Simulation and visualization of material flows in sanitation systems for streamlined sustainability assessment

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ABSTRACT

New and alternative sanitation systems are increasingly discussed and find their way into implementation. However, discussions on sanitation concepts often are held in a rather emotional way. Furthermore, not all the available sanitation concepts might be known to the decision maker. The work presented here attempts to contribute to a good discussion and decision making process by compiling available technologies, by defining easy-to-implement criteria for a sustainability assessment method and by integrating these results into a simulation tool which allows to visualize the related resource fluxes (e.g. those on nutrients, such as N, P and K) and to analyse different sanitation options with regard to their capital and operational costs and with regard to environmental impact criteria such as greenhouse gas emissions. Whilst the calculations are to be considered as being approximate in their nature (due to uncertainties or lack of suitable input data), this tool allows the planners, with sometimes little modelling experience, to consider the characteristics of sanitation systems. Whilst starting from earlier work, such as Eawag's Sanitation Compendium and work on material flow analysis, work described in this contribution merges resource flux modelling, easy-to-use simulation and visualization and methods of life cycle assessment and life cycle costing. The simulation tool is freely available on https://www.ifak.eu/en/products/sampsons.

Key words | life cycle assessment, life cycle costing, material flow analysis, new and alternative sanitation systems (NASS), simulation, visualization

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INTRODUCTION

New and alternative sanitation systems (NASS) are based on the paradigm change of turning end-of-pipe systems into resource-oriented sanitation systems. Often, they represent small and decentralized wastewater systems. The consideration of NASS has several implications: NASS introduce a broad variety of additional system options. Decision processes for the identification of an optimal sanitation system for a given context become more complex, because they have to consider additional system characteristics, such as separation of material flows or recovery of energy and materials. On the other hand, NASS provide numerous benefits with regard to resource recovery and closing water and nutrient cycles. Hence, NASS are considered in developed as well as in developing countries (Horn *et al.* 2013; Tilley *et al.* 2014).

In order to support an unbiased comparative assessment between NASS and conventional system options, a number of sustainability criteria, which consider potential economical, ecological, social and technical aspects have to be analysed. Material flow analysis (MFA), life cycle assessment (LCA), life cycle costing (LCC) and multi-criteria decision analysis (MCDA) are useful methods for such an evaluation. In general, the concept of sustainability, upon which the SAmpSONS simulator is based on, follows the widely accepted paradigm that the lower the potential environmental impacts, the lower the financial costs, the lower the potential social impacts and the lower the need for adapting existing technological solutions to changing circumstances, the more sustainable is a defined sanitation system. These above-mentioned sustainability assessment

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methods are best supported by appropriate software. Furthermore, the software-supported visualization of MFA, LCA, LCC and MCDA results contributes to an increased comprehension of strengths and weaknesses of system options. Undoubtedly, several software systems are available which can, in parts, support the evaluation of sanitation options; see, for example, Mustajoki & Marttunen (2017) for a recent overview of MCDA-supporting software in environmental planning processes. However, some of them are not easily accessible to sanitation planning engineers, because they are expensive or require extensive training and time in their use. Sophisticated evaluation frameworks have been set up (e.g. Spuhler *et al.* 2018), but there is still a need for an easy-to-apply tool accessible to the planner. Furthermore, combining concepts of dynamic simulation, visualization of mass flow results by means of Sankey diagrams and performing a holistic sustainability assessment, at the same time, are rarely found in this combination. A strong requirement for the development of a robust simulation tool for planners has been identified according to first efforts of setting up a spreadsheet-based tool of the Working Group KA-1.1 (Technologies of New Sanitation Systems) of the German Water Association (DWA). This paper presents recent developments towards a software system called SAmpSONS featuring such characteristics and thus allowing a streamlined sustainability assessment of sanitation systems, based on promising results of earlier approaches (e.g. Campos *et al.* 2012; Ormandzhieva *et al.* 2014). The SAmpSONS software system has been made freely available on https://www.ifak.eu/en/products/sampsons. At present, SAmpSONS focuses on Central European sanitation conditions and includes a library of related key system components, but adaptations are conceivable.

MATERIALS AND METHODS

Developing SAmpSONS consisted of five steps: initially, a **sustainability assessment method has been designed**. Furthermore, a **general-purpose software system**, capable of static and dynamic simulation and equipped with features for MFA, LCA and LCC including appropriate visualization functionalities, has been identified. It serves as the development environment used for implementation of SAmpSONS. In a next step, **detailed data** including process descriptions, material and energy consumption, performance data and costs **have been collected** for a large number of system components, e.g. wastewater collection, transport, treatment and disposal technologies. The compilation of related fact sheets was based on data from system manufacturers, reports and literature. The respective fact sheet template will also facilitate definition and implementation of future technologies in SAmpSONS when they emerge. The fact sheets resulted in a 'library' of sanitation technologies, **implemented as simulation modules** for SAmpSONS. Examples of real-world sanitation systems and their detailed evaluation served for **validation**; they also illustrate how SAmpSONS can be used in order to perform a sustainability assessment of systems' options. Furthermore, visualization of resource flows (e.g. N, P) illustrates the fate of these resources within the system. Data aggregated over the entire sanitation system, involving elements of LCC and LCA, then provide support for selection of 'most sustainable' sanitation options. In the following, each of the five steps is described in more detail.

