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Multi-criteria framework for the selection of urban sanitation systems

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Abstract
During the last decades a wide variety of urban sanitation systems has been developed and improved, all with specific advantages or drawbacks over the conventional system. Because most systems are relatively new, specific information on the various aspects of the performance of these systems lacks. The development of novel technologies and sanitation approaches does not only lead to a higher variety in system choices. It also affects existing decision support methodologies, because arguments that were not put forward earlier for conventional systems are strong drivers to develop new sanitation approaches. The core objective of this research was therefore to develop a multi criteria framework to assess and benchmark the technical performance of new and existing sanitation technologies with a maximal level of transparency and traceability, but with a results presentation that is simple and understandable for the stakeholders.

Keywords: Multi-criteria assessment, urban sanitation, performance, sustainability

1 Introduction

Nowadays, there is a large variety of urban sanitation systems with multiple options all over the process train: collection, transport, treatment and disposal; varying from low to high technology and from centralized to decentralized systems. Because most systems are relatively new, specific information on the various aspects of the performance of these systems lacks, generating a controversy about the sustainability of urban water systems. This lack of knowledge about novel systems is a barrier for scaling up the implementation of ecological sanitation. According to Saywell (2007), "The conventional approach to sanitation planning creates an artificial barrier between technical decision making and institutional analysis in its broadest sense. This result in technically "appropriate" systems which don't work, or which don't achieve the objectives that some people value highly, crucial to

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changing this paradigm is to acknowledge in a more effective way that many of the "objectives" of urban sanitation systems may actually be in conflict; a real discussion about the payoffs is needed." Also Starkl et al. (2004) describes "the limits of the wide-ranging problem, one group that emphasizes in environmental benefits (nutrient recycling, keeping the water cycle clean), whereas the opponents stress on social and cultural criteria (arguing that such concepts are not compatible with the peoples attitudes to wastewater and cannot be integrated into the existing system), environmental risks of the system and other drawbacks." These facts confirm the need of sound evidence regarding system performance to overcome this discussion and achieve optimal implementation of sanitation infrastructure.

However, development of novel technologies and sanitation approaches does not only lead to a higher variety in system choices. It also requires modification in decision making methodologies and assessment. New technologies' characteristics do not fit in traditional assessment frameworks, because some arguments that were not put forward earlier for conventional systems are now strong drivers to develop new sanitation approaches (e.g. nutrient recycling), and others parameters need to be re-defined (e.g. net load discharges instead removal percentages) in order to make fair comparisons.
In addition, decision making dynamics are complex as well, Starkl et al. (2004) explains how different stakeholders have different preferences regarding criteria objectives in sanitation in Austria, and similar situations can occur all over the world. Also sanitation objectives became more complex aiming to achieve sustainable standards. The challenge of decision making is to link local needs with those systems' characteristics. As it was stated by Van der Ryn and Calthorpe (1986) as quoted by Mouritz and Newman (1997), "Sustainability implies different solutions for different places. Like the word appropriate, sustainability is qualified by its context."

Solving this problem requires multi-objective optimization and consequently, multi-criteria decision analysis has become an indispensable tool for dealing with complex decision problems in different fields which involve a number of conflicting objectives and a variety of stakeholders. According to Mysiak (2005), "Multi-criteria decision analysis (MCA), constitutes both a framework for structuring decision problems which encompass multiple decision criteria and alternatives, and a set of methods to generate or elicit and aggregate preferences regarding the performance of these alternatives. Consequently, MCA represents added value to both the decision process, first by helping the decision maker learn about the decision problem and explore the alternatives available and the decision outcome and second by helping elicit value judgments about trade-offs between conflicting objectives." Solving multi-criteria problems not only means to find an optimum solution, but also to facilitate understanding of and discussions on the different alternatives towards finding the most suitable solution during a process, in which stakeholders with diverse background, interests and points of view participate.

