SIMULATING NUTRIENT AND ENERGY FLUXES IN NON-NETWORKED SANITATION SYSTEMS

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ABSTRACT

Increasing resource constraints mean that cities need to adopt and implement more resource efficient sanitation systems. Many of these are based on non-networked solutions and use innovative treatment technologies, but the majority of which have only been applied at the small-scale. Simulation models provide a cost-efficient means to simulate these technologies under several scenarios and to assist the identification of the most sustainable sanitation solution for a given case study city. These provide city managers with a tool to aid decision-making from a macro-perspective to assess the application of these technologies within their city. However, existing simulation models for sanitation planning in developed countries focus mainly on networked systems and are, thus, not appropriate for the situation in many African and Asian cities.

This paper presents the ongoing development of the "NewSan" simulator for modelling the fluxes of human excreta from household to final disposal/reuse, focussing on fluxes of nutrient, energy and water. The simulator enables a comparison of conventional sanitation systems (i.e. flush toilet and pit latrines) with "new" sanitation systems such as urine diversion and vacuum toilet systems. The simulator aids in determining sustainable sanitation solutions for the boundary conditions of the respective site based on material flow analysis. The amount of nutrients and energy available for recovery provide an indication of the economic potential of waste reuse. This paper illustrates its adaptation and application to the context of non-networked sanitation systems, using a city in Africa (Durban) as an example. The model outputs include the main fluxes of nutrients, water and energy and, thus, their available amount for recovery, volume and quality of treated waste for reuse, and an estimate of indicator bacteria reduction. The amount of nutrients and energy available for recovery also provide an indication of the economic potential of waste reuse.

Key words: MATERIAL FLOW ANALYSIS, NUTRIENT FLUXES, SANITATION TECHNOLOGIES, SIMULATION, URINE DIVERSION

INTRODUCTION

Inadequate provision of facilities and services for disposal of human excreta is a major cause of disease world-wide and improving sanitation is known to have a significant beneficial impact on health both in households and across communities. Ever increasing needs, scarce and declining resources, unorganised management systems and inefficient traditional techniques have aggravated the wastewater management problems in developing countries.

In developing countries sanitation systems are at a cross road and this has raised the demand for an urgent shift in the approach to waste-water management and planning in developing countries (Tayler et al., 2003). There has been significant research and development in the field of sanitation technologies. Still the professional in the field of sanitation might not be familiar with the entire range of all possible sanitation systems and the innovative technologies. Selection of appropriate sanitation technology plays a vital role in understaning the process of building a complete sanitation system. Moreover, the scarcity of resources (e.g. water, nutrients and energy) makes it imperative to choose and implement resource efficient and sustainable sanitation system.

Most of the existing simulation models for sanitation planning in developed countries primarily focus on networked systems and therefore, are not applicable for the sanitation planning in many countries such as South Africa, India, Sri Lanka, and Peru. So, it is important to assess various sanitation options and their applicability for any given case study site with the visualisation of nutrient and energy fluxes.

The main aim of this work is to develop a simulation tool to model flux of residual wastes from streams in the sanitation service delivery chain, focussing on nutrient and energy fluxes. The novelty of this work lies in the adaptation of an existing resource-flux simulation methodology used on networked systems to calculate nutrient and energy fluxes specifically for dry or low-flush sanitation systems.

MODEL DEVELOPMENT

The "NewSan" simulation tool was developed from 'LiwaTool', by adapting it to non-networked sanitation systems. The "LiWatool"simulator, developed by ifak, is already being successfully applied for sustainable management of water and wastewater systems (Schütze et al., 2011).

