Application of the analytic hierarchy process to the analysis of wastewater nutrient recycling options: a case based on a group study of residents in the city of Zurich

Francisco Contreras, Keisuke Hanaki, Toshiya Aramaki and Claudia R. Binder

ABSTRACT

The recycling of anthropogenic nutrients derived from the wastewater management systems is often characterized by a complex and uncertain scenario, due not only to the nature of the process but also to the involvement of different stakeholder groups. Over the past 10 years in Switzerland, policies regarding the use of sewage sludge as fertilizer have gradually shifted to a ban on use in agriculture. As a result, alternative methods for the recycling of anthropogenic nutrients may play a relevant role in the near future. This paper uses the analytic hierarchy process (AHP) to examine more closely the nutrient-recycling dilemma by analysing the preferences of a group of German-speaking residents in the city of Zurich for various management scenarios. Nutrient recycling by the use of urine separation toilets and the BioCon treatment process are presented as possible management alternatives in addition to current practice. The study shows that AHP can incorporate the respondents' preferences and multiple objectives when evaluating alternatives with different attributes.

Key words | analytic hierarchy process, anthropogenic nutrient recycling, BioCon process, urine separation

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INTRODUCTION

The selection and implementation of wastewater treatment (WWT) is a complex process involving different stakeholders. In fact providing effective treatment has become a pressing matter for municipalities, as society not only considers the technical aspects but also the long-term ecological sustainability. Over the years, concerns about treatment have increasingly recognized that the use of end-of-pipe technologies is not always suitable for addressing all the problems. In some countries, emphasis is given to the recycling of nutrients present in wastewater – in Sweden policies with this goal have become part of the long-term strategy for the sector (Kalmykova *et al.* 2012).

In the context of sustainable WWT, systems oriented towards increasing the removal of pollutants and the recycling of nutrients is strategic. Phosphorus present in wastewater is a limited resource and reducing the need for commercial fertilizers is part of the driver behind recycling. From the decision-making perspective, the scenario surrounding recycling has changed over the years, and the role of stakeholders has shifted from being merely recipients of impacts to playing an active part in the implementation of recycling schemes. Consumer acceptance will be key in the successful application of future programs. According to Pahl-Wostl *et al.* (2003), citizens will have to make important decisions in their roles as tenants and consumers buying products fertilized with nutrients from such recycling schemes. This article applies the analytic hierarchy process (AHP) methodology to analyse the preferences of a group of residents in the city of Zurich based on a questionnaire survey about the recycling of anthropogenic nutrients from wastewater by urine separation and sludge treatment by the BioCon process.

Analytic hierarchy process

The AHP, developed by Saaty (2008), provides a succinct and rational framework for structuring decision-making, allowing the representation of quantitative and qualitative

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attributes, and supporting the ranking of preferences towards the alternatives and evaluation criteria for individual or group decisions by pair-wise comparisons.

AHP is divided into four steps. The first step covers the establishment of a hierarchical structure for decisions around the alternatives and evaluation criteria. The second step establishes the pair-wise comparison matrix that establishes the relative weights for the alternatives based on a nine-point weighting scale allowing judgments in terms of *equal importance, slight importance of one over another*, *essential importance*, *demonstrated importance, absolute importance* and *intermediate between two adjacent judgments*. The relative weights of the elements are determined by estimating the eigenvalue and eigenvector of the pair-wise comparison matrix. The third step incorporates the consistency analysis by estimating the consistency index (CI) for $n \times n$ comparison matrix: $CI = (\lambda_{max}-n)/(n-1)$. The judgment consistency ratio (CR) is calculated using CI and the random consistency index (RI), where $CR = CI/RI$. The CR value is within parameters if equal to or less than to 0.10 or 10%, otherwise judgments should be reviewed. The fourth step focuses on estimating the relative weights of different alternatives and criteria on the matrix to be aggregated at each level following the structure delineated on the hierarchical map to the final value.