Several efforts have been done lately to define multi-criteria methodologies able to aid in the selection of urban water systems and some authors have assessed sustainability of wastewater treatment systems using different tools such exergy analysis, economic analysis and life cycle assessment (LCA), (Muga, 2007). Some studies have been carried out with these methodologies, but they are not comparable because they differ in objectives and boundaries definitions. Existing multi-criteria methodologies offer a broad range of methods in order to achieve a unique score per alternative, but weighting and aggregation among different criteria usually leads to sub estimation, overestimation or bias.

2 Objectives

The main objective of the research in this article was to define a set of indicators that clearly describes performance of urban sanitation systems, and a methodology to evaluate this multidimensional information. The framework should facilitate comparison among technologies and provide valuable and understandable information for discussion during decision making processes. One of the requirements for the framework is therefore transparency and traceability; it means that the process to transform raw data into indicators and the final calculation of the indices must be clear and understandable for the different stakeholders. Also information should be easily retrieved to know why one technology is better than other in a specific criterion.
The aim of the framework is technological assessment; the functional unit is the process train of urban sanitation system: collection, transport, treatment and disposal of domestic wastewater. The starting point of the system is the drinking water supply at household level, followed by the different discharges of wastewater, urine and feces, the collection at source (if applicable), the treatment processes, and the final discharges into the ecosystem. The purification treatment required for piped water, and rainwater systems are not included.

3 Methodology

The development of the framework was done in three stages (see figure 1), the first step is the review the objectives of sanitation systems, then identify the main principles related to the technical performance and define a set of criteria to evaluate each principle; the second step was the review of existing decision support methodologies for selection of water and wastewater technologies and finally, in the third stage, different methodologies found in the existing frameworks were tested for the development of the framework.