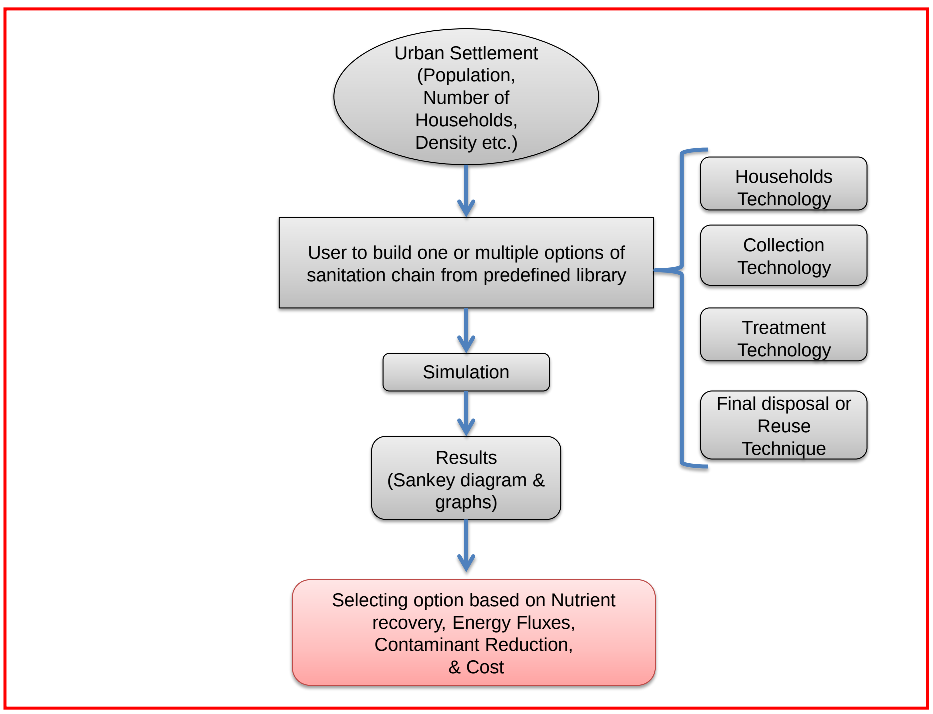


Figure 1 : Model Concept

NewSan represents the entire sanitation system from household to final disposal/re-use (Figure 1). The fluxes were defined and modelled based on information from literature. It uses the principle of material flow analysis to estimate the amount of nutrients, energy, organic matter, indicator bacteria in the system streams. For nutrient fluxes, N, P, and C were modelled, while organic matter is modelled by BOD and COD. Indicator bacteria were defined as faecal coliforms. Energy flux simulates the energy consumption/production in the sanitation system. In total, 7 fluxes (N, P, C, BOD, COD, Energy, Bacteria) were defined under each stream, and

16 input/output streams (Table 1) were adapted and modelled based on Tilley et al. (2008). Nutrient fluxes (N, P & C) and BOD & COD are expressed in kg/day; Energy in kWh/day or kWh/m^3; and indicator bacteria in count/L.

Table 1 - Colour code for all streams used in the model (Adapted from Tilley et al. 2008)

Abbrev.	Name	Line colour	Abbrev.	Name	Line colour
AW	Anal Cleansing water		EX	Excreta	
BL	Black water		FA	Faeces	
BG	Biogas		FL	Flush water	
BW	Brown water		FS	Faecal Sludge	
CO	Compost/Ecohumus		OR	Organics	
DF	Dried Faeces		SU	Stored Urine	
DM	Dry cleansing Materials		TS	Treated Sludge	
EF	Effluent		UR	Urine	

Capital and operational costs estimation is used for cost-evaluation of the whole sanitation system. For the purpose of model development, most of the cost equations used in NewSan were taken from SANEX (Loetscher 1999), while some were taken from existing case studies or sanitation projects publications. However, the costs are not inflated to 2012 figures as inflation rate has not been implemented yet in the model. NewSan simulator permits the user to modify the cost functions or even to include new ones.

Various mathematical equations were taken from literature (Loetscher 1999; Gutterer 2009; Jönsson & Vinnerås 2004) and used to calculate nutrients, organic matter, indicator bacteria and energy amount, and costs within each stream. For calculating the amount of input nutrients in the sanitation chain, values suggested by Jönsson et al. (2004) were assumed, and the data required by equations for various countries were taken from FAOSTAT (2009). Figure 2 illustrates the definition of models and costs functions by NewSan.

