41st WEDC International Conference, Egerton University, Nakuru, Kenya, 2018

TRANSFORMATION TOWARDS SUSTAINABLE
AND RESILIENT WASH SERVICES

Pre-selecting appropriate sanitation system options as an input into urban sanitation planning

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PAPER 2885

Structured decision making (SDM) frameworks such as CLUES and Sanitation21 support urban sanitation planning by prioritizing decision objectives, identifying decision options, quantifying consequences, clarifying trade-offs, and balancing for opposing stakeholder preferences. However, current research focusses on the selection of a preferred option, assuming that the options to choose from are already known. Given the growing number of sanitation technology and system configurations, as well as the multiple criteria that those should fulfil, providing a good set of decision options is far from trivial. In this paper we present an approach for the pre-selection of locally appropriate sanitation system options that: (1) is systematic and therefore transparent; (2) is based on stakeholder objectives, thus increasing ownership; (3) can deal with a large number of both conventional and novel options opening up the decision space; and (4) considers uncertainties related to novel technologies and the local conditions.

Introduction

The critical role of sanitation for development has been recognized as a human right and reaffirmed by the Sustainable Development Goals. Despite these efforts, the world has been falling short of achieving the Millennium Development Goal for sanitation while it has met the targets for drinking water. One reason for this is that the focus of most of the sanitation projects in the past has been on toilet provision without considering important aspects such as collection, treatment, or operation and maintenance. This has led to inappropriate technology choices and frequent failures (MONTGOMERY et al. 2009, STARKL et al. 2013). A sanitation system (*SanSys*) is defined as a set of technologies (*Techs*), which in combination manage wastewater flows from the point of generation to a final point of reuse or disposal (MAURER et al. 2012, TILLEY et al. 2014). A sustainable *SanSys* not only protects the human health and the environment, it is also technically, institutionally, and socio-culturally appropriate and financially viable (SUSANA 2008). Today it is recognized that conventional sewer-based *SanSys* cannot be the only solution to achieve universal sanitation. The definition of sustainable sanitation has led to the development of many novel *Techs* showing several advantages for expanding urban areas in developing countries. These include reduced water, space, and energy requirements, as well as increased opportunities for stakeholder participation, private sector involvement, and resource recovery (e.g. DRECHSEL et al. 2011, LARSEN 2011).

Identifying an appropriate and sustainable *SanSys* a complex decision-making problem given the large number of *Techs* and corresponding *SanSys* configurations, the multiple criteria, and often opposing stakeholder interests. The complexity is further increased by the significant uncertainties related to performance data of novel *Techs* and the rapidly changing local conditions in expanding urban areas. Structured decision making (SDM) can help in such complex situations. SDM is a collaborative and facilitated decision making framework combining multi-criteria decision analysis (MCDA) and environmental science. CLUES and Santiation21 are useful SDM frameworks for urban sanitation planning (LÜTHI et al. 2011, PARKINSON et al. 2014). But these frameworks focus on the selection of the best *SanSys* option, assuming that the *SanSys* decision options to choose from are already given. In practice, *SanSys* decision options are often randomly assembled, indicating a lack of transparency and a preference for conventional approaches which -may be inappropriate. A good set of *SanSys* decision options should be (i) limited (manageable by the SDM framework), (ii) locally appropriate (considering the socio-demographic, environmental, and physical conditions), and (iii) divers (including a broad and unbiased range of conventional and novel approaches).

In order to enhance transparency of urban sanitation planning, we have developed a systematic procedure for the pre-selection of locally appropriate *SanSys* options, which follows three steps: (1) the identification of locally appropriate *Techs* from all potential *Techs* using screening criteria and attributes (appropriateness assessment); (2) the generation of entire *SanSys*; and (3) the selection of a sub-set of locally appropriate *SanSys* that is limited and divers and can feed into the SDM process (Figure 1). The aim of this paper is to presents the procedure and to discuss lessons learnt from field testing in Nepal. The presented procedure limits itself to the technical aspects of the *SanSys* and does not consider financing or institutional options.

