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Article

Identification of Key Factors for Urban—Industrial Water Reuse: A Multi-Criteria Analysis Case Study

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Abstract: The industrial reuse of existing municipal wastewater treatment plant (WWTP) effluent can play a major role in improving water security in urbanized regions facing scarcity. As the complexity of engineered direct water reuse is related to various economic, technical, legal, social, environmental, and public health aspects, multi-criteria analysis (MCA) is a feasible decision-making tool in this context. The present work aimed to establish the relevant key factors for the application of MCA, wherever plant planning, design, and construction did not previously consider reuse practices. The adopted methodology considers the proposition and valuation of key criteria, based on the existing literature, expert consultations, statistical analysis, and the application of MCA to a real municipal WWTP located in Campinas city (São Paulo State, Brazil). The 13 proposed criteria encompass multiple categories, and their relevance is demonstrated, given the high significance frequencies assigned. The best values are related to effluent quality, health risks, and treatment reliability, in addition to environmental costs and benefits. The application of those criteria in Cooperative Game Theory (CGT) and Compromise Programming (CP) methods is proved to be suitable, considering the characteristics of the studied area (i.e., highly urbanized with a history of water scarcity). Among nine surveyed end-users, the first position in the hierarchy corresponds to the largest industries with the shortest distance from the WWTP.

Keywords: urban water reuse; multi-criteria analysis; decision support models; water reclamation

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1. Introduction

Brazil is faced with water supply and demand concerns, as the population is largely concentrated in a geographical region where the availability of water resources is unfavorable [1]. About 42% of Brazilians live in the Southeast [2], the country's most populous and developed region, which has only 6% of Brazil's fresh surface water [3], but presents a high demand for various water uses, such as industrial, agricultural, irrigation, hydroelectric power generation, and public supply [4]. The high urbanization degree has contributed to the quality deterioration of freshwater sources (especially those that cross large urban centers) as, in Brazil, only 49.1% of sewage goes through some kind of treatment, this rate being 55.5% in the Southeast region [5].

Droughts have become longer, more frequent, and more severe in Brazilian regions in recent years, as related to global climate change. In 2019, around 22 million Brazilians were affected by this, and an estimated 60.9 million people reside in cities suffering from water shortages [6]. In 2014 and 2015, Southeastern Brazil—especially the State of São Paulo—faced a historic drought [4], a scenario that returned in 2021. Such water insecurity scenarios are expected to tend to get worse. Furthermore, it has been predicted that, by 2030, water consumption in Brazil will increase by 24%, as compared to 2019, driven by the urbanization process and economic expansion [3]. In addition, the COVID-19 pandemic has reinforced the need for a safe drinking water supply in order to ensure favorable conditions for personal hygiene and to prevent the spread of the coronavirus contagion [1,6]. The quantitative and qualitative scarcity of water resources, coupled with the tendency towards an increased demand for drinking water—due to both population growth and economic development, which also contributes to a rise in conflicts over water use—has pushed the search for alternative solutions that aim to meet current and future demands for this natural resource. In this context, the non-potable reuse of treated wastewater represents a promising contribution for achieving water security by relieving the demand pressure on the public supply system. This practice can satisfy less restrictive demands, whose application can be subject to a health risk assessment, making better quality water available for priority uses such as public supply.

Water reuse consists of recovering water from a variety of sources, then treating and reusing it for beneficial purposes [7]. Among the applicable reuse options, urban–industrial use, identified as use in the irrigation of green areas, yard washing, and as input in production processes, among others, can bring significant economic, health, and environmental benefits [8]. Therefore, it should be considered as one of the flows in the urban water balance. As for the benefits of the reuse of treated wastewater treatment plant (WWTP) effluent, one can cite increased water availability, environmental improvement through reduced pollutant load associated to non-treated effluent discharge into water bodies, opportunities to expand agriculture, artificial aquifer recharge, and other additional benefits, such as wastewater reclamation [9,10].

In this context, water reuse can be seen as a tool to achieve a circular economy in the sanitation sector, thus contributing to the 17 Sustainable Development Goals (SDGs) proposed by the United Nations in 2015 [11]. Among these goals, SDG 6 deserves special attention, as it seeks to ensure the availability and sustainable management of drinking water and sanitation for all. Of particular note, target 6.3 focuses on improving water quality by reducing pollution and eliminating waste, reducing the proportion of untreated wastewater, and substantially increasing recycling and safe reuse; last, but not least, target 6.4 aims to greatly increase water use efficiency and reduce the number of people suffering from water scarcity. Alternative water sources, such as the use of reclaimed water, should be considered when aiming for sustainable water management [12].

Despite the environmental advantages, the great resistance against the reuse of water from domestic effluents is related to the guarantee of public health safety and popular acceptability. The public's acceptance and perception of water reuse is critical to its effective implementation [13]. Consumers survey analysis can provide information on their perceptions regarding alternative water sources utilization, especially in crisis situations [14]. Therefore, the regulation of parameters and procedures for water reuse offers legal and institutional subsidies for the recognition of this practice. Many institutions in countries without regulated parameters for the rational reuse of water from wastewater base their concepts on the United States Environmental Protection Agency (USEPA) Guidelines for Water Reuse, precisely due to the wide range of applications and criteria given therein [15]. In Brazil, there is still no federal regulation with guidelines, directives, and criteria for the reuse of water from domestic wastewater; however, the update of the Sanitation Legal Framework, Law No. 14.026/2020, foresees the reuse of treated sanitary effluents as alternative non-potable sources, whose reference and standardization norms should be established by the National Water and Basic Sanitation Agency (ANA) [16].

The decision-making process for the selection of water reuse options is complex, requiring the consideration of several factors. Thus, a simplistic analysis based only on the costs involved is not appropriate. In addition, the growing awareness of natural resources fragility necessitates an increasingly responsible attitude in any decision-making situation. Thus, a question arises about what key factors can express—in a multi-criteria analysis—the main economic, technical, legal, social, environmental, and public health aspects, aimed at direct reuse, notably in the context of a pre-existing WWTP, whose reuse practices were not previously considered in plant planning, design, and construction.

In this sense, through the definition of key preponderant factors, the adoption of adequate decision-making support tools would be favorable to identify the best solution in the context of the decision process. Multi-criteria analysis (MCA) is a useful approach that can incorporate a combination of quantitative and qualitative information, while also considering the preferences of various stakeholders [17]. The use of multi-criteria analysis methods to aid decision-making in water reuse actions from domestic [18–20] and industrial [21] effluents has confirmed the wide applicability of such approaches for this purpose. There are several multi-criteria analysis methods, which have been used by researchers in varied research fields. Among those methods, there are the ones based on multi-objective mathematical programming, such as Cooperative Game Theory (CGT) and Compromise Programming (CP), which utilize the concept of metric distance [22,23].