Sustainability assessment method

The aim of SAmpSONS is to support decision-making processes at the pre-planning stage between different system alternatives from the perspective of sustainability. This aim affects the sustainability assessment method to be employed. First, SAmpSONS should generate clear key figures that include nearly all key dimensions of sustainability assessment. The system boundaries defined for SAmpSONS include all processes related to the collection, transport, treatment and potential energy or nutrient recovery of wastewater or biowaste streams. The functional unit has to be defined flexibly depending on the particular application situation; normally, it is related to a particular amount of wastewater and/or biowaste (for a specific number of households or inhabitants) passing through the technical system described above. The evaluation functionality of SAmpSONS allows both the analysis of the individual sustainability criteria and the aggregation into an overall sustainability score via MCDA, which is an established method for assessment applicable to the field of technical infrastructure (Lienert *et al.* 2014). MCDA tools are usually based on a hierarchical structure of objectives, criteria and indicators. Commonly, the results of MFA, LCA and LCC methods can be integrated into a MCDA tool on criteria and indicator level (Myllyviita *et al.* 2017). For example, 'net present value', a result of LCC, is an appropriate indicator for economic criteria. Secondly, low effort for data provision is eminently conducive to the actual use of the tool. Preconditions for indicators are, on the one hand, that their values can be easily determined and, on the other hand, that they are meaningful for the criterion to be mapped. It should be noted, however, that each indicator result comes with inherent limitations with regards to uncertainties of the underlying data or subjective value judgements. The reliability and uncertainty of the results obtained in SAmpSONS needs to be evaluated on a case-by-case basis.

Creating an MCDA tool is a complex process, often involving nearly all stakeholders (Gregory *et al.* 2012; Lienert *et al.* 2013; Lück & Nyga 2017). To design an MCDA tool with as few indicators as possible, but also with as many indicators as necessary to describe sanitation systems appropriately, a heuristic approach was chosen, mainly based on products of earlier work. In addition to the already mentioned spreadsheet of the DWA working group KA-1.1 and a guideline to the German standard A 272 (Hillenbrand *et al.* 2018), the *Environmental Sustainability Assessment Tool* (ESAT, Schulz *et al.* 2012) is one of these products. ESAT was developed with the aim of a comprehensive sustainability assessment of water infrastructures based on MFA, LCC and LCA using the example of Australian water infrastructure systems. However, special emphasis was placed on a reduced number of criteria and indicators, so that the tool is easy to use. Another preliminary work is a newer and more comprehensive MCDA tool for evaluating water infrastructures in Central Europe (TWIST++, cf. Sartorius *et al.* 2017a, 2017b, 2018). This MCDA tool comprises a total of 21 criteria with 33 indicators, each of which has been evaluated for applicability in SAmpSONS. The criteria incorporated in SAmpSONS have also been carefully selected based on relevant prior work (e.g. Remy 2010; Schulz *et al.* 2012; DWA 2017; Sartorius *et al.* 2017a, 2017b, 2018).

Table 1 describes the objectives, criteria and indicators of the MCDA tool developed for implementation in SAmpSONS. In addition to the three objectives of classic sustainability assessment (ecology, economy and social issues), it also contains the objective of flexibility. The flexibility indicator which can be understood as the 'adaptability to changing circumstances', is based on three factors: (a) amortized costs, (b) disturbance potential for the inhabitant and (c) grey energy. These factors are combined in SAmpSONS using a defined calculation algorithm. A total of five criteria have been assigned to the objective 'ecology', while the other three objectives are each only covered by one criterion each. Each criterion is measured using one indicator. An over-evaluation of the objective ecology can be remedied by weights assigned to objectives and criteria. Therefore, in an actual assessment, the objective 'ecology' does not have more weight, but it can be measured more holistically.

Simulator development

As a base for simulator development, the open simulation system for algebraic, discrete and dynamic systems SIMBA# (Alex *et al.* 2013; ifak 2018) has been chosen. Besides definition of resource fluxes and modules (e.g. for

Table 1 | SAmpSONS sustainability assessment criteria and indicators

	Criterion	Description	Indicator
Ecology	Eutrophication potential (EP)	Quantity of the characterized nutrient input on land, water and air. Essential substances contributing to EP: N, P, COD, NH_3 emissions.	kg PO_4 equivalents
	Energy input	Specification of both final energy demand and primary energy use.	MJ
	Greenhouse gas emissions (GHG)	Total amount of all greenhouse gas emissions. Significant substances: CO_2, CH_4, N_2O.	kg CO_2 equivalents
	Organic matter	Chemical oxygen demand (COD).	Percentage of elimination or retention
	Organic micropollutants/ pharmaceutical residues	Pollution by ecotoxicological substances is represented by proxy substances (here: Diclofenac).	Percentage of elimination or retention
	Physical footprint	Surface area required by the system.	m^2
Economy	Life cycle cost	Economic impact of the system. All costs and revenues are valued over the life cycle.	Net present value (€)
Social issues	Social acceptance	Qualitative indicator evaluating the acceptance of a system by relevant stakeholders.	Rating scale
Flexibility	Flexibility	Flexibility with regard to changing general conditions.	Rating scale

different treatment technologies as identified by the collection of fact sheets), solution of systems and visualization of results (e.g. by Sankey diagrams), it also allows the specification of evaluation functions serving for assessment. A designated editor has been used for the definition of models (process equations and parameters) and sustainability assessment functions. Based on this, SAmpSONS has been derived which is now accessible to the end-user without license fees.