Over the years AHP has been extensively applied as a decision support tool in scenarios involving several alternatives and stakeholders (Subramanian & Ramanathan 2012). AHP was regarded as a suitable tool for integrating public preferences in the selection of wetland management alternatives in Australia, based on quantitative and qualitative criteria reflecting the goals of economic, conservation and recreational achievements (Herath 2004). Bottero *et al.* (2011) used AHP to evaluate anaerobic digestion, phytoremediation and composting as alternatives for WWT with high-organic content produced from cheese factories located in the Italian Swiss region. The authors worked on a criterion focused on technological, environmental and economic goals considering 13 specific criteria. Contreras *et al.* (2008) analysed municipal solid waste management (MSW) scenarios in the city of Boston by life cycle assessment (LCA) and AHP. The authors focused on the changes in stakeholders' preferences when faced with controversial MSW treatment alternatives, namely biogasification of organic waste and export as refuse-derived fuel to other states. The study considered four criteria addressing environmental, social and economic goals while considering limited landfill capacity.

MATERIALS AND METHODS

Background information

The city of Zurich is located in one of the most populous regions in Switzerland, where the vast majority of residents live in urban areas. Over the past decades, the population has reached 358,540 inhabitants for the year 2007 in an area of 91,000 km^2 (SFSO 2006). WWT is to a large extent a conventional system based on mechanical and biological processes with carbon, nitrogen and phosphorus removal. At the national level, figures indicate that from 210,000 Mg of sewage sludge generated during 2006, about 90% was treated either by incineration or landfilling, while 10% was used in agriculture, although not for crops and vegetables. Concerns over possible consequences to health and the environment due to potentially toxic substances and handful micro-organisms lead to the banning of sludge from agriculture (Perritaz & Mayerat 2007). Nevertheless, future nutrient availability might be still a matter of concern considering the increasing demand from other regions. According to Ott & Rechberger (2012), more than 90% of the world reserves of phosphorus are concentrated in a few countries which might affect international trade, and in the case of European countries the domestic supply is limited. Despite the possible future demand of phosphorus from anthropogenic sources and the technological options available, the scenario involving the use of a recycled nutrient as fertilizer are a matter of debate.

In the case of stakeholders, concerns have been partially driven by a series of factors ranging from the presence of micro-pollutants to the applicability of recycling schemes. As an example, 57% of the farmers in a survey considered it a good idea to introduce urine-based fertilizers in agriculture while 42% were eager to buy such of fertilizers, depending of the type of their crops. As the study affirms, *'farmers did not question the possibility of hygienic urine-based fertilizer but rather they didn't believe that it was possible to remove micro-pollutants'*. Hurdles associated with the application of sludge or recycled nutrients in agriculture are yet to be addressed. In this debate, local authorities' acceptance is not limited to following current policies but also to consider their feasibility. As such, what are the options and difficulties of finding a viable market, what will be the perception of these products, would farmers be ready to use a urine-based fertilizer and would the consumer be ready to buy this kind of food. For example, market issues were one the factors contributing to the sludge agriculture ban (during the summer of 2001 the Migros and Coop supermarket chains stopped selling agricultural products fertilized with sludge) (Ruth Baderscher, Swiss Federal Office of Agriculture; personal communication April 24, 2007) (Lienert *et al.* 2003). From the perspective of residents, awareness may not be restricted to the presence of pollutants on recycled nutrients but also focused on environmental problems related to WWT. Eutrophication of rivers and lakes is still a matter of concern, and the reduction of nitrogen and phosphorus concentrations in wastewater streams is one of the factors triggering the improvement of treatment systems (Perritaz & Mayerat 2007).

Over the years, several technologies for separating phosphorus from wastewater and sludge have been developed as an alternative to sludge application. According to the Dichtl *et al.* (2007) study on new technologies, there are three different approaches: recycling directly from digested sludge, recycling from sludge liquid and recycling from ash following sludge incineration. Of these, the most common are precipitation of ammonium phosphate (also called struvite) and phosphorus recovery from ash. According to Linderholm *et al.* (2012), several of these technologies have been implemented in Nordic countries by companies such as Cambi, Kemira, BioCon and Purac, among others.