The objective of present work was to establish the relevant key factors that should be prioritized in the decision-making process for the urban–industrial reuse of WWTP effluent, focused on the management of water resources in the urban environment. Therefore, through bibliographic research and a field survey, economic, technical, legal, social, environmental, and public health criteria were listed. Then, we tested and validated these criteria through the application of multi-criteria analysis methods.

2. Materials and Methods

The methodology was structured to determine and evaluate the key factors in decision-making processes for the urban–industrial reuse of treated WWTP effluent in medium- and large-sized cities. Then, the proposed criteria were tested in a real scenario using the Cooperative Game Theory (CGT) and Compromise Programming (CP) multi-criteria analysis methods in order to validate their applicability.

2.1. Criteria Definition and Valuation

The criteria were firstly proposed based on the requirements for reuse according to technical literature (e.g., USEPA, World Health Organization—WHO, and others). Then, three brainstorming sessions were conducted among the research group members, resulting in a list of 13 topics. Afterwards, structured questionnaires were used and sent individually by electronic mail to 42 evaluators. These experts were selected according to their proximity to the research subject, including higher education professionals from the private sector, managers, engineers, and technicians from municipal and state sanitation companies, environmental consultants, members of river basin committees, and researchers having experience in the fields of urban sanitation, water reuse, effluent treatment, water resource management, and/or multi-criteria methods.

The structured questionnaire contained an explanatory letter briefly exposing the research context and general guidelines regarding the analysis of the proposed criteria, as well as a form field for assigning the respective scores. Furthermore, there was a blank space for the proposal of new criteria, along with their definition, score, and relevance. As there were no new proposals to include or exclude criteria, the 13 initial criteria listed were retained. The valuation of each criterion was performed individually, by assigning scores that ranged from 1 to 10 (these being the minimum and maximum values of relevance, respectively).

Furthermore, a scale for the degree of importance was established, as described in Table 1, which divided the values considered by the evaluators into five intervals. This degree of importance helps to define the most relevant criteria more clearly, without a need to differentiate very close scores such as, for example, 9 and 10, which are considered as optimal values.

Table 1. Scores assigned to criteria versus importance degree.

Score	Importance Degree
1–2	Irrelevant
3–4	Minor Importance
5–6	Moderate Importance
7–8	Important
9–10	Very Important

2.2. Real Scenario Analysis: Treated Effluent Characteristics and Potential Industrial Users Definition

2.2.1. Characterization of the Study Area

In order to test the developed criteria and apply the multi-criteria methodological approach to choose the best alternative for the industrial reuse of treated effluent in an urban environment, a WWTP was selected in the metropolitan region of Campinas, located in the São Paulo State (Brazil). The city of Campinas has approximately 1.2 million inhabitants, with an urbanization rate over 98% [24]. The WWTP under study (Figure 1) was located in a region characterized as a sub-basin with intensely urbanized areas, high degree of human and industrial occupation, and high rate of soil sealing. In addition, this watershed is subject to critical water shortage events, as experienced in the years 2014–2015 [4], which was repeated in 2021 [25].

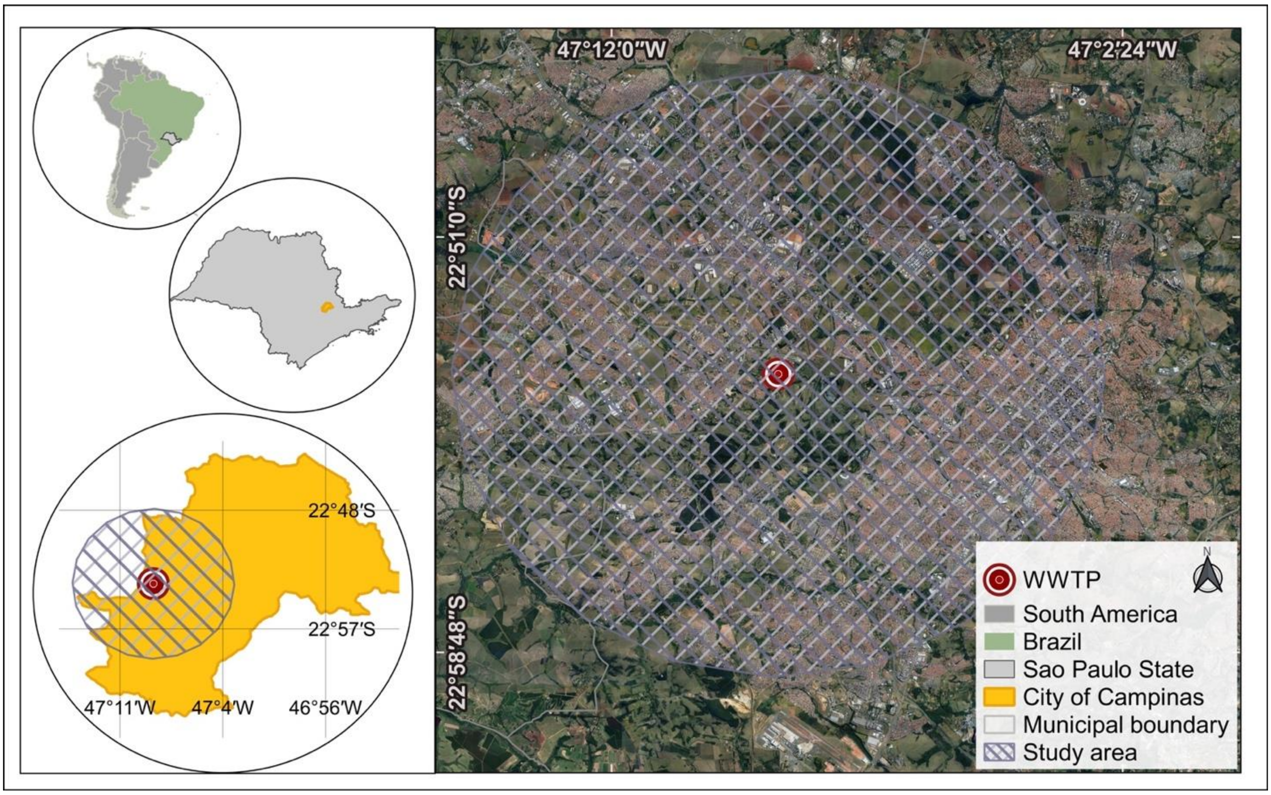

Figure 1. Geographic location of the considered WWTP.