Whilst there is a wide range of detailed and well-established modelling approaches available (such as the Activated Sludge Models of the IWA, cf. Henze *et al.* 2000, and the Anaerobic Digestion Model, cf. Batstone *et al.* 2002), their degree of detail is considered to be far too complex for the objectives of the tool to be developed. These models require a large number of parameters and, for their application, extensive modelling experience. As the intended target group of SAmpSONS are planners, with sometimes little modelling experience, simplified modelling approaches have been chosen here. These go beyond linear transfer functions, which are applied usually in LCA studies; promising approaches such as those by Campos *et al.* (2012) and Ormandzhieva *et al.* (2014) have been further developed and integrated. These then have been coupled with sustainability assessment indicators (cf. Table 1).

In order to represent the various resource fluxes – such as wastewater, greywater, urine, faeces, sludge - (and to visualize them to the user), the resource fluxes have been defined and colour-coding has been assigned, using and expanding those used by Tilley *et al.* (2014), see Figure 1. As main components of the resource fluxes, COD, N, P, Diclofenac and, for the sludge fluxes, also organic dry matter and dry matter, have been identified and are considered in all modelling modules.

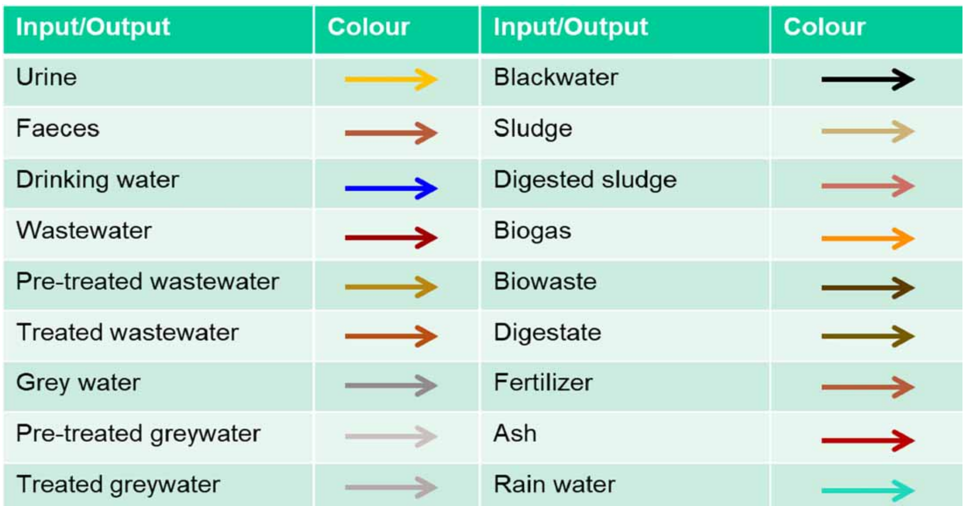
Subsequently, modelling blocks for each of the system components identified in Figure 3 have been defined. They are accessible to the user as a library of modules. Modules also contain functions for the calculation of each of the assessment criteria described. In a simulation run, results of the assessment functions are then aggregated over the entire modelled system and over the simulated time period, resulting in an overall sustainability assessment with regard to the defined criteria. When designing the modules, care was taken that user dialogues are also easy to understand by the novice user.

Figure 2 shows, as an example, a user dialogue for the module 'Conventional large wastewater treatment plant (WWTP)'.

Parameters used for the calculation of greenhouse gas emissions, eutrophication potential and primary energy demand from material consumption, emissions and operation have been taken mainly from the GaBi database (GaBi ts 2017) and integrated into the simulator.

Data collection

The requirements of the simulation model of SAmpSONS are driving the kind of data to be collected for each system component. Several steps are necessary to collect the data. The first step consists in the identification of the system components that are part of conventional and innovative sanitation systems. Figure 3 shows the system components



Input/Output	Colour	Input/Output	Colour
Urine		Blackwater	
Faeces		Sludge	
Drinking water		Digested sludge	
Wastewater		Biogas	
Pre-treated wastewater		Biowaste	
Treated wastewater		Digestate	
Grey water		Fertilizer	
Pre-treated greywater		Ash	
Treated greywater		Rain water	

Figure 1 | Resource fluxes considered in the simulation (extract).