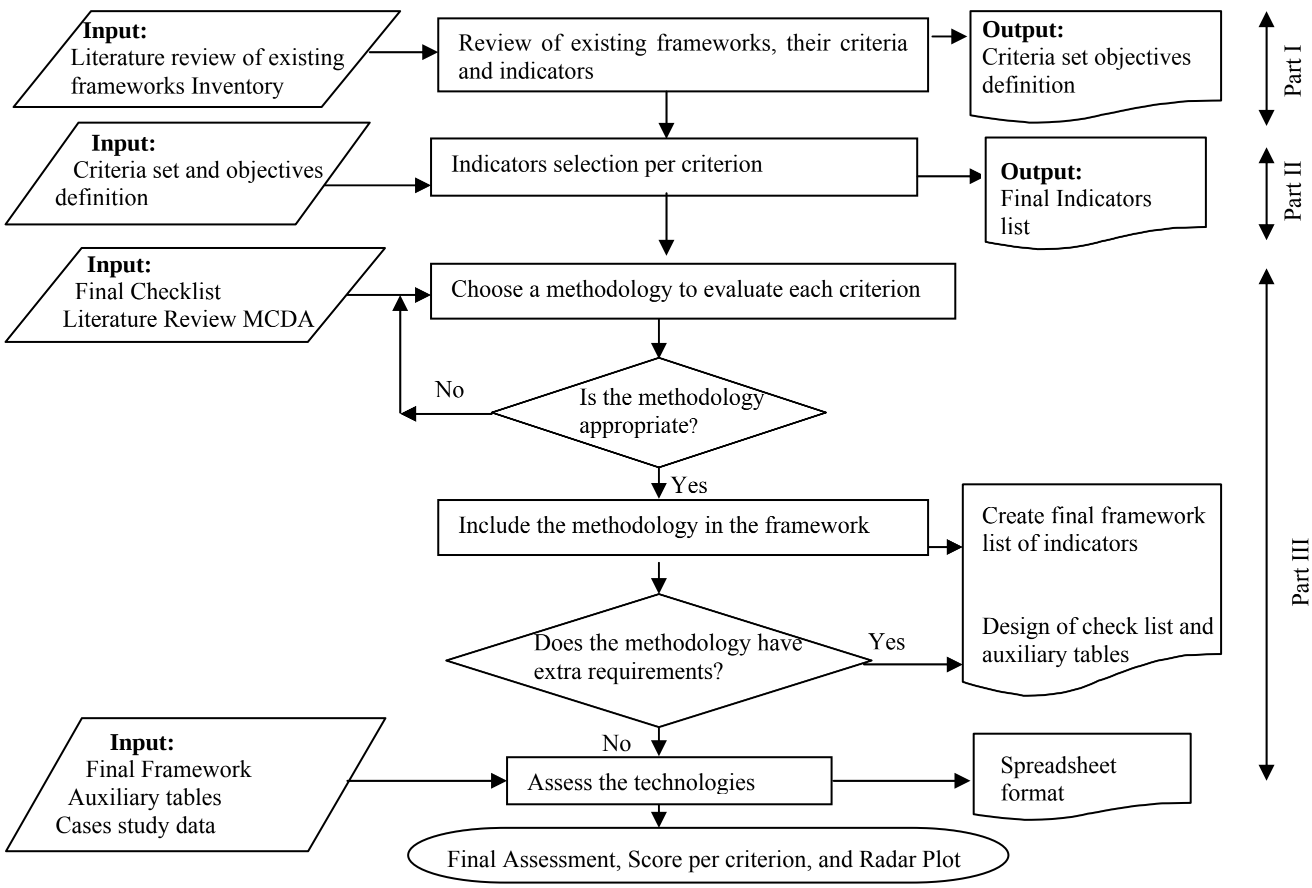

Figure 1: Detailed methodology scheme

4 Results

The framework has four main components, objectives are the basic aims of the framework; principles are essential areas covered by the framework; criteria are a set of variables that describe principles upon which a decision or judgment can be based; indicators are measurable states which allow the assessment of whether or not associated criteria's aims are being met.

The first step is the review of the objectives of sanitation systems, and then the identification of the main principles related to the technical performance and definition of a set of criteria to evaluate each principle. The main objectives for sanitations systems can be summarized as (Pierini, 2005): moving towards a nontoxic environment, improving health and hygiene, saving human resources, conserving natural resources, saving financial resources; other objectives are to have a high degree of functional robustness and flexibility, be adapted to local conditions, easy to understand and thus encourage responsible behavior by the users. Within the first stage, existing methodologies and frameworks, UWP, SWARD, ATV-DVWK, DMF Austria and DMF Romania, (Starkl et al, 2004),were taken as reference point for criteria definition, the most relevant criteria were selected and respective objectives were defined, see table 1.

Table 1: Objectives per criterion

Principle	Criterion	Objective
Public Health	Public Health Risk	Evaluate the public health risk related to a given technology due to the contact of inhabitants with feces, urine, raw wastewater, treated wastewater or sludge.
Environment	Resources use	Evaluate to what extent a given technology makes an efficient use of the resources (water, energy, nutrients and chemicals).
	Impact on ecosystem	Evaluate to what extent a given technology impacts on the ecosystem (water and soil discharges).
Economy	Total costs	Evaluate the total cost of the system. (Capital and operational costs, including potential benefits).
Technology	System robustness	Evaluate system robustness, based on failure records, and possible user abuse.
	System invisibility	Evaluate to what extent a given technology is invisible for the users and the community.
	Contextual Independence	Evaluate to what extent a given technology is independent from external conditions.

The second step was the review of existing decision support methodologies for selection of water and wastewater technologies. There is an extensive list of indicators used for the urban water assessment Balkema (2003), refers to list of indicators developed by Azar,1996; Bengtsson, 1997; Butler, 1997; Emmerson, 1995; ETC, 1996; Finnson, 1996; Helström, 2000: Icke, 1997; Jacobs, 1996; Lundin, 1999; Mels et al., 1999; and Pierini (2005), refers to Otterpohl et al., 1997; Ødegaard, 1995; Kärrman, 1998; Balkema, 2002; Bracken, 2003; SWARD, 2004; DIM SUM, 2005. Based on this review and on relevance, data availability, measurability and understandability, a set of 22 indicators that describe system's performance were selected, see table 2. The indicators are expressed per person per year, except total cost that is calculated per household per year.