2.2.2. Effluent Quality

The treated effluent comes from a WWTP that has been operating since 2005, with an average monthly treatment flow of 320 L/s. The treatment system adopted in the WWTP is an upflow anaerobic reactor, followed by conventional activated sludge. A physicochemical and microbiological characterization of the treated effluent, sampled over a two-year period, is presented in Table 2. The effluent characterization is a primordial step for qualitative and quantitative evaluation of the possible reuse modalities and users, who will be subsequently listed.

Table 2. Physicochemical and microbiological characterization of the treated effluent.

Parameter	Average	±sd [1]	Maximum	Minimum
pH	7.4	0.5	7.9	5.2
Color (mg Pt–Co/L) [2]	122	61	275	47
Turbidity (NTU) [3]	13.4	11.1	49.3	2.5
Temperature (°C)	23.8	2.0	27.0	21.0
Biochemical Oxygen Demand (mg/L O_2)	21.8	14.4	74.0	3.0
Chemical Oxygen Demand (mg/L O_2)	44.9	19.4	102.0	12.0
Ammoniacal Nitrogen (mg/L NH_3)	23.1	11.9	49.4	4.7
Nitrate Nitrogen (mg/L NO_3)	13.07	9.25	30.30	3.45
Nitrite Nitrogen (mg/L NO_2)	0.94	1.17	3.28	0.06
Total Solids (mg/L)	408.0	62.5	604.0	312.0
Total Fixed Solids (mg/L)	303.3	42.7	417.0	247.0
Total Volatile Solids (mg/L)	105.0	49.5	310.0	47.0
Dissolved Solids (mg/L)	382.5	63.3	588.0	296.0
Total Suspended Solids (mg/L)	23.9	27.8	202.0	3.0
Fixed Suspended Solids (mg/L)	9.1	24.4	190.0	<0.1
Volatile Suspended Solids (mg/L)	14.8	10.8	52.0	2.0
Sedimentable Solids (mg/L)	0.84	2.01	8.50	<0.01
Total Coliforms (MPN/100 mL) [4]	2.0×10^5	4.3×10^5	1.6×10^6	7.0×10^3
Fecal Coliforms (MPN/100 mL) [4]	5.1×10^5	1.4×10^5	5.0×10^6	2.2×10^3

[1] sd, Standard deviation; [2] Pt–Co, Platinum-Cobalt scale; [3] NTU, Nephelometric Turbidity Unit; [4] MPN, Most probable number.

2.2.3. Definition of Potential End-Users

A preliminary survey of the industries located in the same drainage basin as the WWTP considered in the study (e.g., textile, metallurgical, chemical, civil construction, among others) was carried out.

Among the 31 industries identified and invited to participate as potential users, nine confirmed their interest in collaborating and sharing data for application in the multi-criteria analysis. Data obtained through e-mail, telephone contact, and conventional mail were registered in a georeferenced database. In order to protect the information given by potential users, each alternative was identified as a Profile (Table 3), ranging from one to nine (I to IX).

The registration and mapping of industries and WWTP was carried out using Geographic Information System (GIS) technology. In this way, the distances from the treatment plant to the potential industrial users were determined (Figure 2), as well as the overlapping of layers with the addition of information necessary to analyze and visualize the georeferenced database. Furthermore, the use of GIS facilitated the monitoring of the project, as well as ensuring the continuous updating of information capable of being used in complementary studies, after the hierarchy resulting from the multi-criteria methods used in this phase of the research.

Table 3. Identification and description of potential end-users.

Profile	Description
I	Medium-sized company (up to 200 employees). Performs machining services and assembly of parts, machinery, and equipment. Average monthly consumption is 70 m^3 of water and the supply source is the public distribution network. It is located 6.4 km from the WWTP.
II	Large company (over 200 employees). The company's products are polyurethane (PU) and polyvinyl chloride (PVC) laminates, and the manufacturing process is thermal curing. Average monthly consumption is 500 m^3 of water and the supply source is through wells, trucks, and the public distribution network. It is located 4.6 km from the WWTP.
III	Medium-sized company (up to 200 employees). The products of this company are detergents, finishes, and waterproofing products, among others. Average monthly consumption is 400 m^3 of water and the supply source is the public distribution network. It is located 10 km from the WWTP.
IV	Medium-sized company (up to 200 employees). The main products are simple paste (lime or cement), mixed paste (lime and cement), normal concrete, high-performance concrete, and paving, among others. The average monthly consumption is 720 m^3 of water, and the supply sources are the public distribution network and a well. It is located 5.1 km from the WWTP.
V	Medium-sized company (up to 200 employees). They carry out the machining of metal parts. Average monthly consumption is 300 m^3 of water. Main supply source is the public distribution network and rainwater collection tanks. It is located 7.01 km from the WWTP.
VI	Small company (up to 25 employees). The products offered to the market are carbide tools and its manufacturing process consists of machining. Average monthly consumption is 60 m^3 of water and the supply source is the public distribution network. It is located 5.5 km from the WWTP.
VII	Large company (over 200 employees). The main products are power tools, gasoline injection systems, and motors. Average monthly consumption is 7000 m^3 of water and the supply sources are the public distribution network and a private network from a conceded source (industrial water). It is located 3.6 km from the WWTP.
VIII	Small company (up to 25 employees). The products offered to the market are PVC laminates. Average monthly consumption is 100 m^3 of water and the supply sources are the public distribution network and truck. It is located 9.8 km from the WWTP.
IX	Small company (up to 25 employees). The products offered to the market are safety clothing for cold, heat, and chemical protection, through the processes of resin, cutting, sewing, finishing with safety closure, and eventual dyeing of cotton mesh. The average monthly consumption is 80 m^3 of water and the supply source is the public distribution network. It is located 6.4 km from the WWTP.