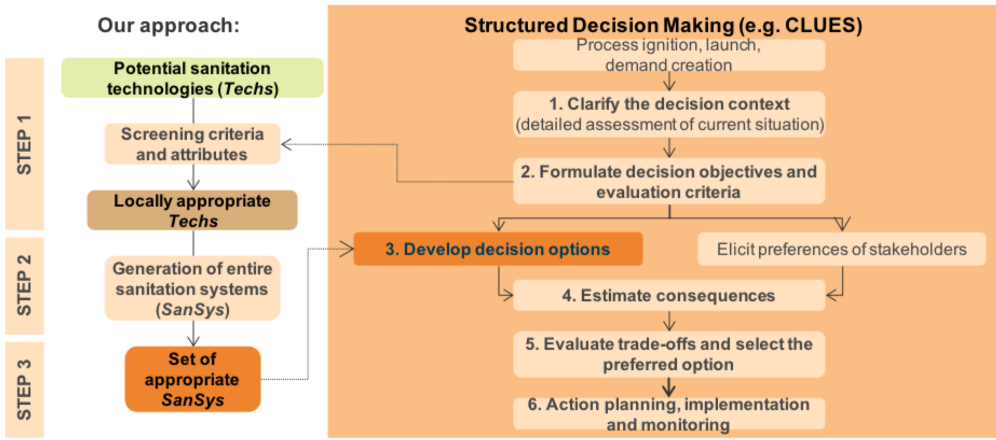

Figure 1. Overview of the procedure and its contribution to the structured decision making

Overview on the procedure

Identification of locally appropriate *Techs* from all potential *Techs*

There are several dozens of potential *Techs* and several hundred thousand of *SanSys* configuration that can be formed therefrom. Such large numbers cannot be looked at in detail with common SDM frameworks. Eliminating inappropriate *Techs* significantly reduces the number of *SanSys* configurations to consider. The appropriateness assessment (step 1) is informed by the fundamental decision objectives (GREGORY et al. 2012, KEENEY 1996) given by the definition of sustainable sanitation. We have constructed a generic objective hierarchy for sustainable sanitation planning using the many literature examples dealing with sustainable sanitation criteria and indicators (SPUHLER et al. 2018). It is based on four fundamental objectives: (i) protection of health and the environment; (ii) technical functionality; (iii) social and institutional acceptance; and (iv) financial and economic viability. For each of these, we have compiled a list of sub-level objectives and commonly used criteria. We then identified the criteria that can be used for the pre-selection based on three conditions: criteria (i) are independent from stakeholder preferences (are exogenously defined); (ii) are relatively stable over time; and (iii) can be evaluated based on data and information available at an early planning stage. We compiled the pre-selection criteria in a 'masterlist of appropriateness criteria'. We specify each criterion by an attribute for the *Tech* and one for the application case (*AppCase*). Each attribute is then quantified using probability density and distributions functions to account for uncertainty of the available data. By matching the *Tech* attribute to the *AppCase* attribute, the appropriateness score for the given criteria can be evaluated (*CAS*). The *Tech* appropriateness score (*TAS*) is quantified by aggregating all *CAS* using the geometric mean function. The *TAS* varies between 0% and 100% expressing the confidence of how appropriate a given *Tech* is in a given *AppCase* (Spuhler et al. 2018).

Generation of entire sanitation systems (*SanSys*)

We use an automated approach in order to account for the entire option space of valid *SanSys*. A *SanSys* is valid if (i) every output *product* of each *Tech* is connected to another *Tech* that can take this *product* as its input; and (ii) no *Tech* has inputs that are not connected to the output of another *Tech*. The *SanSys* appropriateness score (*SAS*) is obtained by aggregating all *TAS* within a system using a weighted geometric mean. The weight allows to control how much systems should be penalized for their length.

Field testing in Nepal

We applied the procedure in Katarniya, a typical emerging small town in the mid-western region of Nepal. The application was embedded within a project of the Swiss Water and Sanitation Consortium (SWC) which used CLUES for the sanitation component.

Identification of decision objectives and criteria for preselection

We organized a workshop with 34 experts in Kathmandu in 2015 to identify locally relevant objectives and pre-selection criteria using the masterlist. The workshop design was based on BOND et al. 2008 and was divided into five parts: (1) brainstorming objectives for sustainable sanitation; (2) structuring objective; (3) identifying corresponding criteria; (4) testing the criteria and identifying those useful for pre-selection; (5) merging the identified criteria with the masterlist. For Katarniya we removed some criteria from the masterlist because they were either (i) not relevant for the stakeholders in Katarniya; (ii) not independent from stakeholder preferences; or (iii) not enough information was available. The criteria used in Katarniya are shown in Table 1.

Table 1. Criteria and corresponding sanitation technology (*Tech*) and application case (*AppCase*) attributes used for pre-selecting appropriate *Techs* in Katarniya (HH= household)