By comparison, urine separation has proven to be an option for nutrient recycling at earlier stages of WWT. Studies shown that urine separation can contribute to the removal of up to 80 and 45% of the total nitrogen and phosphorus found in wastewater while reducing the wastewater generated by 20% (Lundin *et al.* 2000). Despite the available technologies, the authors focused on the BioCon method for nutrient recycling as a result of data availability in terms of input/output factors and operational cost, which are relevant for the characterization of the decision problem at the time the research was conducted. It is not the intention of this research to further discuss or compare these technologies.

Decision scenarios

The decision problem was cast as one involving the choice of nutrient recycling. The existing practice of nutrient import was used as base scenario for assessing the other alternatives. The target group had to make a decision in their role as tenants about whether they were willing to use a urine-separation toilet and whether to accept the initial financial cost. The assessment criteria were based on findings from previous studies focusing on urine separation and phosphorus recycling, and consumer attitudes (Hultman *et al.* 2003; Kvarnstroem *et al.* 2003). Taking into consideration the results of a preliminary test group survey at the University of Zurich and a local colleague's recommendation, an evaluation criteria were outlined for environmental, economic and recycling goals. The environmental goal reflected the desire to protect the local and global environment, whilst the economic goal represented the cost associated with implementation. The last goal captured the desire for a closed nutrient cycle. The goals could have been expanded for the different categories but considering that pair-wise comparison can become tedious, and to reduce inconsistent evaluations, only the most important were considered. The criteria selected included nutrient recycling, greenhouse gas emissions (GHG), eutrophication, acid rain, and cost of operation. The scenarios for the case study were as follows:

- Alternative I 'Business as usual'
- Alternative II 'Nitrogen and phosphorus recycling' by urine separation
- Alternative III 'Phosphorus recycling' from sludge by the BioCon process.

The second alternative of a urine–separation toilet (e.g. NoMix toilets), allowing the separation and collection of household urine from the wastewater stream while requiring the active involvement of residents since households are not equipped for the specific collection system. Tenants were required to participate in collection by installing a urine storage tank, with an initial cost of 810 CHF for the purchase and installation of a urine-separation toilet, compared to 260 CHF for a normal toilet (Schmid 2004). The third alternative focuses on phosphorus recycling by the BioCon method, where residents are not directly required to participate in the process. Dichtl *et al.* (2007) describes the process in three stages namely drying, combustion and recovery. In the first stage dewatered sludge is dried up to 90% before being fed into the incinerator. The resulting slag and ash is dissolved in sulphuric acid before entering a set of ion exchangers, where the cation exchanger allows the collection of iron ions, and in the anion exchanger, sulphate is collected as phosphoric acid after regeneration with hydrochloric acid (further details about the process can be found in Levlin *et al.* (2002) and Pettersson (2002)).

Figure 1 shows the decision-making hierarchy, representing the stages of the evaluation process. At the top is the overall objective, which is the selection of the most suitable alternative. Level 2 represents the assessment of the criteria (also referred as the attributes of the alternatives).

