Economic feasibility study of the SANIRESCH concept in comparison with conventional wastewater treatment

Analyzed for the GIZ office building in Eschborn

Bachelor Thesis by Lisa-Marie Bischer

TECHNISCHE UNIVERSITÄT DARMSTADT

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- Analyzed for the GIZ office building House 1 in Eschborn -

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1. Introduction

The target of this thesis is to examine the economic feasibility of the sustainable sanitation system SANIRESCH (SANitary Recycling ESCHborn) in comparison with a conventional sanitation system. The SANIRESCH system has been installed in the GIZ's office building House 1 (Gesellschaft für Internationale Zusammenarbeit GmbH) in Eschborn, Germany.

This system is designed to treat three different wastewater lines separately. For this reason, a three line piping system has been installed where urine, brown- and greywater are transported separately. The SANIRESCH system has two main purposes. The first one is the precipitation of struvite (magnesium-ammonium-phosphate) from urine, which can be used in agriculture. The second is the water saving potential and nutrient elimination due to brown- and greywater treatment for reuse as servicewater. The wastewater treatment is performed by the use of two membrane bioreactos (MBR).

The aim of this investigation is to make a statement on the economic feasibility of the whole system compared to a conventional wastewater system.

By collecting and taking into account all relevant data for the complete system, it was additionally possible to make a statement on the whole system and also on the individual wastewater lines' efficiencies. This is possible because it became evident, which component of the SANIRESCH system contributes which amount to the costs of the overall project.

1.1. Motivation

The implementation of a system such as SANIRESCH is motivated by two reasons. First, due to the fact that phosphor is a finite element, ways of gaining it other than the conventional mining processes must be investigated. Estimations suggest that phosphor resources will be exhausted within the next 60 to 240 years (comp. CORNEL, P., SCHAUM, C., 2002, p. 8). The precipitation of struvite from urine is a possibility to regain this element.

Overall rising phosphor prices have two major reasons. First is its limited availability due to the fact that this element is finite. This leads to a constant shortage of phosphor combined with an increasing contamination by heavy metals. (comp. SCHAUM, C., 2002, p.149) Second it is not available everywhere but only occurs in certain regions of the world as elemental phosphor which can be gained by mining. This makes it difficult for poor countries' inhabitants to afford phosphor based fertilizers.

Gaining phosphor from urine or wastewater is an alternative source. Looking at struvite precipitation from urine is sensible because 50% of the phosphor in wastewater come from urine (comp. www.eawag.ch, 2012/07/01).

Formerly phosphor in wastewater was regarded to as pollutant but nowadays its value as resource is appreciated. The phosphor based element struvite is valuable as fertilizer for agriculture because it is the preferred fertilizer by plants, which can be gained by precipitation of wastewater. (comp. CORNEL, P., p. 66)

Studies within the SANIRESCH project have proven that there is no obvious difference between the growth on fields fertilized with struvite or with conventional mineral fertilizer (comp. ARNOLD, U., 2010, p.12). Also no loss of harvest has been recorded as an outcome of experiments made with struvite fertilizers (comp. ARNOLD, U., SPOTH, K., 2012, p.12).

Estimations on the substitution potential of mineral fertilizers by those gained from sewage sludge have shown that those alternative phosphor resources can substitute approximately 30% to 40% of conventional fertilizer demand in Germany. (comp. CORNEL, P., SCHAUM, C., 2002, p.13) About 80% of this demand evolves from fertilization in agriculture (comp. CORNEL, P., SCHAUM, C., 2002, p.10). Rough estimations for Germany suggest that approximately 17% - 25% of the mineral based fertilizer consumption could be substituted by fertilizers attained through urine treatment (comp. DWA, 2010, p. 9).

The second aspect of this thesis is the saving of water due to servicewater reuse. Although fresh water fees in Germany have increased less than the inflation rate since the year 2000, wastewater fees since the year 2007 (comp. SZYMANSKY, V., 2011, p.7), it is still sensible to investigate cost saving potentials by water reuse because lower running costs can be realized in every water consuming facility.

The trend towards urbanization leads to a higher fresh water demand and waste water production in and close to cities (comp. CORNEL, P., 2004, p.8). On the opposite, less water is requested and less wastewater is produced in rural areas.