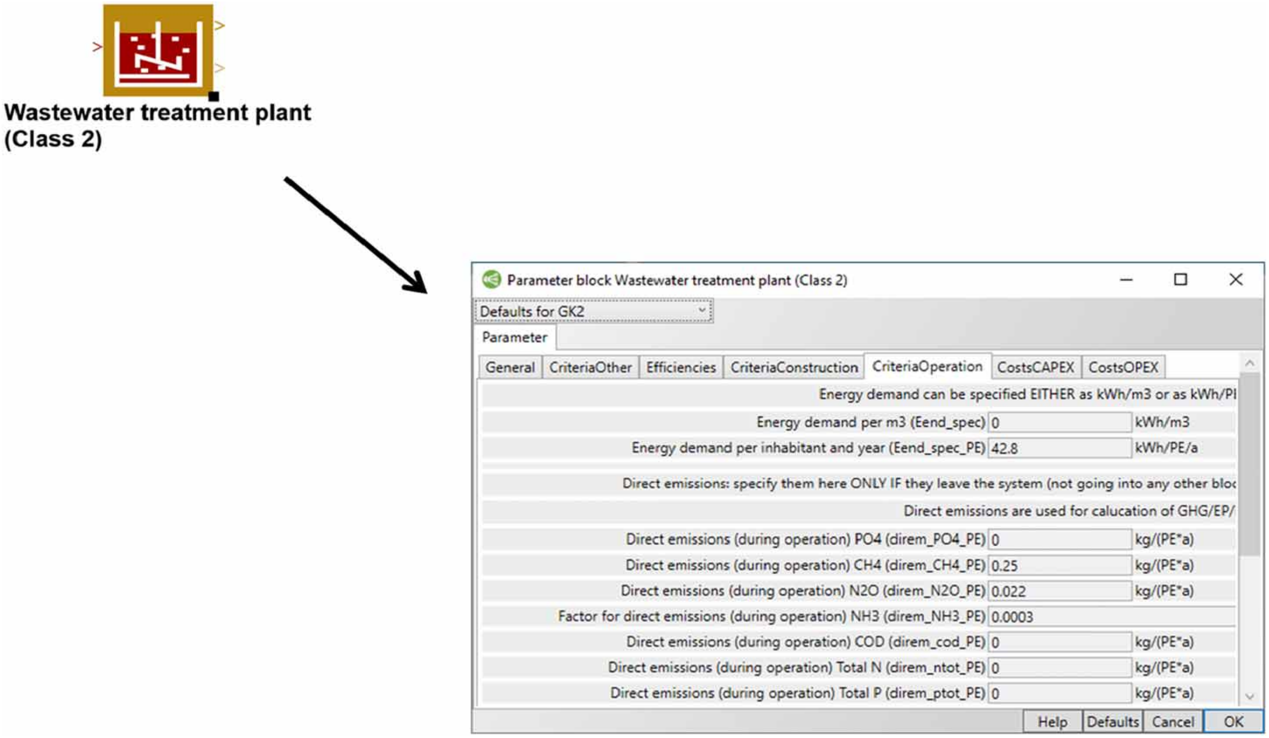


Figure 2 | Extract of user-dialogue of the module 'Conventional large WWTP'.

currently supported by SAmpSONS, categorized according to material flows and process steps. Material flows include the main flows, as there are organic waste, faeces, urine, and greywater. In a further step, the detailed data required for simulation and visualization are collected for each of the system components shown. For this purpose, a fact sheet template has been created. The structure of the fact sheet is based on the data requirements of the sustainability assessment method defined. Figure 4 shows the structure of the fact sheet exemplified for data related to flush toilets. Based on the template, a fact sheet is compiled for each system component. The fact sheets served as the basis for the subsequent implementation.

This fact sheet compilation is based on knowledge sources from system manufacturers, reports and literature (e.g. DWA 2008; Tilley *et al.* 2014). The aim of the data collection is to determine the most realistic values possible. The knowledge sources used have different strengths and weaknesses. For example, system manufacturers are very familiar with the data due to their daily experience. On the other hand, manufacturers' claims are sometimes embellished to improve the marketing of their products, e.g. manufacturers' data on the electricity consumption of small sewage treatment plants tend to be lower than the actual values. Furthermore, some types of data are only documented in scientific literature, such as nitrous oxide emissions from sewers (Short *et al.* 2014).

A subtask of data collection is also to categorize the quality of the data found. A three-part categorization has to be applied: *verified* for data consistently found in several sources, *reliable* for data from a few to individual sources and *assumed* for data derived to the best of our knowledge and belief. The respective category have been noted in the fact sheets. To some extent, it turned out to be difficult to compile data. Certain necessary data have not yet been ascertained. A secondary result of the data collection is therefore the identification of open research questions, such as the quantification of emission data for different technologies. The need for analysis of ecological aspects (e.g. emission data) for technologies often depends on the customer's requirements. The determination of emission data is effort-prone and some manufacturers of technologies avoid the effort for an LCA or a similar analysis without explicit request by the client.