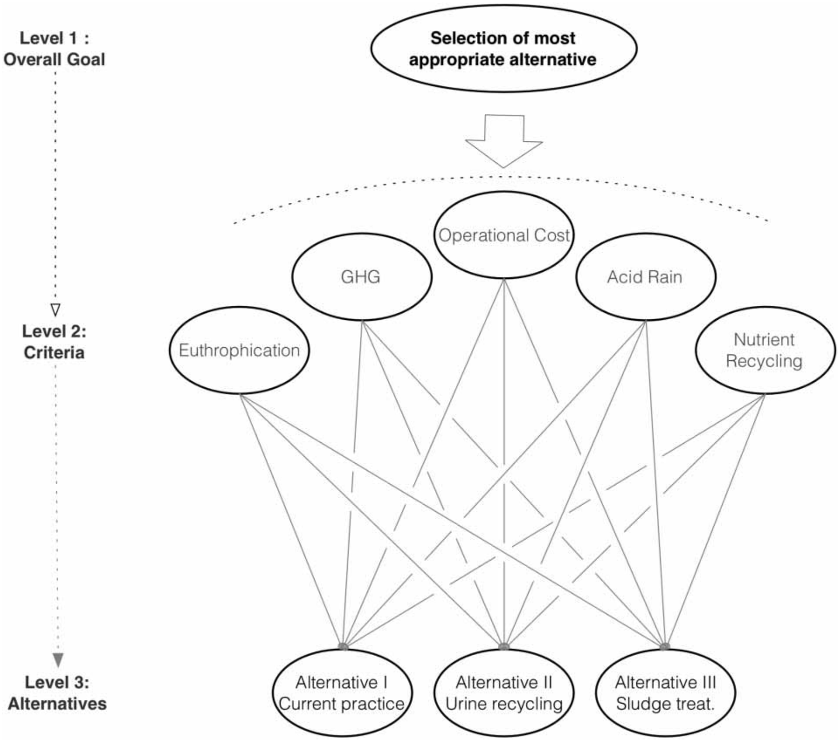

Figure 1 | Hierarchy map for the decision problem.

At level 3, the alternatives for the nutrient recycling scenarios are presented.

Life cycle inventory framework was used to characterize the nutrient recycling scenarios. LCA (ISO 2006) method has been applied for several years to conduct holistic environmental assessment of treatment options. Several authors have used LCA to estimate the environmental loads from wastewater and solid waste systems (Linderholm *et al*. 2012). Data about urine recycling, wastewater and sludge treatment were collected from scientific publications and reports relevant to the boundaries of the study (Figure 2). However, there may be some limitations due to the difficulty of comparing a technology in its pilot phase with a conventional end-of-pipe system. The functional unit has been defined as a the 'treatment of wastewater for one person equivalent per year (p.e./yr).

The boundaries for the first scenario comprises WWT based on mechanical and biological processes with phosphorus elimination, nitrification and denitrification while sludge management is based on co-incineration with household waste. An extended system boundary for the other two scenarios encompasses the effects on the environment due to the use of resources such as materials and energy, and the recycling of nutrients. It was assumed for the third scenario that sludge treatment is based on separate incineration in the BioCon process. The relative operational costs per person was estimated based on Schmid (2004) research about fees for wastewater collection, treatment and urine separation in Zurich. Likewise, Lundin *et al*. (2004) research about the cost of sludge treatment for nutrient recycling in Gothenburg was included in this study.

The information resulting from the inventory was arranged and summarized in relation to the evaluation criteria and expressed as impact factors for global warming, acidification and nutrient enrichment potential (Table 1). To make the alternatives comparable, values were converted into a 2.2 person-per-household unit (SFSO 2006) to allow comparison during the questionnaire survey.

APPLICATION OF AHP

Questionnaire procedure

A group of German-speaking residents was randomly selected on a for survey. The selection was based on the use of the Zurich telephone guide restricted to residents speaking German defined by postal codes ending in 8001,

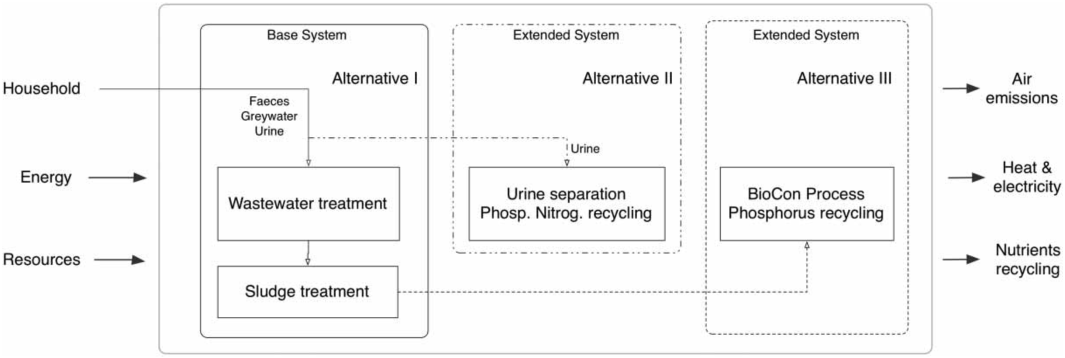

Figure 2 | System boundaries.