NewSan represents every part of the sanitation system by blocks. For example, in the urban settlement block, the user can define various parameters, including population, density, number of households etc. A block library was created for the user to select technologies from various tabs and construct a sanitation chain (Figure 3). All blocks defined by NewSan were put together into a project file in order to make a block library. New blocks can be created by the users themselves to to represent new technologies easily or the user can use the pre-defined library of NewSan.

NewSan can present the results in Google Earth, and export the results to Excel spreadsheets. It also can generate graphs automatically within the model. Based on the graphs and on the Sankey diagrams, the user can easily analyse the results.

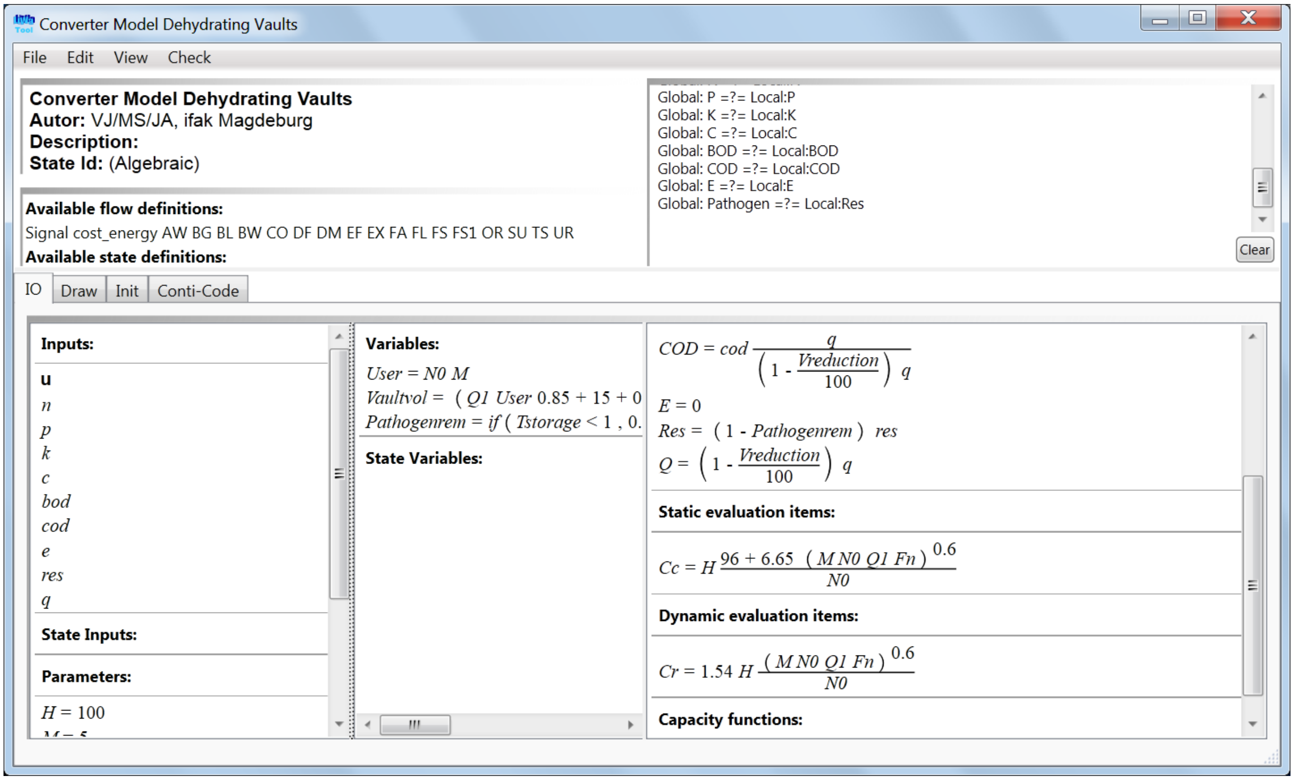


Figure 2 - User interface for definition of models and cost functions

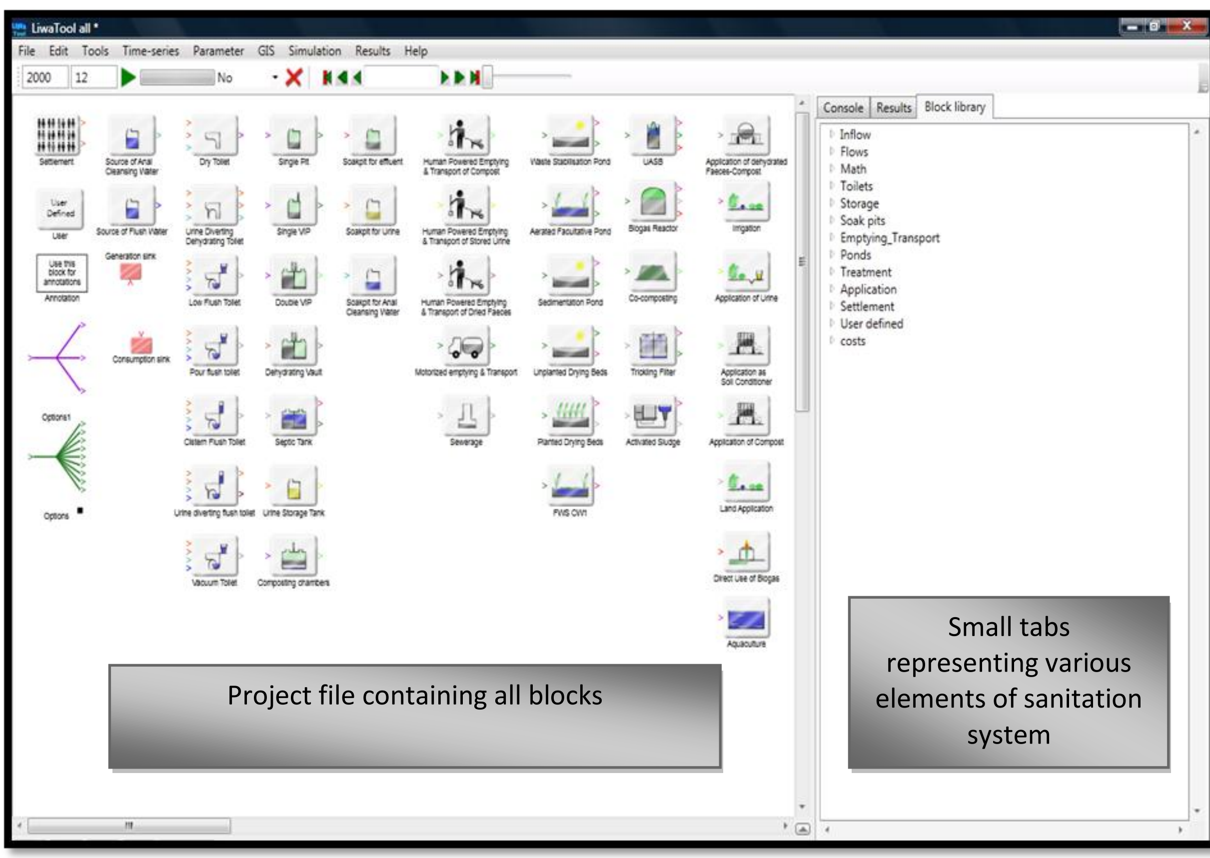


Figure 3 : Current version of NewSan Block Library

MODEL APPLICATION

To illustrate the potential of the NewSan simulator, the eThekwini/Durban case study (Roma et al. 2011) was considered in this project. In eThekwini Municipality, Urine Diverting Dehydrating Toilets (UDDT) were implemented to address the setback with the existing sanitation systems which were Ventilated Improved Pit (VIP) latrines. The high cost of emptying VIPs and the inaccessibility of many rural settlements led to the implementation of a more cost effective technology.