Criteria	*Tech* attribute	*AppCase* attribute	Evaluation scale
Water use	Water requirements	Water availability	Litres/HH/day
Energy use	Energy req.	Energy availability	Hours/HH/day
Temperature	Temperature req.	Temperature range	Degree Celsius
Flooding	Flooding tolerance	Flooding occurrence	Days/year
Vehicular access	Access req.	Accessibility of households	Meters (street width)
Slope	Slope req.	Slope distribution	%
Soil type	Soil type req.	Soil type occurrence	Categorical (clay, silt, sand, gravel)
Groundwater depth	Groundwater depth req.	Groundwater depth occurrence	Meters
Excavation	Excavation req.	Ease of excavation	Categorical (easy, hard)
Construction skills	Construction skills req.	Construction skills availability	Ladder (none, mason, trained mason, construction engineer, supervisor)
Design skills	Design skills req.	Design skills availability	Ladder (none, unskilled labour, mason, trained mason, planning engineer, supervisor)
Spare parts	Spare parts req.	Spare parts supply	Ladder (low tech, technical parts, specially manufactured)
O&M frequency	Frequency of O& M	O & M capacity	Hours/HH/month
O&M skills	O&M skills req.	O&M skills availability	Ladder (none, unskilled, trained labour, technician, supervisor, administrator, engineer, scientist)
Management level	Management level req.	Preferred management level	Categorical (household, shared, public)

Collection of data

We quantified the appropriateness attributes of 40 potential *Techs* based on literature and personal communications (SPUHLER et al. 2018). To quantify the *AppCase* attributes we used the results from a household survey and an interaction workshop in Katarniya conducted by the project in 2016. We complement this data with information gathered during a field visit in May 2017.

Appropriateness assessment

The *TAS* for the 40 *Techs* varied between 71% (conventional sewer) and 100% (human-powered transport). The ranking of the *Techs* is shown in Table 2. *Techs* are ranked per functional group because only *Techs* from the same functional group are true alternatives.

Table 2. Ranking of assessed sanitation technologies (*Techs*) according to their technology appropriateness score *TAS* shown in parenthesis

User interface (U)	Collection and storage (S)	Conveyance (C)	Treatment (T)	Reuse or disposal (D)
• Pour flush toilet (0.97) • Urine diverting dry toilet (UDFT) (0.97) • Dry toilet (0.97) • Urine diversion dry toilet (UDDT) (0.95)	• Septic tank (0.99) • Urine storage tank (0.98) • Double pit (0.97) • Single pit (0.97) • Composting chamber (0.97) • Dehydration vault (0.96) • Faeces storage chamber (0.96) • Vermi-composter (0.95) • Twin pits (0.94)	• Human-powered transport of urine (1.00) • Human-powered transport of dry material (1.00) • Solids-free sewer (0.85) • Motorized transport of dry material (0.73) • Motorized transport of urine (0.73) • Conventional sewer (0.71)	• Urine storage bank (0.99) • Co-composting (0.97) • Struvite production (0.96) • Constructed wetland (0.94) • Anaerobic baffled reactor (ABR) (0.92) • Biogas reactor (0.91) • Faeces drying bed (0.81) • Drying bed (0.81) • Waste stabilisation ponds (WSPs) (0.81) • Sedimentation ponds (0.78) • Activated sludge (0.78) • Sequencing batch reactor (SBR) (0.73)	• Application of urine (0.98) • Application of stabilized sludge (0.98) • Application struvite (0.98) • Biogas combustion (0.98) • Irrigation (0.98) • Application of compost (0.98) • Application of faeces (0.98) • Soak pit (0.94) • Leach field (0.94)

Generation of entire *SanSys* and selection of options

We found 17'955 valid *SanSys* based on the 40 *Techs* (Spuhler et al. 2018). We used nine properties to classify the *SanSys* in 16 different system templates organized in 4 categories (onsite simple, urine, biogas, blackwater). From each template, we selected the *SanSys* with the highest *SAS* (Table 3).

Table 3. Selected sanitation systems (*SanSys*) in the application case (*AppCase*) Katarniya. (*) highest *SAS*. (**) lowest *SAS*. The smallest *SAS* found in absolute was 0.703 (not shown in the table). The *SanSys* with the highest score from each template category is highlighted in bold.

Template category	Template		SAS
Onsite simple	ST.1	Dry onsite storage without treatment	0.959
	ST.2	**Dry onsite storage and treatment**	**0.966** *
Urine	**ST.3**	**Dry onsite storage without sludge with urine diversion**	**0.965**
	ST.4	Onsite blackwater without sludge and with urine diversion	0.958
	ST.5	Offsite blackwater treatment with urine diversion	0.896
Biogas	**ST.6**	**Onsite biogas with effluent infiltration**	**0.953**
	ST.7	Onsite biogas with effluent transport	0.932
	ST.8	Offsite biogas without blackwater transport	0.949
	ST.9	Offsite biogas with blackwater transport	0.899
Blackwater	ST.10	Onsite blackwater without sludge and with effluent infiltration	0.947
	ST.11	Onsite blackwater without sludge and with effluent transport	0.909
	ST.12	**Onsite blackwater with sludge and effluent infiltration**	**0.964**
	ST.13	Onsite blackwater with sludge and effluent transport	0.939
	ST.14	Onsite blackwater treatment with effluent infiltration	0.908
	ST.15	Onsite blackwater treatment with effluent transport	0.888
	ST.16	Offsite blackwater treatment	0.857 **

Presentation of results and selection of preferred option

The selected *SanSys* options serve as a basis for further discussion with stakeholders and possibly the basis for selection of the most preferred option considering the trade-offs. This step was out of scope for us in this particular *AppCase*. However, in Table 4 we illustrate an example application of the MCDA using hypothetical decision objectives.

