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Indicators for the sustainability assessment of wastewater treatment systems

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Abstract

Sustainability challenges us to reflect on wastewater treatment differently. Instead of focussing on end-of-pipe-treatment for emission prevention, attention shifts towards optimal resource utilisation, favouring the development of decentralised systems. But are these systems more sustainable than centralised wastewater treatment systems? What aspects determine sustainability? In an extensive literature review we give an overview of sustainability assessment methods and currently used indicators. Based on this we propose a general assessment methodology that builds on multi-objective optimisation and a complete set of sustainability indicators, yielding insight into the trade-offs made when selecting sustainable wastewater treatment systems. © 2002 Published by Elsevier Science Ltd.

Keywords: Multi-criteria assessment; Multi-objective optimisation; Sustainability indicators; Wastewater treatment

1. Introduction

Conventional wastewater solutions, including water-flush toilets, combined sewerage, and centralised treatment, did not lead to an integrated solution. The mixing of the different wastewater streams makes recovering of the different resources such as water, energy, and nutrients, difficult. In addition, dilution of wastewater streams containing pathogens and toxic compounds such as heavy metals and organic micropollutants makes treatment more complex and requires higher levels of resources such as energy, money, space, and expertise, while still posing pressure on the environment through emissions. Technology offers a wide range of alternative solutions, for instance storage of rainwater in the sewerage system, rainwater infiltration, usage of rainwater for toilet flushing, vacuum toilets, urine separation, anaerobic digestion, etc. These may be interesting constituents of more sustainable wastewater treatment systems. Though, probably the most important question today is whether it is possible to attain more sustainable urban water management through improving the existing centralised systems or whether it is necessary to switch to new decentralised systems.

Could one say that environmental problems have become the reverse salient [1] components of current large-scale systems such as conventional wastewater treatment systems? And that a technological break through can occur once the new decentralised approach is accepted as better than the centralised end-of-pipe treatment? Or is it that a mixture of decentralised and centralised treatment can combine the advantages of both systems? For instance, decentralised treatment for water reuse inside the household and centralised systems to transport wastewater outside the urban area for treatment that enables reuse of water and nutrients in agriculture.

The changing perspective, induced by the request for sustainability, triggers this process of change. However,

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[1] A key to understanding the behaviour of large scale technical systems is the property being reverse salient, which means that a part of a system falls behind in the development and therefore reduces the capability of the whole system. This can lead to closure of a system if it weakens its competitive position in relation to alternatives (Nielsen, 1999).

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before switching towards a more decentralised approach, insight is needed into the sustainability of different systems under different circumstances. Since the alternative systems have disadvantages as well, the trade-offs must be carefully considered. This paper describes the use of a multi-criteria assessment for the sustainability of municipal wastewater treatment systems. The methodology is based on the use of sustainability indicators in multi-objective optimisation for the selection of more sustainable solutions. The description of the sustainability indicators is preceded by an introduction into sustainability and sustainable technology.

2. Sustainability

The concept of sustainable development is based on the observation that economy, environment and well-being can no longer be separated. The definition of sustainable development is often quoted from the World Commission on Environment and Development (WCED, 1987): '*development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs*'. The fundamental principle behind this definition is to accept that all human individuals have equal rights, whether living today or in future. This sketches a concept rather than giving rigid rule that can be applied right away. Therefore, sustainability can and will be interpreted differently by different people, evoking the critique that the term sustainability could mean almost anything (Mitcham, 1995). However, the room left for interpretation proves to be valuable as ideas about sustainability are destined to be discussed over time and place, since different generations will have to deal with different problems, and different cultures and local circumstances will give different perspectives on these problems.

The multi-dimensional character of sustainability is in our view fundamental. We define three dimensions, namely economic, environmental, and social–cultural.