The fact sheet template provides a general guideline of data to be collected without being able to make statements in advance about the relevance of the data collected. Therefore, the sensitivity analysis to be performed as part of the validation may reveal that some of the data determined with significant effort might be of little relevance for the

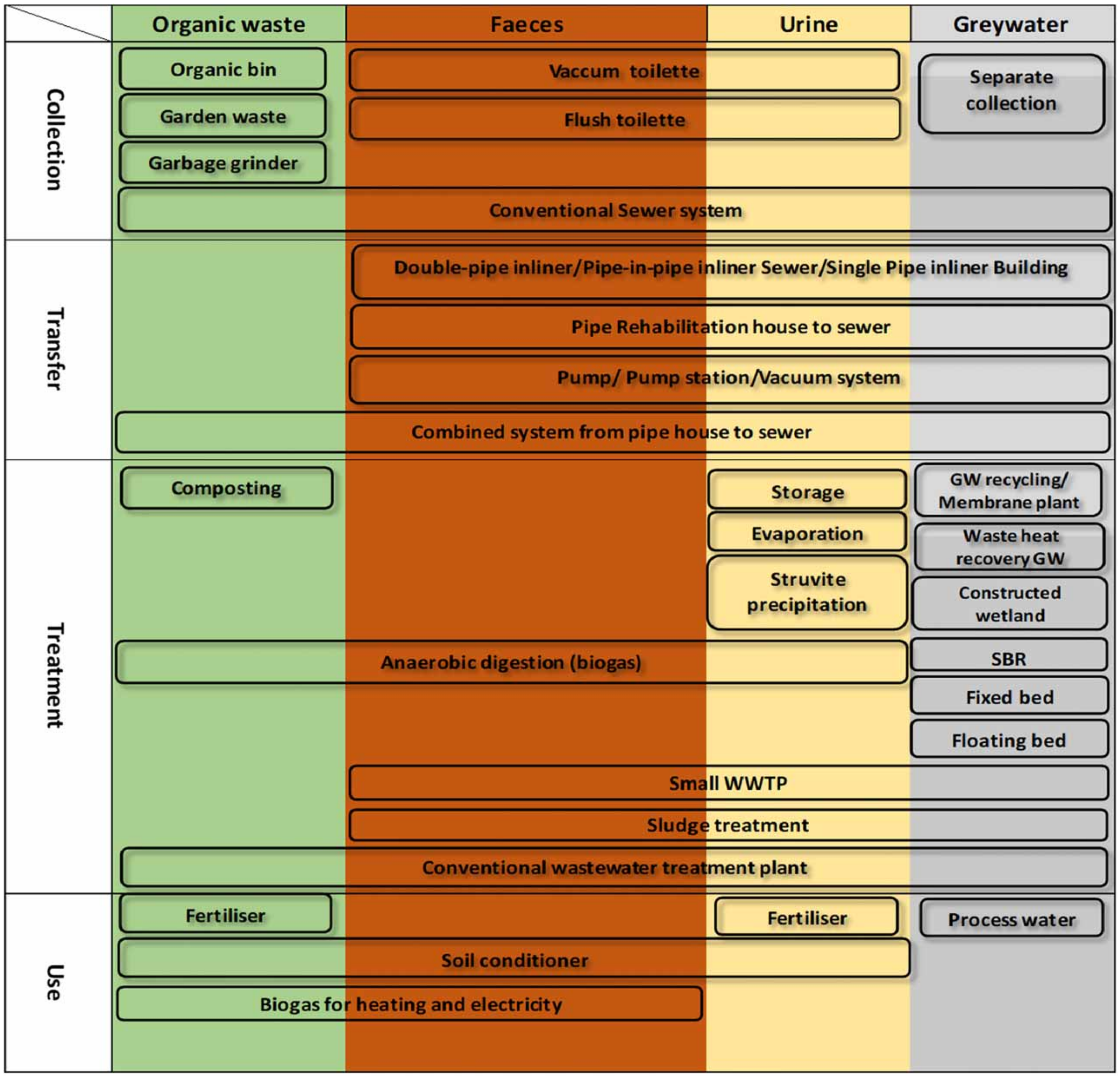


Figure 3 | Categorized system components supported by SAmpSONS.

overall results of the sustainability assessment. It should be pointed out that SAmpSONS allows users to enter more specific data or fill data gaps if these data are available.

Simulator application

Figure 5 shows the user interface of the simulator-modules of the system components (cf. Figure 3). The modules are accessible to the user by blocks, organized in groups of the block library (see right of the figure). By drag and drop and by connecting the various modules, the user can set up the sanitation system as a model in the main window of the simulator. Running a simulation and starting an evaluation routine helps to **visualize** the various resource fluxes (e.g. flows, N, P) throughout the modelled system and to calculate the sustainability indicators defined above. The next section provides an example.

Validation

A validation process for the further development of SAmpSONS has been carried out based on different case studies from several practical projects with the goal of source separation of wastewater (and separated wastewater treatment). The defined sustainability criteria have been evaluated in the selected case studies. The functionality of SAmpSONS can be assessed by comparing the results from existing published evaluations with the results obtained using SAmpSONS for the same reproduced scenarios. Case