Table 2: List of Selected indicators and their respective units

Indicator		units	Description
Criterion 1: Public Health			
1	Risk of contamination of sources of drinking water	High risk = 3, Medium risk= 2, Low risk =1	Identification of hazardous substances, pathways and exposure, to estimate risk to public health - Qualitative risk assessment
2	Risk of skin contact with (black water or brown water)		
3	Risk of skin contact with (grey water, rain water, or yellow water)		
4	Risk of accidental ingestion on swimming waters where treated wastewater is discharged		
Criterion 2: Impact ecosystem			
5	Potential Eutrophication	kg PO_4^3 - eq./ pe. Y	Potential eutrophication produced by discharges of COD, N and P per person per year.
6	Potential Ecotoxicity	kg (1,4 - DCB eq) / pe . y	Potential ecotoxicity produced by heavy metals discharged, per person per year.
Criterion 3: Resources use			
7	Net energy consumption = Energy consumption - Energy recovered	Kwh/pe.y	Energy consumption minus energy recovered of the system per Kwh per person per year
8	Net water consumption	m³ /pe.y	Drinking water consumption-m³ per person per year
9	Nutrients recovered	kg /pe.y	Nutrients recovered in kg per person per year
10	Use of chemicals	kg /pe.y	Use of chemicals in kilograms per person per year
Criterion 4: System Robustness			
11	Failure record	h /pe . year	Total number of hours of system breakdown per year due to failures
12	Shock load resistance	h /pe . year	Estimate number of hours of potential system breakdown per year due to user abuse
13	Operation & Maintenance	h / pe year	Total number of hours of maintenance per year
Criterion 5: System Invisibility			
14	space per household	m³/pe	Indoor-outdoor space required in m³/pe
15	area per household	m²/pe	area required by the system in m²/pe
16	Nuisance	High =3, Medium=2, Low =1	Level of nuisance produced by noise and smell
Criterion 6: Annual Cost			
17	Annual cost	Euro/hh y	Total cost (capital and maintenance) of the system per household per year
Criterion 7: Contextual independence			
	Is the technology sensitive to the following aspects:		
18	Climate	High Sensitivity = 1 Moderate sensitivity=2 Zero sensitivity = 3	Assessment of the influence of external factors like the environment, surroundings, circumstances on the system performance.
19	Socio-economic conditions		
20	Ecosystem conditions		
21	Geological conditions		
22	Other utilities		

Finally, in the third stage, different methodologies found in the existing frameworks were tested for the development of the framework. After that, it was concluded that the most feasible alternative is to calculate "potential" effects. This occurs in the assessment of health risk, and impact on the environment, where multiple variable and several uncertainties are involved. It was also found, that previous assessments based on Life Cycle Assessment showed that system boundaries influence significantly the results; also in order to make an appropriate "cradle to grave" assessment, data requirements are high. The methodologies based on cost shows difficulties to make some of the equivalences, it is based on costs assumptions lacking sometimes of transparency, and the resulting "Total Cost" doesn't offer suitable information for discussion during decision making process.

Outranking methods are as good as the suppositions made, those methods require weight definitions, and only experts can do that based on their knowledge and experience.

The methodology should suit data availability, to avoid misleading results. Sophisticate software capable to make complex analysis have been developed, however the quality of the results depends on the quality of the input data. Complex methods have high data requirements and considerable time allocation, while simple methods are less sensitive to uncertainties and a less precise results are achieve in short time. There is no consensus about the influence of the methodology in the results. But what it is clear is that different methods apply different assumptions, weights or normalizations, users should be aware of them to achieve the expected results.

Most of the multiple criteria methodologies aim to achieve a final score per alternative to identify the best performer; but is it feasible, sufficient and reliable to come up with a unique performance score per technology? Within this approach, for the technology assessment the different criteria should remain separate for the insight it provided when interpreting, also to avoid comparison and weighting among different criteria; that usually leads to sub estimation, overestimation or bias. This approach is helpful for matching local needs with strongest score per criterion to find the most suitable option. Also it promotes the transparency of the assessment and increase stakeholders' trust. The mean of the multi-criteria framework is to facilitate discussion during decision making process. In that sense, transparency of the methodologies is required, in order to be trusted for the different stakeholders. For that reason, it was chosen the criterion level as the highest aggregation level possible.