2.1. Economic

Economic sustainability implies paying for itself, with costs not exceeding benefits. Mainly focussing on increasing human well-being, through optimal allocation and distribution of scarce resources, to meet and satisfy human needs. This approach should, in principle, include all resources: also those associated with social and environmental values (e.g. in environmental economics). However, in practice most analyses include only the financial costs and benefits.

2.2. Environmental

The long-term viability of the natural environment should be maintained to support long-term development by supplying resources and taking up emissions. This should result in protection and efficient utilisation of environmental resources. Environmental sustainability refers to the ability of the functions of the environment to sustain the human ways of life. The latter mainly depends upon the ethical basis: to what extent should policies be anthropocentric and to what extent does nature have endogenous qualities. Although public opinion goes further, public policies mainly remain limited to so-called use-values, which can be incorporated in economic analysis relatively easily.

2.3. Social–cultural

Here the objective is to secure people's social–cultural and spiritual needs in an equitable way, with stability in human morality, relationships, and institutions. This dimension builds upon human relations, the need for people to interact, to develop themselves, and to organise their society.

Similar classification can be found in the literature; for instance, Barbier (1987 in Bergh & Straaten, 1994) suggests that sustainable development is an interaction between three systems biological, economical, and social, with the goal to optimise across these systems by taking into account the trade-offs. The difficulty to express and weigh these trade-offs suggests that the optimisation is a political process rather than a scientific one. This is in line with the vision of the Scientific Council for Governmental Policies (WRR, 1994). The basic philosophy of this council is that when implementing the concept of sustainability, one cannot ignore the uncertainties and the mutual dependencies between the environment and the society. The forthcoming risks for the environment and for the economy will have to be balanced.

3. Sustainable technology

In analysing the sustainability of technology, [2] the different dimensions should be taken into account. To avoid export of the problem over time or space, the solution should be based on a long and global view. Realising that the solution is embedded in a complex

[2] Note that sustainable technology is very similar to what used to be defined as appropriate technology, namely technology that is compatible with or readily adaptable to the natural, economic, technical, and social environment, and that offers a possibility for further development. Sustainability adds the long-term and global view.

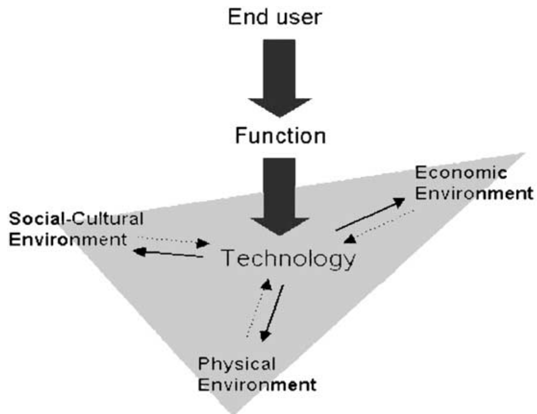

Fig. 1. Technology interacting with the environment.

entirety, one must aim at an integrated solution. Furthermore, a diversity of sustainable solutions must be available for different situations, preferably flexible as to adapt to future changes.

The interaction of the technology with the environment is schematically represented in Fig. 1. The demands of the end user are translated into functional criteria that must be fulfilled by the technology. In order to fulfil its function the technology draws from resources in its environment and affects this environment through contamination. Sustainable technology is technology that does not threaten the quantity and quality (including diversity) of the resources. As the quantity and quality of the resources and the resilience of the environment to emissions change over time and space, the most sustainable technological solution will change accordingly.

4. Assessing the sustainability of wastewater treatment systems

Some researchers try to capture sustainability in a single indicator, for instance through *exergy analysis* or *economic analysis*. However, other frequently used methodologies such as *life cycle assessment* (LCA) or *system analysis*, include multiple indicators. This section analyses the four above mentioned methodologies and their application in assessing the sustainability of the wastewater treatment.

4.1. Exergy analysis

The advantage of the exergy analysis is that the whole comparison is based on a single unambiguously quantifiable indicator, namely exergy. Consequently, no weighting of different indicators is involved. Whilst this property makes this analysis straightforward, it is at the same time its limiting factor, as insight is only gained into the efficiency of the processes but not into the different environmental impacts.