Table 4. MCDA of the *SanSys* with the highest *SAS* from each system template category. The criteria and data are hypothetical. Criteria are not weighted. In this example the *SanSys* from ST.3 is the preferred option.

Options		Nutrient &	Exposure of	Reusability of	Risk of failure	Maintenance	Costs per	**Score**	**Ranking**
ST.2	4 *Techs*: dry toilet, double pit, human-powered transport, application of stabilized sludge 3 Products: excreta, pithumus, transported pithumus	2	4	3	2	2	1	**14**	***2***
ST.3	7 *Techs*: UDDT, dehydration vault, human-powered transport, urine bank, application of faeces, application of urine 4 products: faeces, dried faeces, transported urine, transported stabilized urine	1	2	1	3	4	2	**13**	***1****
ST.6	10 *Techs*: UDFT, human-powered transport, septic tank, biogas reactor, application urine, application of stabilized sludge soak pit, biogas combustion 10 products: urine, transported urine, transported stabilized urine, blackwater, sludge, stabilized sludge, transported stabilized sludge, effluent, biogas	3	3	2	4	3	3	**18**	***4***
ST.12	9 *Techs*: UDFT, human-powered transport urine bank application of urine septic tank co-composting application of compost soak pit 8 products: urine, transported urine, transported stabilized urine, blackwater, sludge, compost, transported compost, effluent	4	1	4	1	1	4	**15**	***3***

Lessons learnt

- The workshop for the identification of decision options helped to: (i) raise awareness at the national level on key aspects to consider when (pre-)selecting sanitation options; (ii) strengthen local capacities in urban sanitation planning theory; and (iv) to localize the procedure.
- Data collection in Katarniya allowed to: (i) create awareness among the target population; and (ii) enhance ownership of target population by integrating their priorities for pre-selection.
- The consideration of uncertainty in the appropriateness assessment is crucial for the application since precise data is not available for many *AppCase* and many (novel) *Techs*.
- The automated generation of *SanSys* can overwhelm local staff. In theory, the process can be further simplified by using only the *Techs* with the highest *TAS* (e.g. top ten) and generating the corresponding *SanSys* manually based on the Compendium (TILLEY et a. 2014).
- Even though the *TAS* of an individual *Tech* might be very low, this *Tech* can be part of *SanSys* with a very high *SAS*. For instance, in our case, the Source with the lowest *TAS* (UDDT) results in the *SanSys* with the second highest *SAS*.
- The final workshop to present and discuss options is crucial to define further planning steps. Either a decision can be made and an action plan can be drafted for the preferred option, or it turns out that more data needs to be collected regarding the relevant decision objectives to further clarify trade-offs. The discussion of options might also lead to the emergence of additional options to consider in the decision.
- The presented procedure remains sensitive to a number of aspects which should be looked at carefully in consultation with local experts and stakeholders: (i) the choice of pre-selection criteria; (ii) the definition of system templates; and (iii) aggregation functions used for the *TAS* and the *SAS*.

Conclusions

We present a systematic procedure to pre-select sanitation technology and system options as an input into an SDM process. The procedure streamlines the planning process by eliminating inappropriate options right at the beginning. As it is systematic, it enhances the transparency of the structuring phase of SDM. The generated set of *SanSys* options is unbiased and includes both novel and conventional options thereby enhancing the probability that potentially more sustainable options are considered during decision-making. Key elements of the procedure are identified along with stakeholder, what increases awareness and ownership. The approach can be applied using data and information generally available in developing urban areas at an early planning stage since uncertainties related to local conditions and *Techs* are explicitly considered. The data collected for the *Tech* attributes is generic and therefore can be used for any other case. To replicate the approach approximatively seven working days including data collection and at least one workshop with stakeholders are required. The conceptual approach of the procedure is generic and could be applied to other complex infrastructure problems such as solid waste management.

Acknowledgements

This work is funded by the Sawiris Foundation for Social Development through the Engineering for Development (E4D) programme of the Swiss Federal Institute for Technology (ETH) Zurich. The authors are very grateful to the Swiss Water and Sanitation Consortium and their local staff in Nepal, as well as the inhabitants of Katarniya for enabling field testing of our procedure.

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