For the criteria assessment several methodologies were tested, finally a different approach per criterion was selected, a brief description per criterion:

Public Health: Protection of public health is the most important sanitation objective and it is closely linked to hygiene. The entire sanitary system should minimize risks and safeguard public health. This covers the use of the sanitary installation, collection, transport, treatment and destination of the treated products. This criterion evaluates the public health risk related to a given technology due to the contact of inhabitants with faeces, urine, raw wastewater, treated wastewater or sludge. One of the most common methodologies to measure this is the quantitative microbial risk assessment (QMRA), this is a sensitive tool that can estimate risks that would be difficult to measure. QMRA four stages are hazard identification, exposure assessment, dose-response analysis and risk characterization. Within this framework the two first stages, hazard identification and exposure assessment, are assessed and a risk estimation is carried out based on them, the dose-response analysis is still under development because it requires to have detailed data of the population.

Impact on the Ecosystem: For environmental assessment many methodologies have been developed, the most extended used is the Life Cycle Assessment. With this methodology, "The environmental impacts are often described as "potential impacts", because they are not specified in time and space and are related to an (often) arbitrarily defined functional unit", (Guinée, 2001). To evaluate to what extent a given technology impacts on the ecosystem, it was done based on the approach of Life Cycle Assessment (LCA) to measure the potential impact of the discharges, the two considered aspects were potential eutrophication and potential ecotoxicity.

Resources Use: The main purpose of the wastewater systems is to collect sewage and to reduce emissions and bacteria to acceptable levels. Moreover, sanitation systems should also optimize the use of resources. The main resource related with sanitation is water, with a high pressure in its conservation since water related problems have been increasing worldwide lately. But also energy consumption, production of fertilizers and use of chemicals are relevant. Although, pressure is increasing in resource conservation, there are no standards or limits that control resource use for sanitation. Methodologies like LCA measure the resource use with the parameter: "abiotic depletion". However, Guinée (2001) concluded that "there is as yet no consensus about what constitutes the best category indicator for "abiotic depletion". In response to that other approaches have been developed, e. g. based on exergy content of the resources, but still there are no clear methodologies for their assessment. Within the framework, to evaluate to what extent a given technology makes an efficient use of the resources (water, energy, nutrients and chemicals) a check list of resources involved in sanitation is included, and normalization per indicator is done based on the maximum and minimum values, from literature review, of the systems under study.

System Robustness: A general definition of system robustness can be expressed as ability of a system, to continue to function despite the existence of faults in its component subsystems or parts. Balkema (2003) in her work defines robustness as the ability to cope with fluctuations in the influent and reliability as the sensitivity of the system to malfunctioning of equipment and instrumentation. For the purpose of this framework, the robustness evaluation is done based on maintenance required, failure records, and possible user abuse. A failure record scheme is developed in order to characterize failures and also a user abuse questioner was developed to determine shock load resistance. Normalization per indicator is done based on the maximum and minimum values of the systems under study based on data from literature review.

Invisibility: One parameter that was not assessed in the past with the conventional system is the invisibility. This criterion become relevant in decision making due to new technologies can require the installation of some visible equipment in the household or in the neighborhood. The successful implementation of the sanitation system also depends on the acceptance from the users, from different studies has been found that users prefer invisible systems; that is one of the reason of the attachment to the old one. For the scope of this framework, invisibility will be assessed by requirements of space and area and also the presence of nuisances: noise and odor. A check list of the area and space required was done and assessment of the user perception for nuisances.

Total Cost: The importance of the cost assessment is to verify if the system is affordable and also to check with local social-economic conditions if the community is willing to invest in the selected technology. Decision makers should be aware that costs can vary a lot from country to country, not only technical device's costs but also labor cost; then direct comparison is not recommended. Always should be compared with local salaries and currencies. In fact, because of their size, small communities do not benefit from the economies of scale possible with the construction of wastewater management facilities for larger communities. Also each project has different characteristics, and also they incur different expenses, and therefore cost estimation has to be adapted for each case. The total cost of the system is calculated by estimating the annual cost, taking into account construction investment and, operation and maintenance costs per household per year.