Table 1 | Summary of the attributes for the alternatives

Criteria	Unit	Alternatives: I (Current practice)	II (Urine recycling)	III (Sludge treatment)
Emissions of carbon dioxide and equivalents expressed as greenhouse gases (GHG)	K Mg-CO_2equiv/year	3.42	2.13	3.08
Sulfur oxide air emissions resulting from the burning of fossil fuel for the generation of energy contributing to acid rain	Mg SO_2/year	38.88	38.26	46.50
Excess of nutrients released into rivers and lakes as the result of wastewater treatment contributing to eutrophication	Mg NO_3^-/year	5.98	1.20	5.98
Phosphorus and nitrogen recycling by urine separation or sludge treatment	Mg/year	–	253 and 768 (phosphorus & nitrogen)	230 (phosphorus)
Cost associated with the operation of the alternatives	CHF/year	440	710	460

8002, 8003, 8004 and 8005 as recommended by researchers at the University of Zurich. The questionnaire was designed to have three phases designed to assess the preferences of the group in relation to the alternatives (Figure 3). The first phase explains to the respondent the context of the nutrient-recycling dilemma and the aim of the study, current WWT practice and a description of the urine-separation toilet and the BioCon process. The respondent is presented with a description of the evaluation criteria and alternatives while providing a summary of their attributes. At the beginning of each phase, respondents are introduced to the concept of pair-wise comparison based on the nine-point scale. In the second phase, the respondent begins to assess the alternatives within each criterion. The order of the pair-wise comparisons is defined by to the hierarchical map of the decision problem (Figure 1). Likewise, the third phase aims to prioritize the evaluation criteria according to the importance assigned by the respondent.

Results and discussion

The Expert Choice software was used to estimate the respondents' answers of the questionnaire based on the eigenvalue technique where the weights describing the importance of each evaluation criteria and alternatives are computed as shown on Tables 2 and 3.

Evaluation criteria

Table 2 shows the weights and ranking of the criteria. Respondents' prioritization differed across the surveyed group – in