Hellström (1997, 1998) used exergy analysis to compare a centralised wastewater treatment plant with a decentralised system incorporating urine separation. He concluded that if nitrogen removal is considered important, the urine separation system becomes an interesting alternative. Furthermore, he found that considerable exergy flows are related to the handling of organic matter, thereby providing the possibility to retain exergy through the production of methane.

4.2. Economic analysis

The economic theory also suggests a single indicator approach. The central thought behind a sustainability assessment based on economic theory is that sustainability could easily be integrated into decision-making if expressed in terms of money. Tools such as: cost-benefit analysis, life cycle costing, and total cost assessment, all balance the expected costs and benefits, and are often the first step in a project. In theory, all kinds of costs and benefits can be included, however in practice these tools are mostly used as a one-dimensional techniques incorporating only financial costs and benefits. The obvious reason is that most social and environmental costs are difficult to quantify.

It is essential to realise that the translation of environmental and socio-cultural indicators into monetary values is a part of the decision-making process since it includes normative choices such as fixing values and weighting factors of different indicators. In a perfect market-economy, prices would reflect the value of things as perceived by society. However, no perfect market-economy exists and especially in the water sector prices are regulated by governmental organisations with taxes and subsidies. As such, an in-depth economic analysis of the sustainability of water supply and wastewater treatment could provide a valuable insight in the 'real' cost of water services.

4.3. Life cycle assessment

LCA is especially developed to assess different environmental impacts encountering during a product's lifetime. LCA is a structured methodology starting with defining the goal and scope of the study. Thereafter, a life cycle inventory of environmental aspects is made, based on mass and energy balances. Finally, these environmental aspects are categorised in environmental impact categories, such as depletion of resources, global warming potential, ozone depletion, acidification, ecotoxicity, desiccation, eutrophication, landscape degradation, etc. These categories can be normalised and weighted to come to a final decision whether to choose one technology or the other. The advantage of LCA is the well-described and standardised structure and the fact that it is applied to a wide range of products and services including the different parts of the urban water cycle (see Bengtsson, Lundin, & Molander, 1997; Dennison, Azapagic, Clift, & Colbourne, 1997; Emmerson, Morse, Lester, & Edge, 1995; Lundin, Molander, & Morrison, 1999; Neumayr, Dietrich, & Steinmüller, 1997; Ødegaard, 1995, and for LCA methodology ISO 14040, 1997, 1998, 2000, 2000).

However, LCA has some drawbacks, the assessment of a complete life cycle requires a large quantity of data. Aggregation of the data into the standardized environmental impact categories means loss of insight into the emissions that are of particular relevance to wastewater treatment. Furthermore, additional indicators are needed to measure sustainability as LCA limits itself to a restricted set of technical and environmental aspects.

The fact that LCA is mostly applied to the operational phase of wastewater treatment only, using adapted environmental categories, or additional categories such as reuse potential, social impact, etc, clearly reflects the mentioned disadvantages of LCA. If it is only the operational phase that is being assessed one should no longer speak of a LCA, but of a chain analysis or environmental impact analysis.

4.4. General system analysis

The general approach followed in a sustainability assessment of water services is a system analysis based on mass and energy balances providing an indication of material use, emissions, costs, and required land area. In principle, LCA is a type of system analysis, based on mass and energy balances and using indicators to assess the environmental impact (note that in LCA the indicators are called impact categories). LCA is usually applied to compare a few technologies on environmental impacts only, while the system analysis, as a rule, assesses more generally and abstractly by capturing the nature of the system in a mathematical description. In the case of urban water systems, the systems analysis focuses on the comparison of whole systems, often on a large number of systems, and uses a multi-dimensional set of sustainability indicators. Both looking at whole systems and using a multi-dimensional set of indicators, is essential to sustainability assessment. Looking at the whole system, one can find integrated solutions that may not be visible when looking at smaller parts of the system. Similarly, optimising in one dimension, for instance the environmental dimension, will improve this aspect of the system but may have unwanted effects in other dimensions, for instance the system may become unaffordable.