This development influences water management. Urban areas have to handle an increasing demand of water whereas rural areas have to cope with the situation that existing sewage water treatment plants' capacities are too big regarding the amount of inhabitants in those areas.

By the use of service water, about 41% of fresh water can be saved in households (comp. CORNEL, P. et al., 2004, p.19). The implementation of wastewater reuse systems would lower the overall demand of fresh water in urban areas. This would be a positive change since water is a resource that is provided by local sources.

With the SANIRESCH system, those two components, struvite precipitation and wastewater reuse, are part of a semi-decentralized water system approach. A semi-decentralized system takes the advantages of a centralized water system, such as a reliable fresh water supply and those of a decentralized water system, such as water reuse at the location of occurrence.

The economic feasibility study gives information if those two components mentioned in the previous paragraph, can be implemented economically reasonable in an office building in Eschborn. To conduct the economic comparison of the alternative sanitation system SANIRESCH and a conventional sanitation system, all accruing costs within both solutions were gathered, structured and updated if this was required.

2. Material and used methods

To make an analysis of an alternative waste water treatment plant's cost efficiency, the SANIRESCH treatment system was investigated (for details on the system see chapter 2.1). The aim was to achieve a proper cost comparison of an alternative and a conventional waste water treatment system under equal circumstances for Germany as place of location.

Currently the SANIRESCH system is installed in the middle part of the GIZ's main office building, House 1, in Eschborn. Thus, approximately one third of the accruing greywater, brownwater and urine is treated within the SANIRESCH project. To make a realistic comparison for a complete office building for an alternative sanitation system and a conventional sanitation system, it has been assumed that the treatment system was installed in all parts of the GIZ's building. For this reason, the amounts of waste water production, fresh water consumption and urine accruing have been adapted to a scenario which involves the whole building. This made it necessary to adapt the amounts of actual demands and productions to the whole building as well as to align the investment, reinvestment and running costs of sanitary installations, piping system and machinery.

2.1. The SANIRESCH-System

The SANIRESCH system consists of three different treatment streams in which greywater, brownwater and urine are transported separately. Urine accrues by usage of waterless urinals and urine separation toilets. The brownwater in this system consists of the water which is produced at defecation including the required flushwater and toilet paper. Additionally it includes the flushwater which is produced after toilets have been used for urination. Greywater occurs at activities such as hand and dish washing as well as cleaning activities.

To make an individual treatment of all wastewater streams possible, two membrane bioreactors (MBR) and a struvite precipitation reactor have been installed.

Those MBRs have been implemented for the purification of brown and grey water so that service water is obtained. This service water in this project can be reused for purposes such as toilet flushing. However it has to be mentioned that at the moment the MBRs are only installed for experimental reasons and do not lead to actual reuse. This is because the GIZ had installed ground water pumps which supply the toilets with ground water as flushwater before the SANIRESCH project was started. Those ground water pumps have to be run to prevent that the ground water level rises too high which would cause problems in the two story underground car park underneath the GIZ office building. Nevertheless, in this thesis it is pretended that such a ground water supply was not given and that service water gained through the MBR-purification process is used in the building.

Furthermore the precipitation reactor for the extraction of magnesium ammonium phosphate (MAP, also called struvite) from urine was installed (for details see appendix, figure 15). The urine which is left over after the precipitation process is simply led to the sewage system. Nitrogen recovery is not taking place. The exact mode of operation for the struvite reactor will be explained in the corresponding chapter, 2.1.3.

At the moment, there are approximately 190 employees connected to the separation toilets in the middle part of the building. In addition, an unspecified number of guests, visitors and external workers have to be considered, using especially the visitor toilets on the ground floor.

The calculations in the following chapters have been upscaled to fictitious 651 employees who are pretended to be connected to the system within the whole building, including a certain number of guests, visitors and interns who are not registered.

