. (2011) used DEA to compare different WWTP technologies. Molinos-Senante et al. (2014) used a non-radial DEA to identify the inputs whose improvements produce a larger contribution to global efficiency. Castellet and Molinos-Senante (2016) proposed the same approach to assess the efficiency of a group of WWTPs located in Spain. Lorenzo-Toja et al. (2015) coupled the DEA with LCA in order to produce an integrated analysis of WWTP performances that includes environmental impacts and input-output efficiency. Recently, Gómez et al. (2017) proposed a double bootstrap approach DEA model to compute bias-corrected efficiency scores. Sala-Garrido et al. (2012b) and Dong et al. (2017) coupled DEA with tolerances approach in order to include the input uncertainty in the WWTP efficiency assessment. Recently, Gémar et al. (2018) used the data envelopment approach to assess 30 Spanish WWTPs with the specific aim to identify changes in eco-productivity. Longo et al., 2018 proposed a two-stage DEA in order to improve the quality of non-parametric benchmarking in WWTPs.

1.1.2. LCA + DEA approaches

Interestingly enough, when including into the analysis also the environmental performances of the WWTPs, rather than focussing only on the operational performances (mainly energy efficiency), the LCA + DEA technique (Lorenzo-Toja et al., 2015) started to emerge in the literature as an increasingly applied approach to obtain performances benchmarks. Recently, Vázquez-Rowe and Iribarren (2015) and Martín-Gamboa et al. (2017) proposed a review study of the available manuscripts that combine life-cycle-based approaches and DEA to assess energy systems, underling the advantages "in term of practicality and soundness". In particular Vázquez-Rowe and Iribarren (2015) proposed a method combining carbon footprinting (CFP) and DEA. LCA + DEA was used by Yago Lorenzo-Toja et al. (2017) to perform a dynamic assessment of 47 WWTPs over a period of 4 years, in order to evaluate not only the change in efficiency between plants, but also the changes in the efficiency of a single plant, due to the variations of numerous temporal factors that can affect it. The approach is very interesting and the efficiency frontier is generated using many plants and the yearly performance values of 4 years. This approach can be efficiently used to evaluate the global WWTP management strategy over the time, but it does not explain if plants change their global efficiency because of a different input-output combination or because of changes in the frontier due to improvements occurring in other plants. In other words, a real increase or decrease in performance of a single plant over time may be masked by the increase or decrease of performances of the other plants.

1.2. Gaps in literature,added value and novelty of the paper

As shown in the Section 1.1, many authors benchmarked the performance of WWTPs against reference values taken by literature. Instead, to the best of our knowledge, only few contributions assess the trend of performance of WWTPs on short term: the manuscript of Doherty et al. (2017) and, limited to pump consumption, the work of Torregrossa et al. (2017c). None of them takes into consideration the global performance of the plants, but they are rather focussed on energy consumption. As discussed above, LCA + DEA was also used by Yago Lorenzo-Toja et al. (2017) for assessment of yearly changes in WWTPs performance. Gémar et al. (2018) assessed the changes of WWTP productivity feeding a DEA algorithm with the yearly aggregated data of 30 WWTPs. They employed a non-radial DEA model, called weighted Russell directional distance model (WRDDM), which allows to obtain an eco-efficiency index for each input and output (both desirable, to be maximised, and undesirable, to be minimised) taken into account by the model, in addition to generating a global efficiency index and allowing the construction of an efficiency frontier.

All the DEA and LCA + DEA approaches previously discussed use annual data in which the DMUs are various WWTPs. In other words, DEA has been mainly used to compare the efficiency of various WWTPs among each other, generally relying on temporally averaged performances (yearly averages). To the best of our knowledge, a DEA application with higher time resolution has never been attempted.