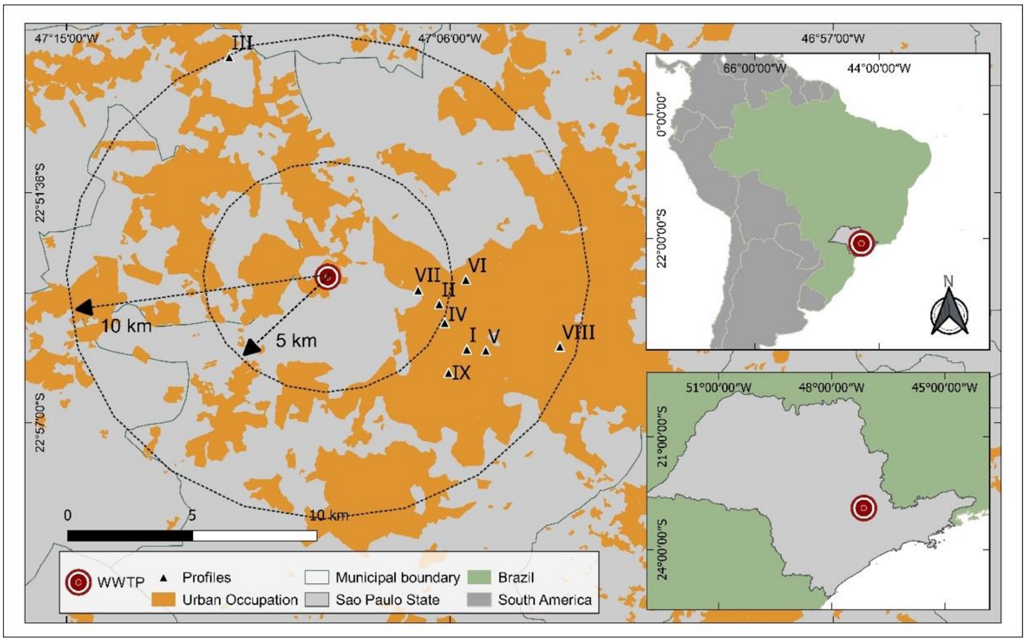

Figure 2. Industrial profiles surrounding the WWTP.

2.3. PayOff Matrix and Alternatives Hierarchy Sorting by Multi-Criteria Methods

After obtaining the criteria, the assigned scores, and the alternatives for effluent reuse around the WWTP, we proceeded to study the hierarchy of reuse alternatives within a multi-criteria environment. The criteria and the average scores obtained were applied to the multi-criteria methods of Compromise Programming (CP) and Cooperative Game Theory (CGT).

2.3.1. Compromise Programming (CP)

In this approach, the "best" solution is defined as the point that, for the set of efficient solutions, minimizes the distance of all feasible points from an objective point (often called the "ideal point"). The purpose of this method is to achieve a solution that is as close as possible to the ideal point. The distance measure (L_p) used in this method is defined as [22]:

$$L_p(x) = \left[\sum_{i=1}^{n} \alpha_i^p \left|\frac{f_i^* - f_i(x)}{f_i^* - f_{i,w}}\right|^p\right]^{1/p}, \tag{1}$$

where α_i is the weight attributed to criterion i; f_i* is the optimal value of the ith criterion; $f_{i,w}$ is the worst value obtainable for criterion i; $f_i(x)$ is the result of implementing a decision x in relation to the ith criterion; and p is the proportionality applied to deviations, with $1 \leq p \leq \infty$. In this work, the value $p = 1$ was adopted, such that all deviations of f_i* were considered to be indirectly proportional to their magnitudes.

2.3.2. Cooperative Game Theory (CGT)

This approach is also distance-based; however, instead of minimizing the distance to an ideal point, as in the CP method, the "ideal solution" is the one that maximizes the distance from a given minimum-level "status quo" point. The distance measure used is the geometric distance ($g(x)$), given by [23]:

$$g(x) = \prod_{i=1}^{n} |f_i(x) - f_i^*|^{\alpha_i}, \tag{2}$$

where α_i is the weight assigned to criterion i; f_i* is the ith element of the status quo point; and $f_i(x)$ is as previously defined.

Regarding the weights (α_i), we selected four scenarios, obtained through statistical analysis of the results in the answered questionnaires: namely, with respect to the average (Scenario A), the maximum (Scenario B), the minimum (Scenario C), and the mode (Scenario D) of the scores.

To construct the PayOff matrix and apply the methods, we adopted value functions on a scale for users within each criterion, ranging from a minimum value equal to 1 (least favorable) to a maximum value (most favorable) equal to 5. Once the PayOff matrix was established, the hierarchy of alternatives, sorting for potential of water reuse around the study WWTP, was constructed.

3. Results and Discussion

3.1. Identification and Valuation of Key Factors

Concerning identification of the criteria, a return rate equal to 71% of the 42 volunteer evaluators contacted was recorded, resulting in a total of 30 answered questionnaires that assisted in the definition and analysis of key factors (criteria). The fundamental key factors identified in the analysis of secondary and primary data (here named as criteria) are presented and described in Table 4. The criteria choice was supported by agents who experience frequent and severe events of water scarcity and had the purpose of subsidizing the application of decision-making support models for the purpose of urban–industrial non-potable WWTP effluent reuse in urbanized watersheds.

Table 4. Description of the criteria identified to analyze the potential for reuse of WWTP effluent reuse for urban–industrial purposes.

Code	Criteria	Description
C01	Distance	Distance between the supplier, the WWTP, and the potential user (metric measurement).
C02	Quality of WWTP effluent	Compliance to physico-chemical and bacteriological patterns required for a given use.
C03	Availability of reuse water	Sufficient quantitative supply (supply of reuse water), as required by the user (demand).
C04	Qualified labor	Actions related to the care required, both in handling and transporting reuse water (training, safety equipment, and others).
C05	Risks (Toxicity)	Considers the health risks (including waterborne diseases) due to the use of and possible physical contact of workers, consumers, and the environment with the reuse water.
C06	Post-treatment need	Considers the need to improve or adapt the treatment at WWTP for a given use (purpose). If post-treatment is required, it is considered least favorable for the reuse.
C07	Environmental Benefits	Environmental contribution of the reuse practice, measured by the ratio between the standards required for reuse and for discharge into water bodies.
C08	Acceptability	Expresses the degree of sacrifice or openness to the use of a new source of non-potable water resource for less restrictive purposes.
C09	Image	The concern about political or market projection for adopting water reuse by the end-user (environmental marketing).
C10	Reliability	Expresses the degree of safety, by the end-user, over the effluent treatment for the preservation of the reuse practice.
C11	Mean of transportation	Considers the importance degree of transportation in the implementation of water reuse (cost of implementing a distribution network or water tank truck).
C12	Environmental costs	Considers monetary expenses related to the consumption of drinking water and the destination of the generated effluents (user-pays principle).
C13	Maintenance and monitoring costs	Maintenance and monitoring costs, as well as monetary expenses for the maintenance of the wastewater reuse and monitoring system.