Analog to the ratio of the numbers of female and male employees in the current system, there are 335 women and 316 men supposed to work in the upscaled scenario (GIZ, 2012, project documentation). The numbers of the upscaled scenario are the numbers that are used in this thesis since they are supposed to represent the circumstances that would exist if the alternative sanitation system SANIRESCH was extruded to the whole House 1. The number of male and female users will affect the amount of needed flushwater later on in the calculations. This is because men are thought to use the waterless urinals when urinating, where no flushwater is needed. Women are supposed to use the urine separating toilets both for urinating and defecating. If those toilets are only used for urination, a smaller amount of flushing water is used than for flushing after defecation. These differences in behavior are the main reason why the numbers of male and female employees are displayed separately. Detailed information on the occurring urine and the produced brown- and greywater are displayed in tabele 16 in the appendix.

This upscaling was carried out because the aim of this thesis is a comparison of the SANIRESCH and a conventional system assuming that both systems are run in the whole office building.

Each employee who is attached to the sanitation system is thought to have a workload of 250 days a year (GIZ, 2012, project documentation). The building is supposed to be worked at during 314 days of the year, which represents roughly the number of days a year, reduced by weekends and public holidays.

The assumption that the treatment plant is installed for all users of House 1 rather than the actual situation leads to a higher rate of uncertainty in all calculations, since numbers have been determined according to the current system, that is the implementation of the treatment plant for the middle part of the building. Hence it has to be factored in that the calculations in the upscaled system undergo more estimation than the actual system would include. The bigger scenario also leads to the need to adjust certain plant parameters as to configure them correctly regarding the higher fictitious number of users and the higher amounts of waste water and urine they bring along.

Nevertheless, scaling up the system is mandatory, as to enable the process of making a proper comparison with the conventional sewage system, which is still installed in the other two parts of House 1. An overview of the SANIRESCH system’s wastewater streams is depicted in figure 1.

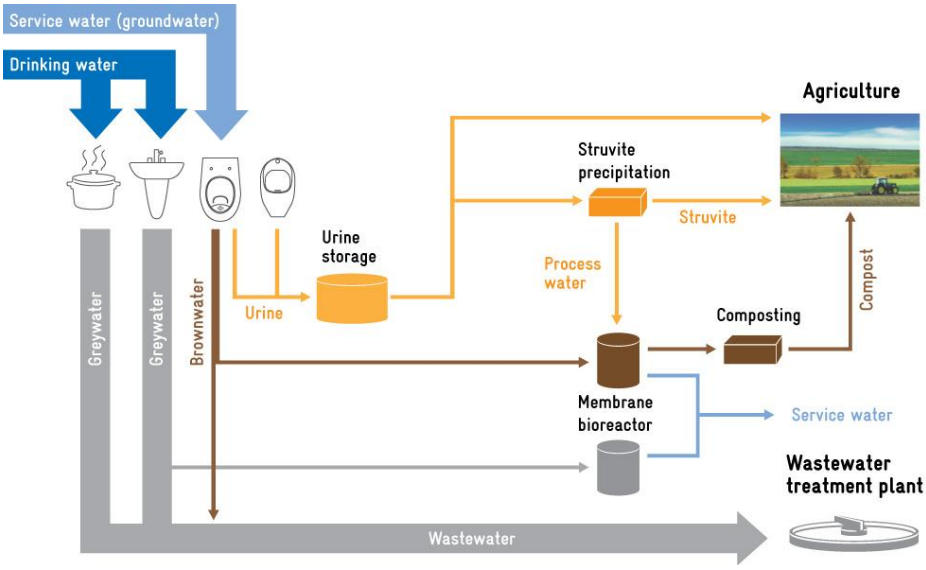


Figure 1 - SANIRESCH waste water streams (www.saniresch.de, 04.07.2012)

2.1.1. Necessary sanitary installation

In order to separate the waste water streams, alternations in the sanitary installation have to be made compared to a conventional sanitation system. The main change consists of the need of three different piping-systems (one for brownwater, greywater and urine each), the installation of urine-diversion flush toilets, also called NoMix-toilets, and waterless urinals.

Within the middle part of the building, where the SANIRESCH system is currently practiced, there are 38 urine-diversion flush toilets and 23 waterless urinals installed. The urine-diversion toilets are equipped with two flush choices. The small flush option uses 1 – 3 l per flush; the big option uses six l (comp. BRAUM, 2011, p. 14 f). For the small flush option, a mean of 2 l per flush is assumed.