Factsheet System Component: Flush toilet

Status: complete

Topic	Information	Description	Value	Unit	Reference / Knowledge source	Comment
Component name		conventional flush toilet				
Short name		flush toilet				
Component description		n.a.				
Capacity		n.a.				
Life span			10	years	http://www.sustainableminds.com/showroom/	
Space requirement			0.5	m2		
Input - Material Flows						
	Material Flow 1	tap water	40	L/PE/d	DWA (2017): Korrespondenz Abwasser, Abfall 2017 (64), Nr. 12.	500 litres of urin and 50 litres of faeces per person per year
	Material flow 2	faeces	1.5	L/PE/d		
Output - Material Flows	Material Flow 1	wastewater	41.5	L/PE/d		
Performance (e.g. treatment efficiency)		n.a.				
Raw and auxiliary material usage						
	Material 1	GWP	20.2	kg/unit	IBU EPD Sanitärkeramik Duravit; https://ibu-epd.com/veroeffentlichte-epds/	exact material composition not known, therefore indication of the environmental impacts of the production (based on a total weight of 27.1 kg)
	Material 2	EP	0.008	kg/unit		
	Material 3	Primary Energy Demand	741.5	MJ/unit		
Energy consumption						
	Energy 1	n.a.				
Direct Emissions		n.a.				
Costs/revenues (LCC)						
	Investment costs		213.60	€	estimate	estimated via Google shopping
	Installation costs		70	€		estimated one hour installation time by a specialist
	Operating costs		0	€/a		
Raw and auxiliary material usage	Revenues		0	€/a		
	Depreciation period		10	years		according to lifespan
Comments and assumptions:						

Figure 4 | Fact sheet of system component 'flush toilet'.

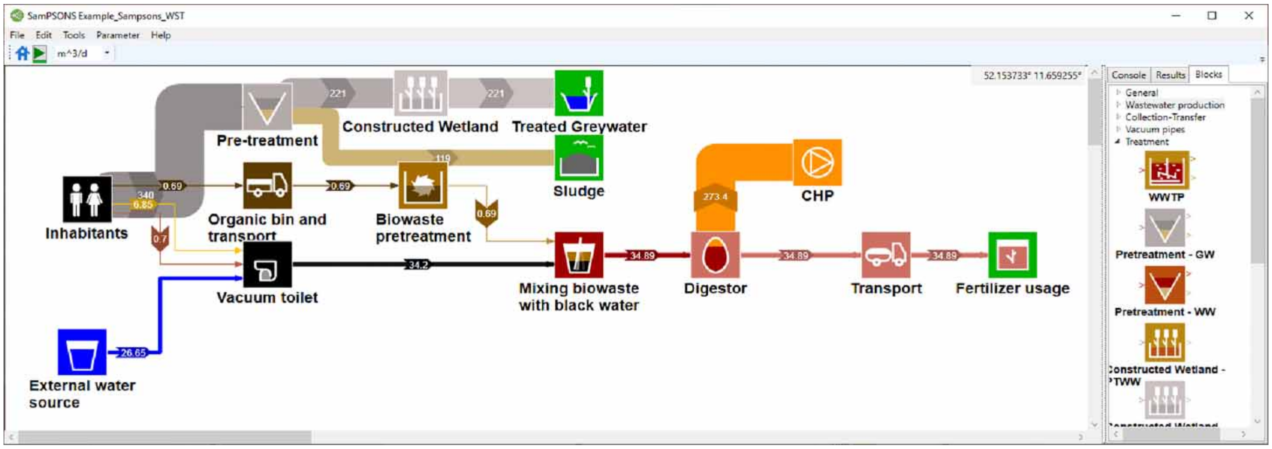


Figure 5 | User interface of the simulator.

studies used for the validation of SAmpSONS include the following:

SCST Berlin

In the EU demonstration project Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater (SCST), different technologies were implemented and tested. In order to identify potential advantages and disadvantages in comparison to conventional systems, an LCA was carried out. The study in the SCST project is based on the ecological comparison of an at-source-separation sanitation concept with a conventional sanitation concept for a mid-sized urban settlement (5,000 inhabitants) in Germany for different scenarios. In addition to the ecological part, economic parameters (such as capital and operational expenditure for infrastructure) were used to show their influence on the eco-balance (Remy & Ruhland 2006).

Wohlsborn

The community of Wohlsborn with 500 inhabitants is located in the Thuringia region of Germany. Its wastewater infrastructure is in the need of rehabilitation. Wohlsborn was a model area in the project TWIST++. From this project, different planning alternatives for the use of NASS and for the rehabilitation of the deprecated infrastructure have also emerged. In the TWIST++ project an assessment of sustainability has been elaborated with particular emphasis on the economic aspects in rural areas (Sartorius *et al.* 2017a, 2017b).

Campus Birkenfeld

The Birkenfeld campus of Trier University of Applied Sciences represents a successful example of a sustainable development on a conversion area. It is a study place for 2,350 students. Based on the already existing zero-emission approach on the Birkenfeld campus, it will be further developed into a 'Wastewater-Free Campus'. Due to the economic aspect in the Birkenfeld project, a reliable basis of data is available. The existing data set actually will be processed for the validation of SAmpSONS (Roediger Vacuum GmbH 2012).

Nutrient-, energy- and CO_2-balance

Based on a report of the working group of DWA mentioned above (DWA 2017), different variants of NASS are compared with a conventional wastewater concept. The comparison is made based on material and energy balances for 50,000 inhabitants. The overall aim of the analysis has been the identification of existing potentials for the increase of efficiency by modifications or adaptations of the centralized system. For the validation, the most important parts are the results of nitrogen and phosphorous loads as well as primary energy and CO_2 (DWA 2017).