Among all the 13 defined criteria, economic (C12, C13), technical (C02, C03, C06, C10), public health and social (C05, C08, C09), technical–economic (C01, C04, C11), and environmental–legal aspects (C07) were covered. The scope of the criteria, with respect to different perspectives, can facilitate adequate planning and effective management of the reuse project [19].

The listed criteria proved to be relevant during the evaluation and application process, as can be seen in the results that follow (Figure 3). The distribution of scores given by the evaluators maintained a trend toward assigning high degrees of significance.

From Figure 3, it can be seen that the criteria were considered by most of the evaluators as “Very Important”. Those that received a score of 9 or higher were: C02—Quality of Treated Effluents (80%), C05—Risks (76.7%), C10—Reliability (66.7%), C12—Environmental Costs (53.3%), and C07—Environmental Benefits (53.3%). Among the highest scored, it is possible to find all categories of aspects (i.e., economic, technical, legal, social, environmental, and public health), reflecting the impartiality of the multi-criteria analysis.

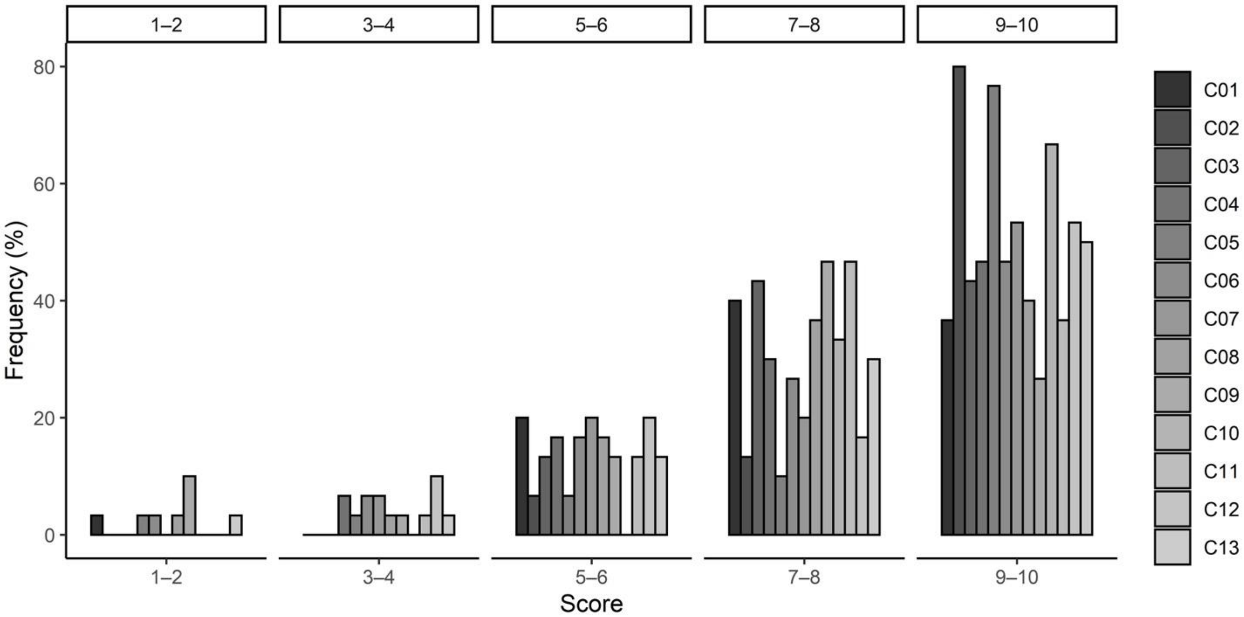

Figure 3. Frequency analysis of the criteria developed in this study.

The quality of WWTP effluent (C02) criterion, referring to the physicochemical and microbiological parameters of reuse water, stood out as the most relevant, precisely due to the characteristic of use to be employed; that is, avoiding damage to health and to the production process. The more restrictive the use, the greater the need to control the qualitative parameters of the reuse water. The practice of reuse has been intensified, regarding the variety of applications in the industry, ranging from less restricted (e.g., water for toilets, cleaning of patios, and irrigation) to more controlled (e.g., for use in the production process and the operation of machinery) [15]. It is worth highlighting the importance of continuously monitoring the quality of the treated effluents in order to guarantee the minimum requirements necessary for each intended use.

Risks (C05), which considers the toxicity associated with human exposure to reuse water, represents the necessary caution for handling water. This criterion, listed among the most important (Figure 3), is certainly associated with C02 and the adequate employability of the treated effluent for less restrictive uses. Furthermore, when considering any human exposure—both in handling and transporting reuse water—it is necessary to educate staff and implement protective measures at work, which are also measured using C04. The support provided by legislation, based on the fit-for-purpose approach, minimizes the risks of contamination. In Portugal, following the decree-law DL119/2019, through the assessment of risk and its minimization, the criterion of multiple barriers has been adopted, which includes, for example, barriers to limit contact with reuse water [26].

Reliability (C10) was identified, in the adopted importance scale, as a criterion valued from "Important" to "Very Important" by all the consulted evaluators, having received no grade lower than 7 (Figure 4). Ensuring the quality standard is fundamental for resource management actions; despite the concern shown through the analysis of the criteria C05 and C02, it was found that stakeholders had confidence in the services offered by the local company (Profile), which showed interest and openness to the reuse of WWTP effluent in their industrial facilities. Public acceptance is also relevant for the industrial sector. Actually, household consumers' first criterion for acceptance of tap water relates to water quality [14]. It has been demonstrated that public acceptability for water reuse is low for everyday activities that require direct physical contact with water, such as hand-washing and laundry, while greater agreement has been identified for urban–industrial reuse (i.e., production processes, garden irrigation, and toilet flushing) [8]. Therefore, the reuse of

WWTP effluent in the industrial sector has been popularly supported. Additionally, greater acceptability can be expected in water scarcity scenarios [13].