Like in LCA, the different system analysis methods are difficult to compare as the goals and scopes and assumptions differ with each study. System analyses that compare a relatively small number of systems have been performed for instance by Mels et al. (1999), Kärrman (2000), and Otterpohl, Grottker, and Lange (1997). Otterpohl et al. (1997) compare a centralised wastewater treatment system with a small-scale anaerobic digester for blackwater [3] and organic household wastes in combination with constructed wetlands for greywater [3] treatment. The conclusion of this research is that separate treatment of black- and greywater has the advantage of using less energy, materials, and reduces emissions to receiving waters.

The ranking of a large number of systems can also be done by comparing the systems two by two based on all selected indicators (for instance, is system A more affordable than system B?, is system A more affordable than system C? etc.). In this way, a relative ranking is obtained which may be captured in a decision matrix. These matrices are combined to reach a final decision. This approach is applied to wastewater treatment by Ellis and Tang (1990), Tang and Ellis (1994) and Tang, Wong, and Ellis (1997), using 20 parameters including technical, economic, environmental and social–cultural factors, to rank 46 wastewater treatments systems. Based on several case studies, they conclude that their method is useful for selecting wastewater treatment systems.

Ellis and Tang (1990), Tang and Ellis (1994) and Tang et al. (1997) compare different configurations of wastewater unit operations, however, if one models each unit operation separately, the number of configurations is dramatically enlarged. This is illustrated by the screening analysis of Chen and Beck (1997), which they used to classify and review over 120 unit operations for wastewater drainage and treatment. Chen and Beck constituted 50,000 candidate wastewater treatment systems. Comparison of the feasible candidate wastewater treatment systems led to the conclusion that today's common place technologies, including activated sludge, the trickling filter, etc., are rarely chosen as a constituent in a satisfactory wastewater treatment system. While systems including constructed wetlands, waste stabilisation ponds, and membranes emerge as essential to success. Chen and Beck use fixed processing units that do not provide decision makers with the freedom to adapt to local conditions or to incorporate different assumptions.

In contrast, a sanitation expert system such as SANEX (Loetscher, 1999) uses information on local circumstances to screen out inappropriate sanitation

[3] Greywater is defined as the dilute wastewater stream from households, mostly taken as total domestic wastewater minus the toilet wastewater. Wastewater from the toilet is referred to as blackwater, and is a mixture of yellowwater (urine) and brownwater (faeces).

systems. With SANEX the choice was made to provide a user-friendly interface rather than a transparent model providing insight into the equations and assumptions used.

The ORWARE model (Dalemo, 1999; Sonesson, 1998) is again a more theoretically oriented decision support tool. The static substance flow model is developed for evaluation of the environmental impact of waste management in different geographical areas, especially focussing on the return of nutrients to arable land. The 43 indicators included are all related to chemical compounds, such as BOD, metals, nutrients, and solids.

4.5. Different assessment tools

In general it is possible to conclude that all of the above methodologies can lead to new insights when applied to the urban water system. Exergy analysis, economic analysis, and LCA provide specific insights into (energy) efficiency, 'real' costs, or environmental impacts, respectively. The system analysis is a more general approach and can, through the use of self-defined sustainability, include a wide range of aspects, for instance exergy, costs, environmental impacts, or even social–cultural aspects such as acceptance, convenience, etc. Different tools, including mass and energy balances, exergy analysis, cost-benefit analysis, and environmental impact assessment can be used to quantify the sustainability indicators. The methodology can be structured in three phases: (1) goal and scope definition, (2) inventory analysis, and (3) optimisation and results, similar to LCA. The last phase is essential for a sustainability assessment, as the assessment must integrate the different tools, weigh the different indicators, and look for trade-offs being made. The next paragraphs describe such a sustainability assessment in more detail.