Contextual Independence: For an adequate technical assessment, not only it is required to have a performance score but also to identify how this performance is affected by the context. The contextual independence criterion aims to assess the influence of external factors like the environment, surroundings and circumstances on the system performance. The contextual independence is a constant value per technology and reflects its versatility. A high score in contextual independence means that this technology fits in different environments and local conditions; meanwhile, low score means that the technology can be used just under specific external conditions. The relevance of this criterion lies on the requirement of choosing sanitation technologies according to local context. The aspects considered are climate, socio-economic, geological and ecosystem conditions, and dependence of other systems. Factors that may influence system performance are numerous and widely varied in nature, for instance social acceptance, habits or cultural believes, but they are not including in the scope of the framework. Also events like earthquakes or terrorist attacks can affect systems' performance but the uncertainty to predict their occurrence and impact makes not possible to assess them in this framework.

Communication is also a key factor, for that reason it is important to keep in mind the relevance of how to show the results in order to provide and added value during the discussions in the decision making process. To facilitate comparison those scores are normalized in a scale from 0 to 100; low and high performance respectively a detailed description of the formulas per case is included in the annex. An example of the system performance benchmark is shown in the radar plot in which a comparison is made of conventional sewerage and centralized wastewater treatment facilities against with three cases with urine separation in Sweden and one in the Netherlands, see figure 2. During the testing phase, it was necessary to make some assumptions based on literature review to fill out some gaps of information. The main data gaps founded during testing the framework were related to discharges into the environment, and resources use. With this graph is possible to compare the performance of each system regarding each criteria, and it is also possible to identify the trade-offs of each system. As it was expected, none of the technologies can be chosen as the "best" all of them have different levels of performance in different aspects.

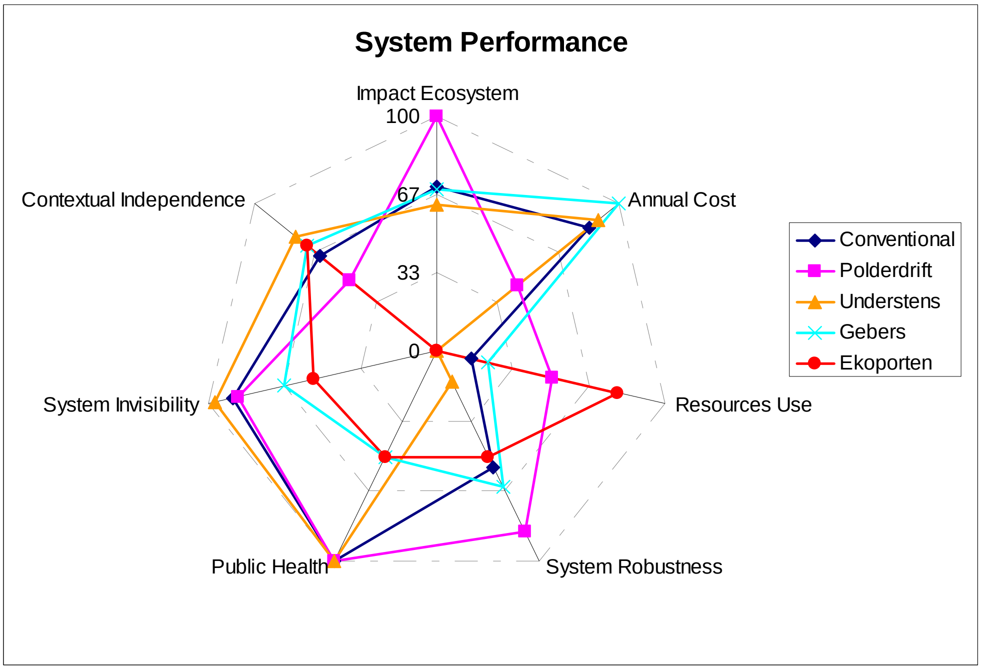

Figure 2: Example of the system performance benchmark: comparison of the conventional wastewater management system with 3 cases with urine separation in Sweden and 1 in the Netherlands