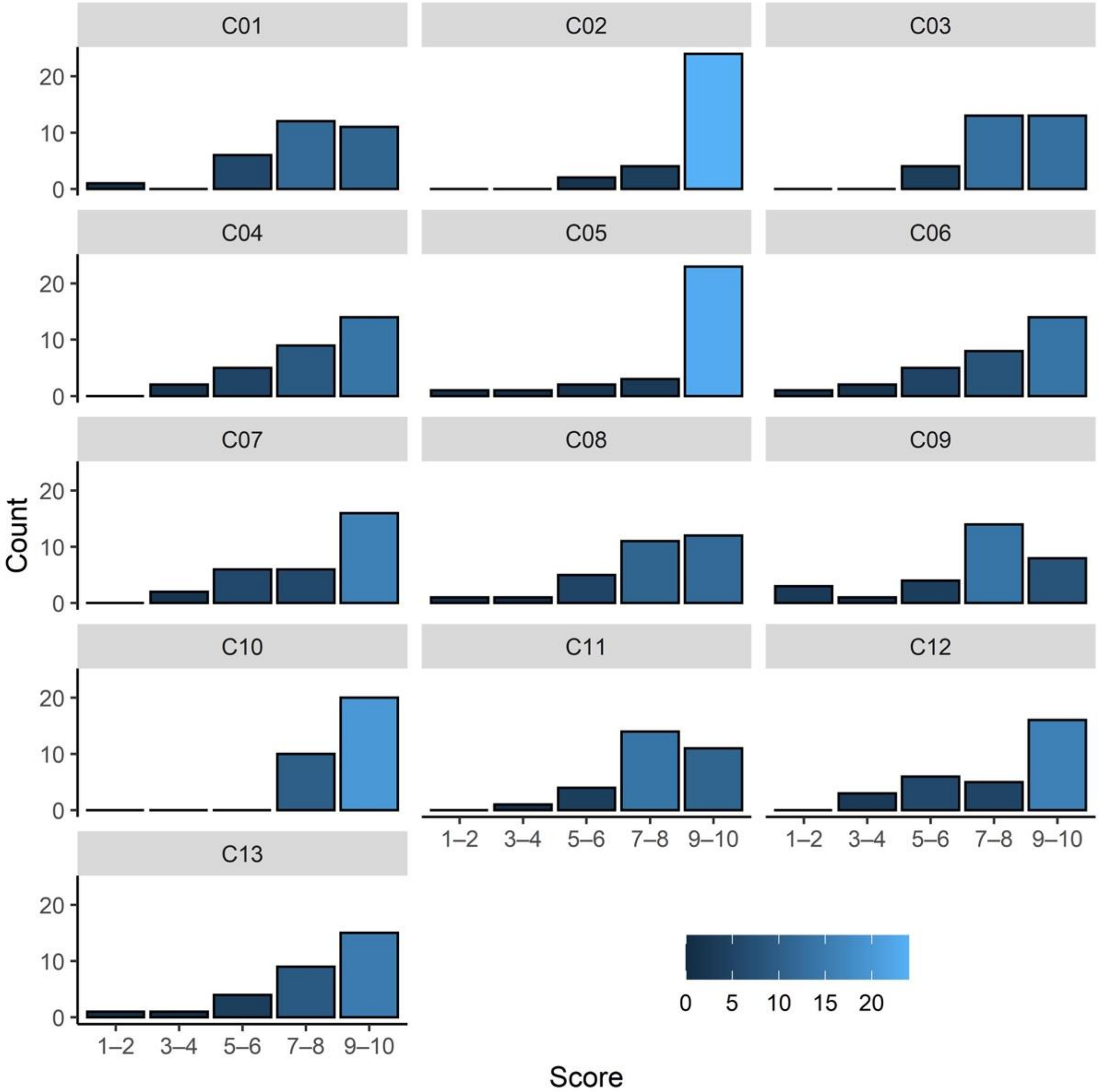

Figure 4. Frequency of distribution of the degree of importance for the 13 proposed criteria.

The environmental costs criterion (C12), which considers the role of the user–payer, demonstrates the growing need for development due to environmental requirements and charges; the latter referring to the allowance of raw water collection and effluent discharge into water bodies. The cost-effectiveness recognition of the resource that reuse water represents in the industrial sector is already perceptible, principally in developed countries such as the United States of America, precisely due to water scarcity [15]. The practice of reusing treated effluent benefits the user by reducing monetary expenses on bills related to water consumption from the public distribution network and, therefore, for the collection and removal of sewage, as the practice of charging for sewage collection in Brazil is proportional to the registered water consumption. It should also be noted that the reality faced, regarding the depreciation of water bodies quality in urbanized basins [27,28], requires improvement of the drinking water treatment process and, consequently, an increase in cost per treated volume.

An increase in cost related to monitoring and maintenance of the reuse water supply system (C13) must be avoided. From the user's point of view, an increase in monetary expenses for the management of the alternative supply source cannot exceed what has been saved through the reduction in the consumption of potable sources. The experience related to water stress in developing countries differs from the practical perspective of water reuse in developed countries [8]. From the point of view of the industrial sector, the criteria related to economic factors—costs and expenses—are the most prioritized in urban cities in India, which is characterized by high population density and water demand [19]. These characteristics are similar to those of the region studied in this work, with India being a developing country and similar to Brazil, in this regard. The scale factor is widely observed in the application of the criterion: the higher the average consumption used by the Profile, the lower the proportion is given to this factor.

The criterion relating to the distance between the reuse water supplier (in this case, the WWTP) and its potential user (C01) had a similar evaluation to the criterion that considered the degree of importance of the means of transport in the implementation of water reuse (C11; Figure 4), both being understood as "Important", according to the scale of significance indicated in Table 1, depending on the scenario considered for the reuse water supply. The distance between the supplier and the user has an impact on (among other factors) the transport form and, consequently, the costs involved in transporting the reuse water to the potential consumer. In this regard, especially for urban areas, where the reuse water producer is close to potential consumers, with the constant availability of treated effluent, it provides a promising alternative source of water [12], potentially reducing the pressure on the demand for surface and groundwater [13]. According to the profiles of the interested industrial users (Table 4), the range of distances determined strengthened the feasibility of reuse around the WWTP when considering 10 km as a threshold [29].

The degree of importance of criterion C03 reflected the concern regarding the regularity guarantee on the availability of reuse water, not being considered "Irrelevant" or of "Minor Importance" by any of the evaluators (Figure 4). An increase in the volume of collected and treated sewage is a result of the advancements targeted by SDG 6, in relation to the provision of sanitation services that must a priori accompany the growth of urban areas. When considering different existing contexts, we may take Brazil as an example, where the present study is based: only 49.1% of the sewage generated undergoes some type of treatment [5]; a 90% figure has been set as a goal to be reached by the year 2033, as signaled in the Sanitation Legal Framework [16]. With the expansion of collected and treated sewage volume, there is the prospect of an increase in the reuse water supply, encouraging the willingness of potential users to carry out the practice of reuse for several purposes.