The SCST example was chosen to validate the ecological part of SAmpSONS because the study by Remy (2010) has put its focus on LCA. Hence, it can serve as a good reference for evaluation due to the application of new sanitation systems in a full scale. In Figure 6, one of the scenarios of Remy (2010), which has been simulated using SAmpSONS, is shown. For the validation, the comparison with the identical scenarios from the given reference was made. The presentation options for the results include not only Sankey diagrams for the visualization of different flows (e.g. nutrients), but also tabular and graphical representation of LCA results.

In the selected scenario, faeces and urine are drained by a vacuum system and co-digested with bio-waste. The mixture is directed to the digester. Due to high contamination with pathogenic microorganisms of this flow, it has to pass through hygienization (70 °C for 1 h) in the digester. Here, the organic content is partially degraded under anaerobic conditions and transformed into biogas, which is used, in a combined heat and power plant, to generate electricity and heat. The digester residues contain a large amount of dissolved nutrients due to the contribution of urine. These valuable nutrients would be lost if the residual sludge was just to be dewatered and composted. Therefore, in this scenario, it is assumed that the digestate is directly applied as fertilizer. However, it has to be taken into account that the transport volume is relatively large and the NH_3 emission by the application of this kind of fertilizer is higher than in the case of a stabilized product such as compost.

Figure 7 shows the nitrogen load after simulation in the selected scenario represented as a Sankey diagram (flows in [m^3/d]; loads in [kg/d]).

RESULTS AND DISCUSSION

The work presented in this paper has two main results: (1) the development of the modelling, visualization and evaluation engine and (2) the compilation of a set of relevant system component fact sheets. A simulation

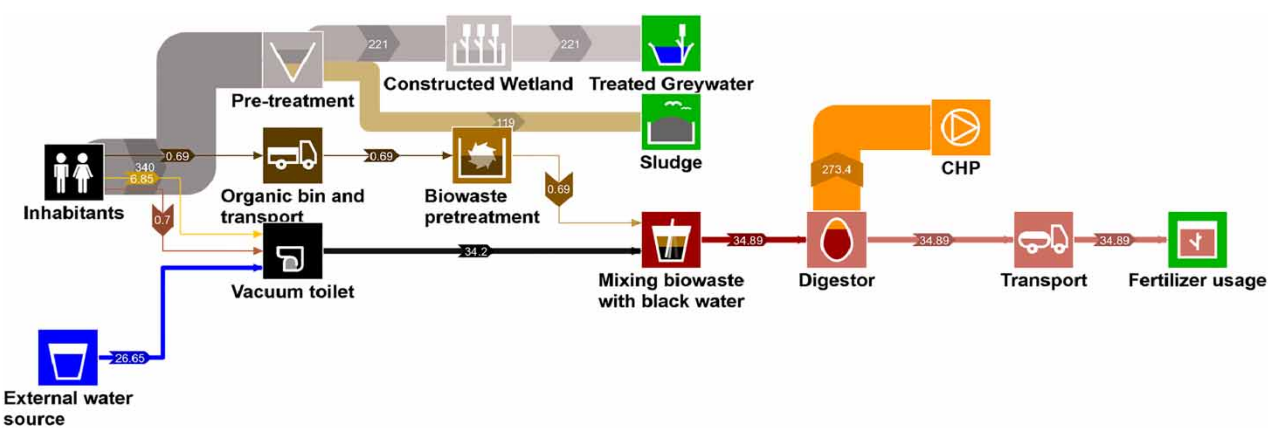


Figure 6 | Illustration of wastewater flows [m^3/d] in the scenario with co-digestion of blackwater and separated greywater treatment (N.B. The outputs of the 'Inhabitants' block shown in the figure refer to the biowaste, greywater, urine and faeces fluxes).

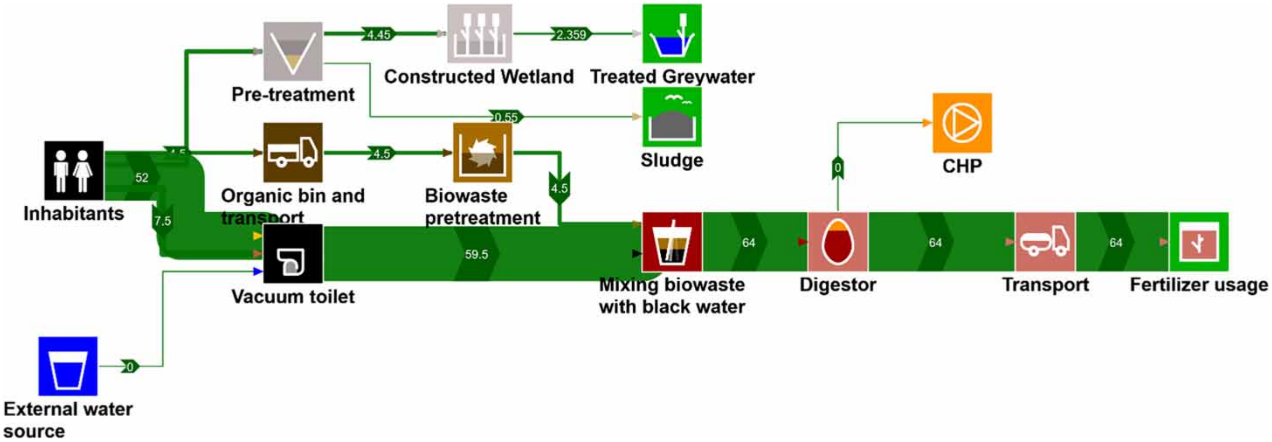


Figure 7 | Illustration of nitrogen fluxes [kg/d] in the scenario with co-digestion of blackwater and separated greywater treatment.