In the upscaled system, the number of toilets has been set to 102 (comp, WU,Y., 2011, p. 58) and the number of urinals to 57. The numbers have not been simply tripled, because there are additional toilets and urinals installed in the ground floor of the middle part in House 1 due to high visitor traffic. This extra sanitation does not exist in the left and right wing of House 1.

To enable the separation of the three different waste water streams (greywater, brownwater, urine), individual pipelines must be installed. The need of this leads to significantly higher investment costs than within a conventional installation. Costs for the alls piping systems and the sanitary installations can be found in chapter 3, tables 3 through 6.

Furthermore, the running costs for the operation of urine separating toilets and waterless urinals are much higher than they are in a conventional scenario, since there is a high wearout of components which are responsible for the mechanical separation process and the stop of odor nuisance. Also there is the need for special cleanup treatment on a regular basis which also requests additional cleaning substances. For thorough calculations on this also see excel-sheets in the appendix.

In the interim report on the SANIRESCH project, the percentaged number of broken components compared to the total number of broken parts was apparent. Those components were valves, bowden cables, rubber rings, wash pipe connections and distance washers. However, to make calculations on a fictitious longer service life, a corresponding reference was needed. The valves were chosen as reference components for that reason, since a statement on the service life of those could be made due to the fact that the GIZ maintains documentation on exchanged valves. Additionally the ratio of broken valves and other components was known (comp. WINKER, M. et al., 2012, p.9). This led to the outcome that for every valve that breaks, 1.13 bowden cables, 0.43 wash pipe connections, 0.47 rubber rings and 0.3 distance washers needed to be exchanged.

Though there was a service life time of 221 days given for the valves in the interim report, this given service life did not seem adequate, since it also included many valves which have been build in and out again for experimental reasons and therefore reduced the overall running time unnaturally (comp. WINKER, M. et al., 2012, p.9) . As to figure out an appropriate service life, the technical documentation of built in valves which is maintained by the GIZ was consulted. Within this documentation, a timeframe in which no experimental replacement of valves has occurred was chosen as to generate a significant median for those values. The median rather than the average was chosen as outliers do not influence the overall outcome as strong.

This results in a service life of 495 days/valve. The service lives of the other components were calculated corresponding to the number of broken parts. For the other components this led to a service life of 429 days for bowden cables, 776 days for wash pipe connections, 759 days for rubber rings and 945 days for distance washers. (Calculations can be found in the appended excel sheet)

2.1.2. Membrane bioreactor technology

The service water, which is gained from the treatment of both MBRs, is of high microbiological and particulate quality due to the ultra filtration modules' small pore size of 38nm. The small pore size guarantees an absolute proper filtration with most bacteria and viruses retained (comp. WINKER, M. et al., 2012, p.15). This leads to the fact that the filtrated water meets bathing water requirements and can be reused for purposes such as toilet flushing, hand or laundry washing.

Regarding the residue of pharmaceuticals contained in the inflowing and the processed water of the brownwater MBR, Bisoprolol and Ibuprofen could be detected in the inflowing wastewater. In the processed servicewater only Ibuprofen could be detected. All other common pharmaceuticals did not appear within the detection limit of 1 $\mu g\ l^{-1}$. Concerning the greywater MBR, neither in the inflowing, nor in the processed water pharmaceuticals could be detected.

(comp. Winker. M. et al, 2012, p.34)

Additionally, nitrification takes place in both reactors. However, an anaerobe surrounding cannot be obtained, since the membrane needs a constant airflow to avoid a blockage. Hence, denitrification cannot take place in this system, which means that the nitrate cannot be reduced to nitrogen gas and thus, nitrate remains in the water.

As mentioned in chapter 2.1, brown water is produced when users defecate and when flushing the urine separation toilets after urination. The amount of grey water is gained by collecting tap water which is used for hand washing, water which is used in one of the kitchenette sinks or by one of the dish-washers.