By analyzing the results for criterion C06, which deals with the need for post-treatment of the effluent, it was considered a significant criterion, and depends on the purpose of the reuse water. As the need for post-treatment can have an impact on the costs required to carry out the reuse practice, this factor can directly influence the adhesion interest of the potential user and the acceptability of the treated effluent (C08). A procedure already carried out in some locations, which aims to promote acceptance, is making adjustments in the effluent treatment facilities at the WWTP in order to achieve the quality required by the end-user, such as required additional levels of treatment that may include oxidation, coagulation, and filtration, among others [15].

Considering the water reuse applications and the possibility of reducing the flow of water supplied and treated by water companies for drinking water supply to industrial consumers, environmental benefits (C07) can be promoted through ecosystem maintenance and support for water security in the urban environment. Another point to keep in mind refers to the water treatment process as a generator of residues, especially the sludge from settling tanks and backwash water from filters [30]. The environmentally adequate disposal of this waste is still a major challenge, both in Brazil and worldwide, and the possibility of reducing the flow of water adducted and treated through the practice of reuse will contribute to reducing the generation of such waste.

Although reuse of treated WWTP effluent has the potential to reduce water supply system demand, it can also decrease flow availability in the receiving water body [13]. The input of effluents from wastewater treatment plants can favor the recharge and maintenance of the water source and aquatic life. Conversely, the reuse of wastewater contributes to mitigating negative environmental impacts, given the minimization of effluent discharge—even from secondary treatment—in water resources, thus configuring quality and aesthetic benefits to the water resource [9]. A more extensive investigation is required to understand the balance and influence of these many processes [13]. By adopting reuse as a marketing strategy and obtaining environmental certifications, the industrial sector aims to achieve public recognition, which is a most desired outcome. However, the criterion related to the public image (C09) of the reuse practice presented the lowest average weight among the grades issued by the evaluators, with the highest percentage of significance as irrelevant among all criteria.

It should be noted that the criteria assessment was based on the individual perception of each evaluator, which was influenced by their professional and local experiences. Furthermore, the interests of the evaluators influenced the degree of importance of every criterion, being stakeholders from companies and industries involved in the process target the economic aspects in order to maximize profits and minimize subsidies; meanwhile, unrelated stakeholders (i.e., academics) may be more concerned with the technical and sustainable aspects [8,19]. In this way, in every application, the scenario and local characteristics should be observed, as well as future needs, in view of the re-evaluation of the criteria and selection of evaluators.

3.2. Criteria Validation and End-User Hierarchy by MCA in a Real Scenario

The results obtained by applying the CP and CGT methods, considering the PayOff matrix (see Table S1, Supplementary Materials), to the four adopted scenarios resulting from the statistical treatment of the scores assigned by the evaluators, are shown in Tables 5 and 6, respectively.

Table 5. Hierarchy of potential users obtained through application of the CP multi-criteria method.

Scenario		Profile								
		I	II	III	IV	V	VI	VII	VIII	IX
A	mean	8°	1°	6°	4°	7°	5°	2°	3°	9°
B	maximum	8°	1°	6°	4°	7°	5°	2°	3°	9°
C	minimum	7°	1°	6°	4°	8°	5°	3°	2°	9°
D	mode	8°	1°	6°	4°	7°	5°	2°	3°	9°

Table 6. Hierarchy of potential users obtained through application of the CGT multi-criteria method.

Scenario		Profile								
		I	II	III	IV	V	VI	VII	VIII	IX
A	mean	8°	1°	7°	4°	6°	5°	2°	3°	9°
B	maximum	8°	1°	7°	4°	6°	5°	2°	3°	9°
C	minimum	8°	1°	6°	4°	7°	5°	3°	2°	9°
D	mode	8°	1°	6°	4°	7°	5°	2°	3°	9°

Analyzing the ranking of potential industrial users resulting from the application of CP and CGT methods, the same pattern was observed for scenarios A, B, and D by the CP method, and scenario D by the CGT method.

Regarding the first two positions, of the four scenarios evaluated, Profile II was unanimously ranked first by the CP and CGT methods. Secondly, there was a predominance of 75% for Profile VII among the eight hierarchy scenarios analyzed, only changing positions with Profile VIII in the application of both CP and CGT methods under scenario C, where it corresponded to the minimum result.

Profiles II and VII, listed as the two best choices (1st and 2nd positions), correspond to larger industries, with the highest number of employees and monthly water consumption average, and were among the top three companies with shorter distance to the WWTP. It was also observed that, according to the information provided by the industries, Profile II stood out in relation to Profile VII, as it benefited from the score attributed by the evaluators to the criterion C02 (Quality of the treated effluent), associated with the uses for reuse water desired by the industry, which were more in line with the qualitative aspects of the WWTP effluent.

However, Profiles I and IX predominated in the last positions; that is, in eighth and ninth place, respectively. These positions corroborate the information made available by the industries which showed a lower predisposition and initial conditions to adhere to the reuse of treated effluent, as confirmed by the analysis of the PayOff matrix, in which 53.8% of grades 1 and 2 were assigned to Profile IX, followed by 38.5% to Profile I.

In addition to the results shown in Tables 5 and 6, Figure 5 illustrates the results generated by the CP and CGT methods for the scenario that considers the average of the scores, in which only the hierarchical inversion of alternatives III and V stands out (between the sixth and seventh positions).