system including modules for each of these technologies has been set up. During the development, current knowledge gaps have been identified, motivating future research. An example of a current knowledge gap is the inherent uncertainty of data affecting the sustainability assessment indicators (e.g. N_2O emissions in WWTPs). A further example are widely unknown energy benefits associated with the recovery of nutrient-rich substances (e.g. digestate).

Rainwater has a considerable influence on the load of the sewer system. From the point of view of material flows, however, it is less important. Therefore, rainwater is only included in the system options if it increases the sewer volume – and thereby the amount of building material required.

Among the main challenges of the development process was the compilation (and, often, lack of availability) of reliable data about technology components. Thus, major effort is necessary to validate the results of the sustainability performance of example sanitation systems. The validation of the results is still an ongoing task and part of the ongoing initial research project. The main benefit of SAmpSONS can be seen in the quick sustainability performance assessment of various sanitation system components. The main advantage compared to other available tools is that users can flexibly choose from sanitation technologies integrated into SAmpSONS and combine them for individual application situations. However, this also leads to one main challenge: supposedly similar sanitation technologies differ in many ways in reality, and this complexity is difficult to capture with the default values as integrated in the data fact sheets. SAmpSONS responds to this challenge by allowing the user to change the given values. It is planned to carry out further validations based on the case studies mentioned above. The individual case studies do not all allow for a comprehensive validation of all sustainability criteria included in SAmpSONS, however, overall all sustainability criteria will be evaluated (e.g. SCST Berlin allows for the assessment of environmental criteria, Campus Birkenfeld allows for the assessment of economic criteria).

Expandability and further development of the simulator

Due to the flexibility of SAmpSONS, new technologies and variants of technologies can be implemented easily in SAmpSONS. Therefore, future technological developments can also be integrated. In addition, all values provided in the fact sheets can be adapted by the user based on better knowledge or more appropriate representation for a given situation. For the integration of further sanitation technologies, first of all, a fact sheet must be prepared. After a (peer) assessment, the fact sheet gets implemented in SAmpSONS. For the assessment of a fact sheet, the DWA working group KA-1.1 'Technology and Design' will act as an independent consultant.

A relevant area of interest for SAmpSONS is the indicators. Few indicators mean few data to be obtained, but more indicators increase the reliability of the result. In the future, it needs to be confirmed that (a) the small number of selected indicators is sufficient and (b) the most suitable indicators have been selected. For example, it is currently being discussed whether the Diclofenac indicator for the micropollutants criterion should be replaced by ibuprofen due to the much larger emission. Furthermore, increasing the number of indicators could not be detrimental to the usability of SAmpSONS as long as no further data needs to be collected in the concrete application scenario, because data required relies on default values provided in the implementation phase. In theory, it is also possible to extend the sustainability assessment by evaluating additional indicators (e.g. acidification potential, photochemical ozone creation potential, resilience of the technology or further social or health-related criteria). In addition, it is currently being considered whether the characterization of the indicators should be included in the selection. The DPSIR framework divides the indicators into status indicators, which describe the current status of the environment, and pressure indicators, which quantify the respective impact on the environment. For SAmpSONS, the pressure indicators are of primary importance, which currently make up a large part of the indicators, such as for the criterion 'eutrophication potential'.

SAmpSONS fills a niche in the field of sustainability assessment software that makes it particularly suitable for the pre-planning of sanitary systems: It does not require as much data as, for example, the TWIST ++ assessment software (Sartorius *et al.* 2017b), it allows the flexible design of sanitary systems from different, individually developable components, which would not be immediately possible with spreadsheet-based systems such as the ESAT tool (Schulz *et al.* 2012), it does not require license fees as, for example, the GaBi database (GaBi ts 2017) requires it, and it allows complex calculations, as with similar straightforward solutions such as the above mentioned spreadsheet-based tool of the DWA Working Group KA-1.1, were not possible.

CONCLUSIONS

With the more widespread consideration of NASS, further options for the implementation of a sanitation system are available. The resulting more-complex decision-making process can be supported with the help of SAmpSONS in early phases of the planning process. SAmpSONS allows comparative streamlined sustainability assessment and visualization for user-defined sanitation systems. The results of SAmpSONS presented for the different, clearly defined sustainability indicators are considered valuable for generating a more holistic and detailed basis for decision-making processes. Future work encompasses the extension of the software implementing additional technology components. Furthermore, the accuracy of the results has to be improved by integrating more reliable specific data. As SAmpSONS has been made available to the public, it would now be important to apply SAmpSONS to as many real-life case studies as possible in order to validate the results, address potential weaknesses, improve data quality and overall assess the usefulness of the tool. For this further development of SAmpSONS, it would be very important to organize and fund the ongoing maintenance and extension of the tool.

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