The data taken from the eThekwini case study (Roma et al. 2011) and used by the NewSan were:

- 75,000 household UDDTs have been installed in 65 peri-urban and rural areas of eThekwini Municipality;
- Total number of population served by UDDTs is approximately 450,000 considering 6 people per household;
- Urine soakpit is used for urine disposal;
- Double vault for faeces storage and drying. Removal of dried faeces is done after one full cycle (6 or 12 months);
- Investment cost of UDDT per household is EUR 585;
- Total investment cost of the project is EUR 62,179,000, which is equivalent to EUR 833 per household.

Based on the input data three scenarios were simulated:

a) Scenario A: Current situation – UDDTs
The UDDTs installed in eThekwini have a double-vault dry ventilated toilet based on separation of urine from faeces. The urine is diverted to a soakpit located near the toilet. Household members are told to bury the content of the first vault. Total population was served by UDDTs was approximately 450,000 people.

b) Scenario B: UDDTs considering population growth
This is the same Scenario "A" but considering a population growth of 5 % per year during 11 years and that the number of UDDTs is increasing accordingly. Initial population was 450,000 people.

c) Scenario C: UDDTs compared with VIP toilets
This scenario compares the the use of VIP latrines with UDDTs using the same input data as Scenario "A". Simulation could show the benefit of installing UDDTs in eThekwini to replace VIP toilets. Initial population was 450,000 people and no population growth was considered.

Scenario A – Current situation, UDDTs

Figure 4 shows the set up of the current system in eThekwini consisting of UDDT. It shows 3 input streams into the toilet: urine, faeces and anal cleasing water. Although anal cleansing water stream was represented in Figure 3, eThekwini system does not have this stream. The urine is diverted to a soakpit located near the toilet. The double vault UDDTs have two faecal vaults: once the first vault is full, it is sealed and allowed to rest and dry, and the pedestal is moved over to be above the second vault. The dry faecal sludge is manually removed from the vaults and the buried in soil or applied as compost.

Figure 5 illustrates the N fluxes and the daily amount of N potentially produced by the system. Urine stream produced by 450,000 people in eThekwini produce an N amount of 4324 kg/day, whilst 218.2 kg/day of N is generated from the faeces in the dehydrating vault (Figure 5a). Considering that plants demand 100 kg N/ha/year to grow potato or onions (Gensch et al. 2011), the urine produced per year by this community would theoretically cultivate around 15,783 ha. It is worth noting that this value would be substantially lower in reality as the P/N and K/N ratios in urine are slightly lower than in many mineral fertilizers, and lower than what many crops need according to fertilizer recommendations (Richert et al. 2010). However, urine is still considered a well-balanced N-rich fertilizer (Gensch et al. 2011). In total, 4542 kg/day and 570 kg/day of N & P, respectively can be potentially recovered in eThekwini (Figure 5b).