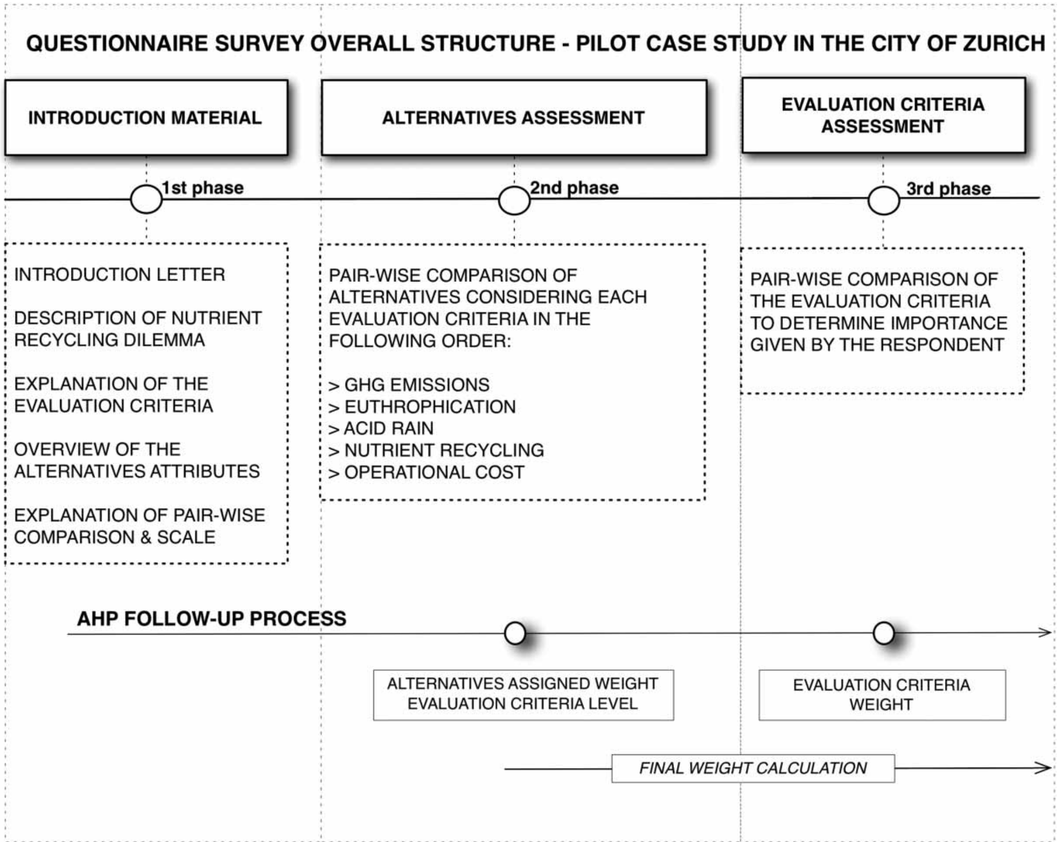

Figure 3 | Phases of the questionnaire survey.

some cases selected categories were ranked higher in comparison to others. For example, some respondents assigned a greater importance to GHGs and acid rain due to SO_2 emissions while others gave the cost a higher priority. When asked to weight the category for recycling of nutrients, more than 0.6 (60%) gave this attribute a lower priority while the remaining group assigned it a greater level of importance. In comparison, the importance attributed to eutrophication was

Table 2 | Weight of the criteria; values are ranked from 1 to 5, where 5 is the highest (R_i … R_n, refers to the respondent number)

	Residents weight distribution						
Criteria	**R_1**	**R_2**	**R_3**	**R_4**	**R_5**	**SUM**	**Total (equal importance)**
Emissions of carbon dioxide and equivalents expressed as greenhouse gases (GHG)	0.201 (3)	0.158 (3)	0.257 (5)	0.262 (5)	0.103 (3)	0.981	0.196 (3)
Excess of nutrients released into rivers and lakes as the result of wastewater treatment contributing to eutrophication	0.051 (1)	0.391 (5)	0.161 (1)	0.182 (3)	0.066 (1)	0.851	0.170 (2)
Phosphorus and nitrogen recycling by urine separation or sludge treatment	0.088 (2)	0.192 (4)	0.194 (4)	0.146 (2)	0.207 (4)	0.828	0.166 (1)
Sulfur oxide air emissions resulting from the burning of fossil fuel for the generation of energy contributing to acid rain	0.370 (5)	0.125 (2)	0.194 (4)	0.262 (5)	0.099 (2)	1.050	0.210 (4)
Cost associated with the operation of the three alternatives presented	0.289 (4)	0.134 (1)	0.194 (4)	0.146 (2)	0.525 (5)	1.289	0.258 (5)
Total	1.000	1.000	1.000	1.000	1.000	–	1.000

Table 3 | Ranking of the alternatives (values ranked from 1 to 3, where 3 is the highest)

	Residents weight distribution							
	R_1	R_2	R_3	R_4	R_5	No. of times the alternative is ranked highest	No. of times the alternative is ranked lowest	Total (equal importance)
Alternative I 'Business as usual'	0.065 (1)	0.109 (1)	0.072 (1)	0.125 (1)	0.814 (3)	1	4	0.237(2)
Alternative II 'Nutrient recycling by urine separation'	0.574 (3)	0.547 (3)	0.649 (3)	0.750 (3)	0.114 (2)	4	0	0.527(3)
Alternative III 'Phosphorus recycling from sludge by the BioCon process'	0.361 (2)	0.345 (2)	0.279 (2)	0.125 (1)	0.072 (1)	0	2	0.236(1)
Total	1.000	1.000	1.000	1.000	1.000			1.000

below expectation, with three out of five respondents giving a lower weight to this category although the eutrophication of lakes is still considered a matter of concern in Switzerland.