5. Sustainability assessment using indicators

5.1. Goal and scope definition

In this phase of the assessment the system boundaries and sustainability indicators are defined. It is important to realise that in the definition of the goal and scope one can rule out sustainable solutions beforehand.

5.1.1. System boundaries

In general a sustainability assessment will not limit itself to a process but will rather be an integrated assessment over a whole chain of processes that provide a certain service. This wide view makes it possible to compare a large variety of integral solutions. For instance, comparison of large-scale and small-scale wastewater treatment systems requires inclusion of the household in order to enable separation of different wastewater streams, to apply different forms of sanitation, and to use and reuse different water sources.

5.1.2. Defining sustainability indicators

The definition of sustainability indicators is an important step, as the selection of sustainable solutions is based on these indicators. A sustainable solution means limited use and limited degradation of resources through harmful emissions, at the same time avoiding the export of the problem in time or space. As described in the Section 3, it is possible to distinguish three types of resources: economic, environmental and socio-cultural. Therefore, the same categorisation is used for the indicators including one additional category, namely the functional indicators (see Fig. 1). While the economic, environmental, and social–cultural indicators give insight into the efficiency of the solution, the functional indicators determine the effectiveness of the solution. This last group, the functional indicators, can therefore be seen as constraints, because it is no use applying a technology efficiently if in the perception of the end user this does not provide a satisfactory solution.

An overview of the different indicators used in literature is given in Table 1. Note that due to different goals and scopes, as well as different terminology, the different research results are not directly comparable. A more detailed description of the sustainability indicators for the different dimensions is given below.

5.1.2.1. Functional indicators. Functional indicators define the minimal technical requirements of the solution. For instance, for wastewater treatment this may be the minimal required effluent quality. Additional indicators may be adaptability (possibility to extend the system in capacity, or with additional treatment), durability (lifetime), robustness (ability to cope with fluctuations in the influent), maintenance required, and reliability (sensitivity of the system to malfunctioning of equipment and instrumentation).

5.1.2.2. Economic indicators. Economic indicators are often decisive when choosing a technology in a practical situation. Commonly used indicators are, of course, costs of investment, operation, and maintenance. Derived indicators are for instance affordability, cost effectiveness, and labour.

5.1.2.3. Environmental indicators. Although sets of sustainability indicators used in literature differ, there seems to be a consensus on the environmental indicators. In all the publications summarised in Table 1, optimal resource utilisation is used as an indicator, particularly addressing water, nutrients, and energy. In addition required land area, land fertility, and biodiversity are mentioned in several studies. Another group

Table 1
An overview of indicators used in the literature to compare wastewater treatment systems

	Az	Be[a]	Bu	D	Em[a]	E	F	H	I	J	L	M	N	O	Ø[a]
Economical indicators															
Costs				C		S	P	S		E		S			E
Labour								S							
Environmental indicators															
Accumulation	P								T						
Biodiversity/land fertility	P			100		S	P							P	
Dissication														Cn	
Export of problems in time and space										T	S				P
Extraction	P														
Integration in natural cycles						S								P	
Land area required/space				1				S				S			
Odour/noise/insects/visual															
Optimal resource utilisation/reuse	P					S	P		St	S			P	P	
Water			S	1000		S	P	S	St		S			Cn	
Nutrients		V	S			S	P	S	St		S			Cn	
Energy		V	S	100	V	S	P	S			S	S		Cn	V
Raw materials		V		10	V	S	P	S						Cn	
Pathogen removal/health			S	1000		S	P	S							
Pollution prevention			S			S	P						P	P	
Emissions															
BOD/COD		V		1000	V	S		S			S	S			V
Nutrients		V		100		S		S			S	S			V
Heavy metals				1000	V	S		S							
Others		V			V	S		S							
Sludge/waste production		V		1000	V	S					S	S			V
Use of chemicals		V		10		S					S	S			
Technical indicators															
Durability			S			S									
Ease of construction/low tech													P		
Endure shock loads/seasonal effects								S						Cn	
Flexibility/adaptability			S			S		S							
Maintenance														Cn	
Reliability/security						S	P								
Small scale/onsite/local solution			S							Te			P		
Social–cultural indicators															
Awareness/participation						S		S		S					
Competence/information requirements						S	P								
Cultural acceptance						S		S							
Institutional requirements						S	P								
Local development			S												
Responsibility							P								