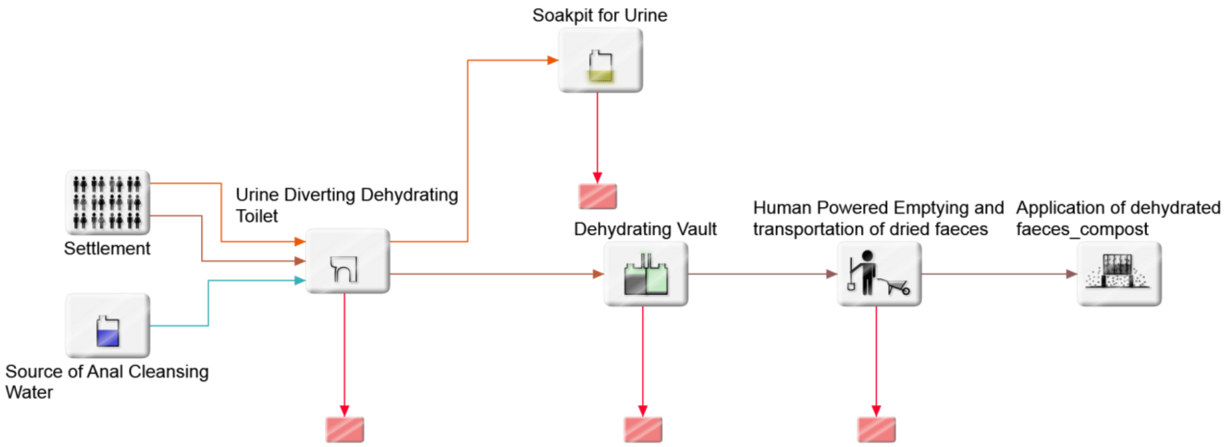
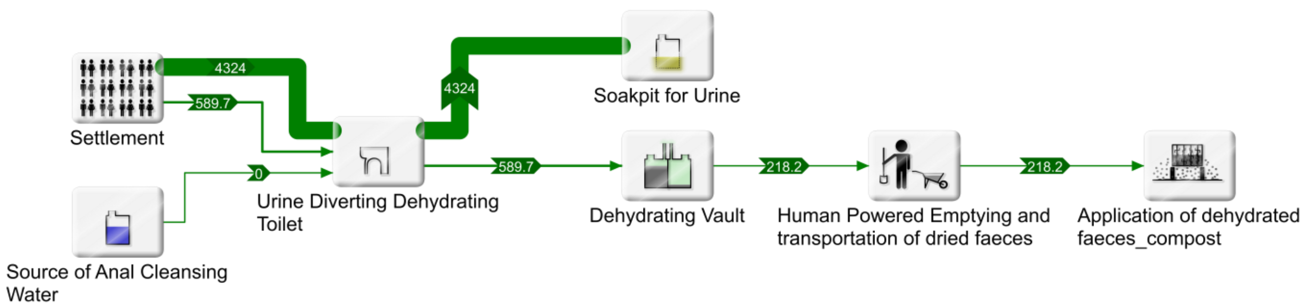


Figure 4 - Scenario “A” setup - eThekwini

(a)



(b)

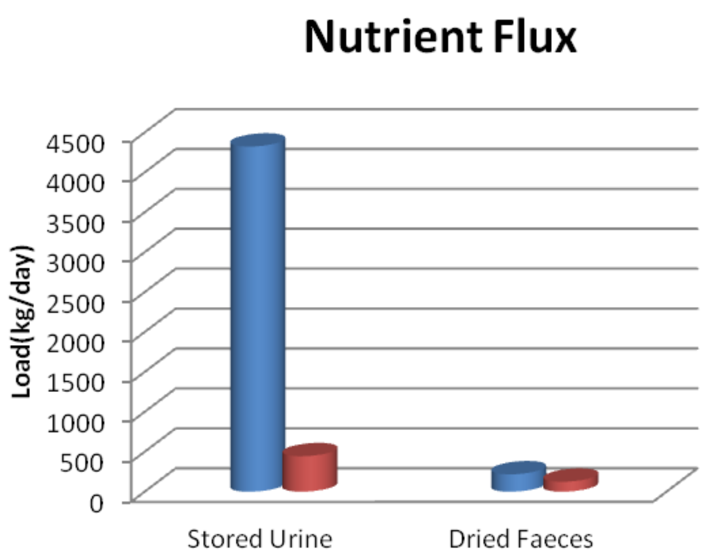
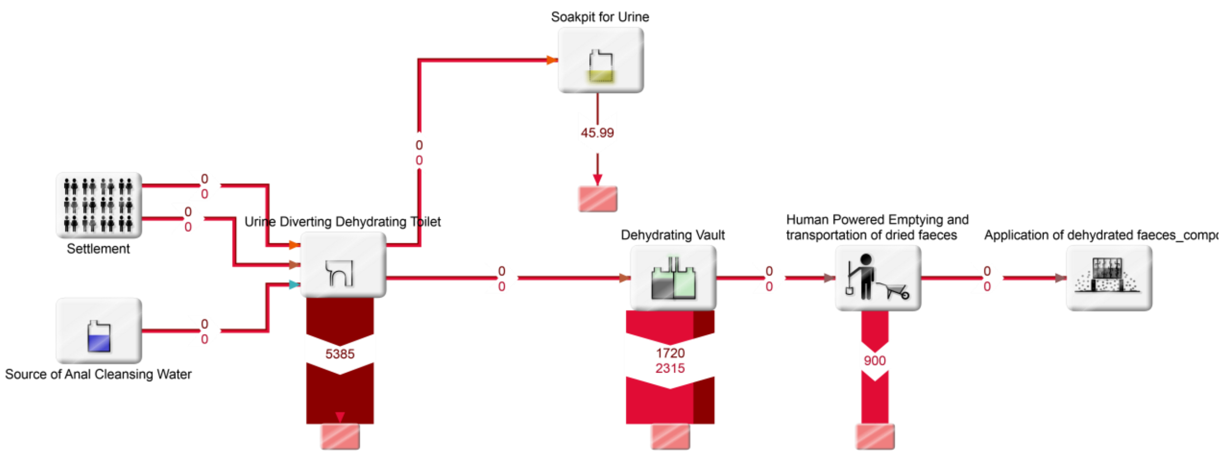