5 Discussion

Developing a framework always implies a trade-off. Oman (2004) highlights the dilemma between showing the complexity of a problem and its simplification in order to make it understandable for all stakeholders involved in decision processes. "Either the process remains on a highly abstract level far away from the real problem, or it reduces the complexity too strongly and thereby looses too much information, so that the results do not adequately reflect the real nature of the decision problem anymore”. The requirements of simplicity, comparability, interpretability may result in over-aggregation, over-simplification of complex relationships, and consequently misleading or even false representation, (Moeffaert, 2003). It is clear that the framework is only a multi-criteria aid, to manage data, facilitate discussion and visualize in a simple mode the different aspects under study and it does not find the “optimal technology”.

Avoiding aggregation of criteria and representing results in a radar plot is satisfactorily for communication and discussion requirements. The figure 2 shows that all the technologies have strong performance in some aspects; the challenge for urban planners and decision makers is to match local needs with those strong parameters. Data is the most important part of the assessment, and their quality and relevance affect the whole decision making process. For that reason data acquisition is a fundamental step in the improvement of sanitation assessment technologies.

Further development should be carried out in the analysis of the “contextual independence criteria”. Sanitation needs and possibilities are linked closely with local conditions, and evaluation of criteria, for instance sources use and cost can be linked with local factors, for instance “resource pressure” or “affordability” respectively. Also it is required to link system performance with user perception in order to achieve a complete overview.

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Annex: Aggregation and Normalization Procedure

	Indicator	units	Normalization and aggregation
Criterion 1: Public Health			
1	Risk of contamination of sources of drinking water	High risk = 3, Medium risk= 2, Low risk =1	**Aggregation:** Find minimum value **Target:** 1 **Normalization:** If d= 1 , then d_{score} 100 If d= 2 , then d_{score} 50 If d= 3 , then d_{score} 0
2	Risk of skin contact with (black water or brown water)		
3	Risk of skin contact with (grey water, rain water, or yellow water)		
4	Risk of accidental ingestion on swimming waters where treated wastewater is discharged		
Criterion 2: Impact ecosystem			
5	Potential Eutrophication	kg PO_4^{3} - eq./ pe. Y	**Aggregation:** According to LCA (see equations 6.3 and 6.4) **Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
6	Potential Ecotoxicity	kg (1,4 - DCB eq) / pe.y	
Criterion 3: Resources use			
7	Net energy consumption = Energy consumption - Energy recovered	Kwh/pe.y	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
8	Net water consumption	m^3 /pe.y	
9	Nutrients recovered	kg /pe.y	**Target:** As high as possible **Normalization:** $d_{score} = (d - d_{min}) / (d_{max} - d_{min}) \times 100$
10	Use of chemicals	kg /pe.y	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
			Aggregation: Average
Criterion 4 : System Robustness			
11	Failure record	h /pe . year	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
12	Shock load resistance	h /pe . year	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
13	Operation & Maintenance	h / pe year	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
			Aggregation: Average
Criterion 5 : System Invisibility			
14	space per household	m^3/pe	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
15	area per household	m^2/pe	
16	Nuisance	High = 3, Medium = 2, Low =1	**Target:** 1 **Normalization:** If d= 1 , then d_{score} 100 If d= 2 , then d_{score} 50 If d= 3 , then d_{score} 0
			Aggregation: Average
Criterion 6 : Annual Cost			
17	Annual cost	Euro/hh y	**Target:** As low as possible **Normalization:** $d_{score} = \lvert [(d - d_{min}) / (d_{max} - d_{min})] -1 \rvert \times 100$
Criterion 7: Contextual independence			
	Is the technology sensitive to the following aspects:		
18	Climate	High Sensitivity = 1 Moderate sensitivity = 2 Zero sensitivity = 3	**Aggregation:** Average of minimums **Target:** 3 **Normalization:** $d_{score} = (d - d_{min}) \times 100 / (d_{max} - d_{min})$
19	Socio-economic conditions		
20	Ecosystem conditions		
21	Geological conditions		
22	Other utilities		