Source: Az—Azar, Holmberg, and Lindgren (1996), Be—Bengtsson et al. (1997), Bu—Butler and Parkinson (1997), D—DTO (1994), Em—Emmerson et al. (1995), E—ETC (1996), F—Finnson and Peters (1996), H—Hellström, Jeppsson, and Kärrman (2000), I—Icke and Aalderink (1997), J—Jacobs, de Knegt, Koedood, and Karst (1996), L—Lundin et al. (1999), M—Mels et al. (1999), N—Niemczynowicz (1994), O—Otterpohl et al. (1997), Ø—Ødegaard (1995).

Note: The numbers in the table indicate the used weighting factors, the abbreviations refer to the terms used in the publications; C—costs, Cn—concerns, E—environmental efficiency, P—principles for sustainability, S—sustainability indicator/factor/criterion, St—steering variables, T—target, Te—technical paradigm, V—variables in the LCA input-output table.

[a] LCA study.

of environmental indicators is emission oriented, for instance the quality of effluent and sludge, combined sewer overflows, and gaseous emissions.

5.1.2.4. Social–cultural indicators. Both social and cultural indicators are hard to quantify and are therefore often not addressed. However, these indicators play an important role in the implementation of technology. This is especially the case, when the end-user is directly involved, like in water use, sanitation, and small-scale on-site treatment. Indicators in this category are for instance:

- *Institutional requirements:* Different wastewater treatment systems will require different regulations and control mechanisms. These requirements should fit in the existing institutional infrastructure of the country or region.
- *Acceptance:* In different cultures, people will have a different perception of waste and sanitation, resulting in different habits. New sanitation concepts, including different toilet systems, may encounter social–cultural difficulties in the implementation. For instance: the need to explain visitors how to use the separation toilet was one of the reasons to remove these toilets from the houses of an ecological village (Fittschen & Niemczynowicz, 1997).
- *Expertise:* The selected technological solution requires a certain level of expertise for installation and operation. If the expertise is not locally available it may be gained through import or training.
- *Stimulation of sustainable behaviour:* Sustainable behaviour can be stimulated by tailoring the technological design such that sustainable behaviour is the most convenient option. Other ways to stimulate sustainable behaviour are increasing the end-user's awareness, participation, and responsibility.

All these indicators can be quantified, either through measurements, cost calculations, or enquiries. However, in a rapid assessment many of these indicators may be estimated using averages, and indications of the influence of a technology on a certain indicator. For instance, a composting toilet may have a potential advantage for 'stimulation of sustainable behaviour' as no water is used and the end-user recycles the compost locally. However, a potential disadvantage may be 'acceptance' because the end-user may perceive sanitation without water unhygienic and may not be willing to use the compost in his/her garden. In this way, these indicators can be used as go or no go decision variables in optimisation. Meaning than one can set the optimisation procedure to only select technologies that have a potential advantage or to not select technologies with a certain potential disadvantage.

5.2. Inventory analysis

In the inventory analysis the sustainability indicators are quantified or indicated qualitatively. Depending on the defined indicators tools such as mass and energy balancing, cost-benefit analysis, risk analysis, and factor analysis are used.