Figure 5 - Simulation of (a) N fluxes (kg/day) and (b) N daily load (kg/day) for Scenario “A” (Blue cone = Nitrogen; Red cone = Phosphorus)

Capital and operational costs of the eThekwini UDDT system is illustrated in Figure 6. It can be seen that capital costs were considered only in the toilet facility, dehydrating vaults and soakpit, while operational costs were included only in the dehydrating vaults and final transportation of the dried faecal sludge (Figure 6a), as for the other parts of the system no information has been available The capital cost per household is illustrated in Figure 6b. The difference between measured and calculated values can be attributed to the fact that NewSan estimated the costs based on SANEX which values are dated from 1995, and eThekwini costs are recent. Also conversion rates and inflation rates of previous years have not yet been implemented in this NewSan model.

(a)



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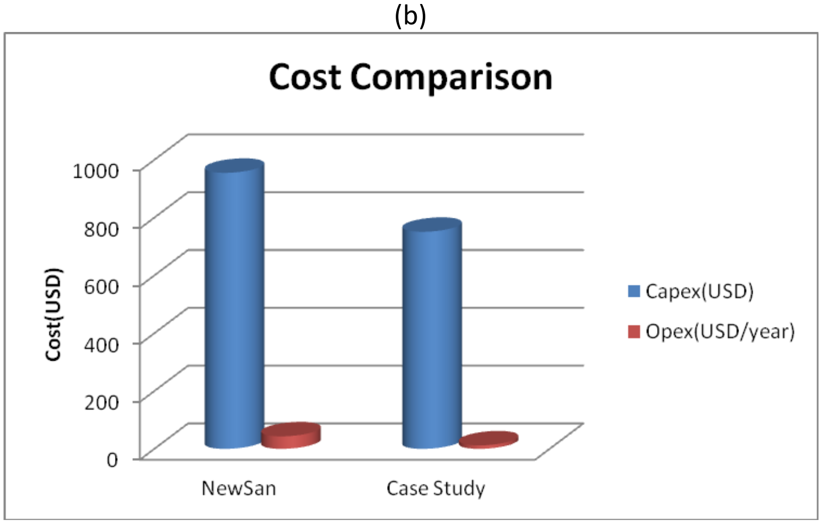


Figure 6 - Capex and Opex for Scenario "A" illustrated in (a) each part of the sanitation chain (capital costs per year and operational costs shown)and (b) as total costs per household. Costs are expressed in USD.