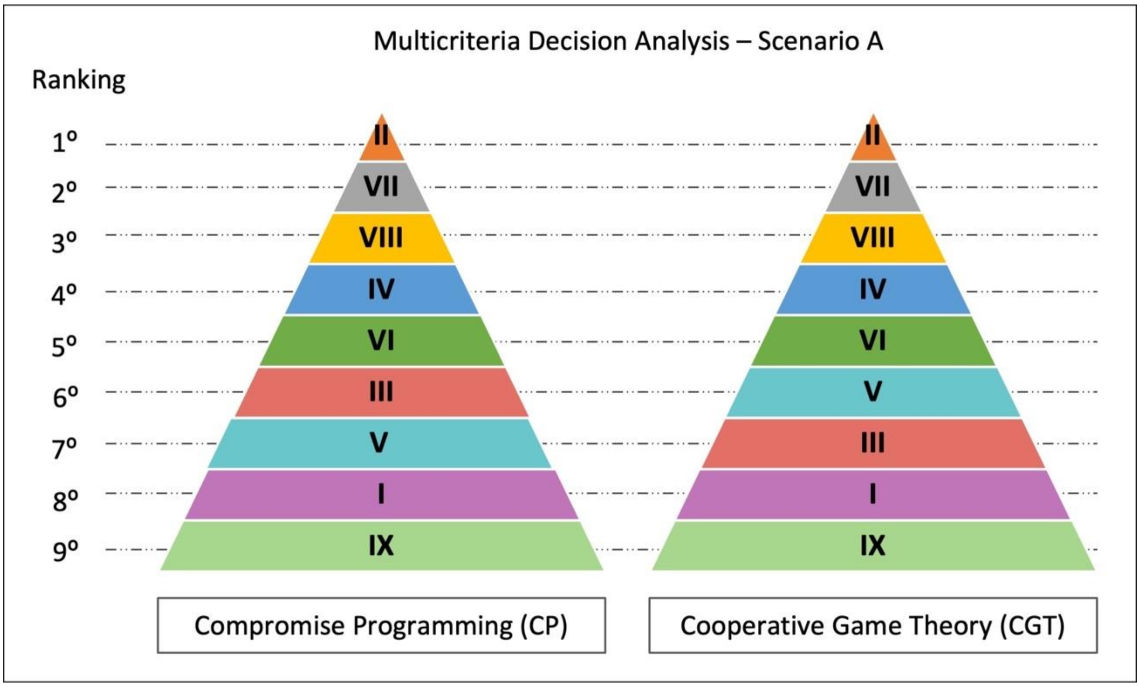

Figure 5. Hierarchy generated by CP and CGT methods to choose the most favorable profile, according to the 13 criteria for Scenario A.

The effectiveness of the 13 criteria, measured by applying the multi-criteria analysis methods designed for the purpose of ranking the nine potential industrial users of the treated WWTP effluent, proved to be feasible and well-founded. The challenge posed to decision-makers and stakeholders to provide the reuse of the locally designed WWTP treated effluent without considering this practice was facilitated, and the classification generated by CP and CPG methods was successful, assuring that the factors contributing to the decision of the best alternative were considered.

The respective scenarios of the given scores reflect the perception of each active stakeholder before the actual social and environmental context. In addition, the accuracy of the information provided by the Profiles listed is also extremely important for the reliability of the result. Multi-criteria analysis methods are based on mathematical calculations, and do not describe the constant action of decision-makers, who must carry out the monitoring, collection of reliable data, and critical analysis of results and final verdict. Besides, MCA methods do not exempt the need to carry out a more in-depth study wherein each Profile receives the treated effluent for the safe implementation of reuse.

It should be emphasized that multi-criteria methods are appropriate tools for helping in making a choice and in the decision process, as they allow for an evaluation beyond what is traditional (technical–economic) by considering various aspects in a subjective manner. They determine options and paths based on concepts that are initially not considered in commercial relations but which, due to current changes and requirements (especially in relation to environmental and social issues), are already being considered as good differentials for any industrial sector.

When establishing a master plan for an urban sewage system, the multi-criteria analysis method can be used a priori to define the most appropriate location for a new WWTP, adding to the usual criteria for analysis and decision the reuse potential of the effluent to be produced, and also a posteriori, for reuse potential assessment from a pre-existing WWTP that did not consider such a criterion during the decision-making design process for choosing the plant location and, furthermore, the type of treatment system, which is precisely the case here considered.

In highly urbanized watersheds where water scarcity is present, WWTPs certainly constitute an alternative source of water to supply urban demands. One of the promising uses in this context is in the industrial sector, with different quantitative and qualitative demands depending on the type, size, and field of activity. Thus, the georeferenced survey of industrial consumers present in the plant's influence area, their clustering by similarity, the qualitative and quantitative requirements of each group, the higher or lower will for changing from drinking water to effluent use, environmental, and legal boundaries are weighted in order to translate such technical, economic, and non-economic criteria into a list of strategic planning priorities and subsequent tactical and operational level actions by the water system manager.

Thus, approach presented here can be used as a tool in the identification and prioritization of potential users, and thus, in the preliminary design of hydraulic transport systems (pumping stations and distribution networks), in the operation or upgrade of the WWTP itself to meet quality demands/requirements, among other management actions.

The authors suggest further research by integrating geographic information systems and multi-criteria analysis methods presented here for setting water reuse feasibility in a deeper or a broader way (scaling out or in), adding concurrent types of applications from a given WWTP, assessing water reuse from several WWTPs at the same municipality, or even (inter)urban indirect water reuse considering major water flows in a complex metropolitan or regional scarcity scenario.

4. Conclusions

This study made technical and scientific contributions to the establishment of criteria that assist in decision-making for the application of urban–industrial reuse of treated effluent from WWTPs, especially considering those inserted in densely urbanized and economically developed regions subject to critical events of water scarcity.

We distributed a questionnaire to evaluators, which were returned with a rate equal to 71%, and made it possible to assess the relevance of the 13 proposed criteria, especially those with an average weight equal to or greater than 9; namely, C02—Treated Effluent Quality, C05—Risks, C10—Reliability, C12—Environmental Costs, and C07—Environmental Benefits.

In accordance with the information provided by the industries, the validation of criteria using multi-criteria methods and weighting scenarios made it possible to rank the best alternatives in first and second place, represented by Profiles II and VII, respectively. Similarly, it was possible to confirm Profiles I and IX as the least viable alternatives for the reuse of the evaluated WWTP effluent.

According to the research carried out, we reinforced the applicability of the criteria defined in this study to aid in decision-making processes regarding the practice of reuse in the industrial sector for characteristic urban–industrial uses (e.g., irrigation of areas, washing of yards, washbasins, and as input in the production process, among others); however, the importance of continuous monitoring throughout the entire decision-making process and the need to review the criteria according to the actual environmental, economic, and social scenario is evident.

The results of this study serve as support for the development of planning tools and for the management of water resources in urbanized areas—especially those characterized by conditions similar to the study area—in order to increase water security. They can also help in understanding the criteria involved in the complex problem of decision-making regarding the practice of water reuse, contributing to a reflection by the actors involved in the search for solutions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14081314/s1, Table S1: Payoff matrix for application in the multi-criteria method, according to the evaluated alternatives (Profiles) for effluent reuse around the WWTP.

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