5.3. Optimisation

It is essential to a sustainability assessment that the dimensions are not judged separately. The judgment should balance the different dimensions of sustainability. As such different tools are combined in an integrated assessment. This makes the selection of sustainable wastewater treatment systems a multi-objective optimisation problem. Different objectives can be:

- minimise costs
- minimise energy use
- minimise land area required
- minimise loss of nutrients
- minimise waste production
- maximise products; clean water, biogas, biomass, fertilisers, compost
- maximise the score of qualitative sustainability indicators such as social acceptance, institutional requirements, etc.

Some of the objectives are conflicting; after all it is not always possible to design a wastewater treatment that minimises cost, energy use and land area, while maximising performance. Therefore, one aims to find a set of Pareto-optimal solutions. These are solutions where one objective can be improved only at the expense of others, thus indicating the trade-offs between the different objectives. A standard technique to solve multi-objective problems is to minimise a positively weighted sum of the individual objectives. In sustainability assessment the objective function is therefore the weighted sum of the normalised sustainability indicators (see for instance Adjiman, Schweiger, & Floudas, 1998; Biegler, Grossmann, & Westerberg, 1997; Schweiger & Floudas, 1998).

Normalisation can be done by dividing each indicator by the difference of the maximum and minimum value, which maps all indicators into the range zero and one. Weighting is a political process and should incorporate the interests of all actors that are affected by the decision that is being taken. For researchers it is interesting to use different weighting factors to find trade-offs between the different indicators.

6. Conclusions

A suitable and often used methodology for sustainability assessment is a system analysis using a multidisciplinary set of sustainability indicators. Similar to LCA, the methodology can be structured into three phases: goal and scope definition, inventory analysis, and optimisation. In the first phase, goal and scope definition outline the research including system boundaries and sustainability indicators. To avoid ruling out sustainable solutions a priori, the system boundaries must be defined to include whole systems rather than system components and the sustainability indicators must reflect all dimensions of sustainability, including all functional, economic, environmental, and social–cultural aspects. Some of the indicators are hard to quantify, however, to assure the integrated and multi-dimensional character of the sustainability assessment it is better to include those indicators qualitatively rather than not at all. In the second phase of the analysis, the inventory analysis, the sustainability indicators are quantified through mass and energy balances, cost-benefit analysis, and actor analysis, or indicated qualitatively. In the third and last phase the most sustainable systems are selected through multi-objective optimisation using the normalised and weighted sustainability indicators as objective function. Literature analysis of LCA case studies reveals that this last phase, in LCA called the impact analysis, is often omitted due the subjective character of this step. Scientists like to avoid the more political process of normalisation and weighting, however, this step is essential to the sustainability assessment. The results of the assessment methods should be used in combination in order to obtain an accordingly balanced solution. It is the scientist, who reveals the decisive indicators, trade-offs, and sensitivity to weighting factors.

The literature of sustainability assessments of wastewater treatment systems lists the following indicators as decisive:

- Organic matter—methane recovery may be essential for sustainable wastewater treatment (Hellström, 1997, 1998, Neumayr et al., 1997, Otterpohl et al., 1997, Ødegaard, 1995), composting seems to be a promising option for sludge handling as well (Dennison et al., 1997).
- Nutrients—urine separation may be essential for sustainable sanitation (Bengtsson et al., 1997; Chen & Beck, 1997; Dalemo, 1999; Hellström, 1997, 1998; Kärrman, 2000; Sonesson, 1998).
- Costs—only few assessments do take costs of water use, and wastewater transport and treatment into account, for instance Chen and Beck (1997).
- Heavy metals—the ability to remove heavy metals is only named by Chen and Beck (1997).
- Land area—land area is named in several studies for instance by Chen and Beck (1997) and Hellström, 1997, 1998, there is however a trade-off with other indicators. Chen et al. for instance, mention land area as a decisive indicator to screen out technologies that lack promise. Nevertheless, they conclude that constructed wetlands and pond systems are among the technologies that emerge as essential to success.

Although several researchers name decisive indicators, none of them gives a clear analysis of the trade-offs made, as such there is still limited insight as to which systems are most sustainable in different situations.

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