On the other hand, the respondent (R3) (Table 2) ranking of the categories differed from the rest of the group with 0.6 of the preferences equally distributed (0.194) across the following categories: recycling of nutrients, contribution to acid rain by emissions of SO_2 and cost. In summary, threats to the global and local environment as well as the cost of operation proved to be main focus of their interest.

Alternatives

Table 3 shows the weights and ranking of the alternatives. Respondents were asked to compare the proposed scenarios by pair-wise comparison based on the nine-point weighting scale from the perspective of each evaluation criterion. In total, the sum of the values for the alternatives accounts for 1 (100%). The consistency ratios were calculated as each resident was required to do 25 pair-wise comparisons, leading to the possibility of making inconsistent evaluations. For each of the respondents, the estimated consistency ratios reached a value of about 10%.

Table 3 shows the number of times an alternative was ranked first by the group of respondents. The second alternative was chosen most often, about 80% of the preferences. Phosphorus recycling from sludge was counted as the second best alternative with about 60% of the respondents while alternative I was the least popular. Although the results may show clearly which scenario was predominant, an analysis of the respondents' individual weight distribution may provide a better insight. For example, respondent (R4) rated alternatives I and III as having the same level of importance, while respondent (R5)'s ranking was different from the rest of the group – a much higher priority was given to current practice (a value of 0.814). As shown in Tables 2 and 3, respondent (R5)'s selection of alternative I was mostly driven by (i) the higher importance given to cost evaluation criterion (with a value of 0.525) and (ii) the lower operational cost of this alternative in comparison to the others.

At the end of Table 3, the total weights are shown, assuming that each of the respondents made an equal contribution to the decision-making. In other words, it was decided to distribute the overall decision weight equally across the group, to give an individual weighting factor of 0.2 to be applied to the respondents' final preferences. About 52% of the weight was assigned to alternative II while current practice was slightly preferred to alternative III. The aggregation of these values reveals how the weight assigned to the first alternative by the respondent (R5) influenced the overall ranking. As such, an analysis of each particular case can provide a better understanding of preference and ranking distribution.

Conclusions

This paper presents AHP as a tool for eliciting the preferences of a group of residents towards competing alternatives for nutrient recycling from wastewater. The results are not intended to provide a representative example of residents' preferences on this subject but instead to focus on the application of AHP when dealing with distinct alternatives for quantitative and qualitative criteria.

Respondents in this study preferred the recycling of nutrients by domestic urine separation despite the inconvenience and the need to change their habits. This choice was mostly driven by the reduction of emissions contributing to GHG and acid rain rather than the concept of nutrient recycling. Likewise, the initial investment cost associated with the purchase of the urine-separation toilet was not a deterrent. However, a different outcome could be expected if we consider that (i) tenants who had not used a urine-separation toilet before are always positive about them and (ii) if the decision problem was limited to urine-separation toilets against current practice, since residents might not be willing to assume the extra final cost or inconvenience.

Regarding CR, respondents showed a certain degree of consistency around 10% but decision problems involving iterative pair-wise comparisons might increase this value. In such cases, structuring a decision problem with fewer criteria or using an alternative comparison and weighting scheme such as the priority scale (De Feo & De Gisi 2010) can reduce the number of comparisons and inconsistent valuations. The success of AHP implementation on a larger scale will also depend on the number of alternatives to compare, the distinctiveness across the criteria and the ability of the respondents to provide credible answers to the questions posed. In circumstances where conflicting scenarios and several stakeholder groups are involved, AHP can be applied in conjunction with group aggregation (Subramanian & Ramanathan 2012).

The application of the study on a larger scale would require additional measures for obtaining representative data from the population. Considering the characteristics of pair-wise comparison, data collection by questionnaire can be implemented either by face-to-face interviews or mail survey depending on the access to resources and the size of the target group. According to Lienert *et al.* (2003), archiving a higher response rate will require the use of personalized correspondence, increasing the number of contacts with the respondent, the inclusion of financial incentives, the use of a reminder postcard and a second questionnaire to all non-respondents.

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