Scenario B - UDDTs assuming population growth rate as 5%

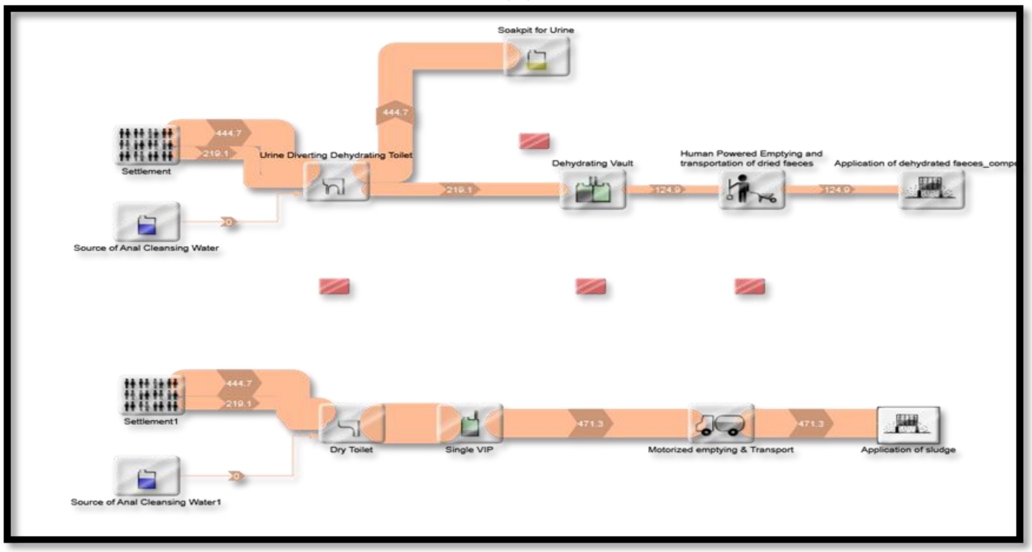
In another simulation, the N load in the final product of UDDT system when a population growth of 5% was added to the initial population. Population has been considered as time series function with increase of 5% every year. The total N load in 2022 will be 7.396e+06 kg/day (7396 ton/day). This output can help stakeholders to estimate the monetary value of their waste to be used as fertilizer.

Scenario C - UDDTs compared with VIP toilets

Figure 7 illustrates P & N fluxes in UDDT and VIP toilet systems for the case of eThekwini. It can be seen that the recovered P concentration from UDDT is 20% larger than VIP toilets, while N production by UDDT is only 12% larger than VIP toilets (Figure 7b).

In a similar way, Capex and Opex per household for both UDDT and VIP systems can be compared. As simulation of Scenario C shows, the capital costs of the UDDT system are much higher than VIP system. For the capital costs of theVIP system, neither waste treatment unit nor the number of the manual pit empyting technology (MAPET) units were considered as these were not in the case study publication. These two factors may have affected the accuracy of capital cost estimation of VIP system. However, the emptying cost of VIP latrines was estimated to be around 60% (EUR 188) more than eThekwine UDDT systems (5 to 10 EUR). Therefore, based on simple cost evaluation UDDT system appears to be a better option than the VIP system.

(a)



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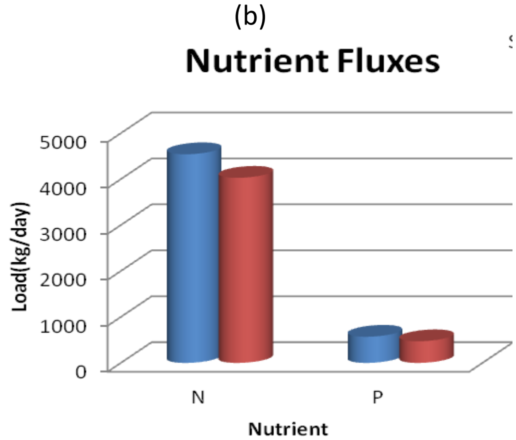

Figure 7: Simulation of (a) P fluxes (kg/day) and (b) N & P daily load (kg/day) for Scenario “A”. (Blue cone = Nitrogen; Red cone = Phosphorus)

CONCLUSIONS

The NewSan simulator assists the user to build sanitation chain and to simulate nutrient, energy and indicator bacteria fluxes for the same. It also gives cost evaluations of the sanitation chain. NewSan enables a comparison of conventional sanitation systems (e.g. VIP latrines) with “new technology systems” such as UDDT. To illustrate the potential of the NewSan, eThekwini case study (Roma et al. 2011) information was applied in the model. It has been possible only to illustrate the simulation of nutrient fluxes and costs due to the lack of

information about energy for this system. Therefore, analysis of various case studies in combination with data of innovative technology will lead to gradual improvement of the model.
Due to its flexible design, the NewSan simulator allows easy extension of the existing block library by modules for newly emerging sanitation options and to modify existing process and cost descriptions.

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