In the actual SANIRESCH system, the grey- and brownwater MBRs are of different size. The greywater MBR is designed to treat 400 l per day, the brownwater MBR covers 550 l per day (comp. WINKER, M. et al., 2012, p.22). For detailed information on the occurring amounts see table 18 in the appendix.

Brownwater treatment

Before the brownwater MBR there is an intermediate storage tank installed that also contains a preliminary purification unit. As mechanical purification there is a screw installed, which lies in a perforated basket. This screw enables the first discharge of bigger materials such as toilet paper and sanitary products when brownwater enters the intermediate storage tank. After this first separation process, the water is led in the tank with stirring device. A stirring of the water in this tank happens to avoid a deposit of material at the tank's conus. A device for sediment discharge is installed at the bottom of the tank's conus. Sediments are withdrawn by suction automatically once a day. To avoid an interference of sediment discharge and the transfer of the brownwater from the intermediate storage tank to the MBR module, the pipe which transports brownwater to the MBR tank is installed at half height.

(comp. WINKER, M. et al., 2012, p.13f)

In the MBR tank, there is a constant flush air input underneath the membrane module to avoid the blocking of it. To keep the brownwater mixed, two additional flush air devices are installed at the bottom of the tank. Much aeration is needed due to the high part of organic matter in the brown water.

(comp. WINKER, M. et al., 2012, p.15)

The brownwater MBR and the relevant storage tank of the current installation are depicted in figure 2. Further, it must be mentioned that the primary treatment of the brown water in the fictitious scenario is designed differently than shown in figure 2, which describes the current situation of the SANIRESCH system being installed. In the upscaled scenario that is analyzed in this thesis, the application of one sedimentation tank and one buffer tank is presumed before the MBR unit, other than the application of only one intermediate storage tank with preliminary treatment in the actual system.

This is necessary because the amount of brown water is higher in the fictitious scenario and the actual preliminary treatment is not sufficient for this amount of water.

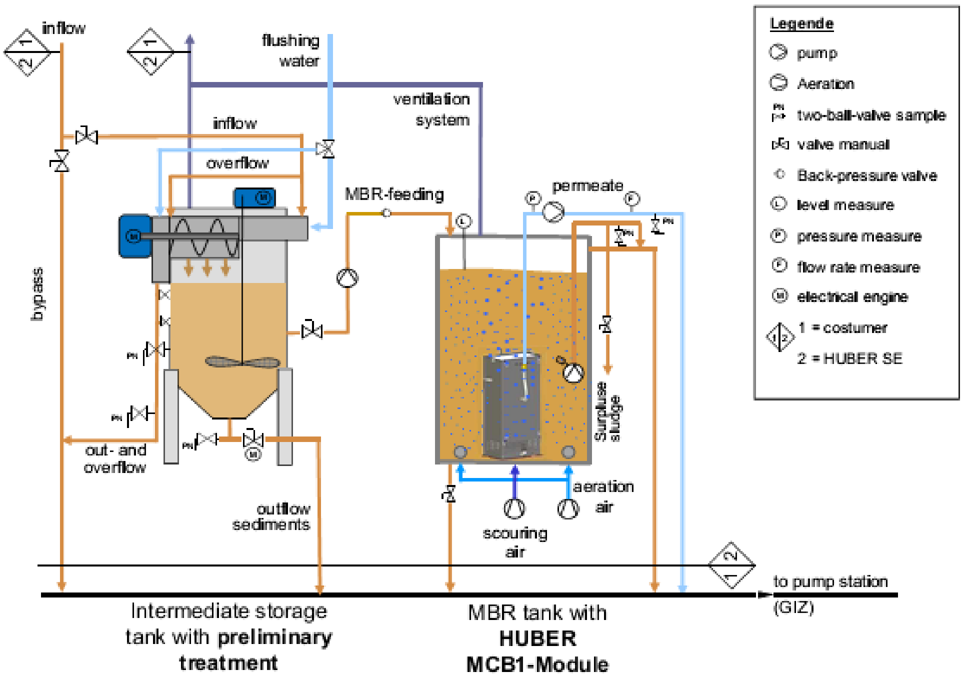


Figure 2 - Brown water MBR (HUBER Brown Water Treatment, 2011)

Within the greywater treatment unit the requirements of aeration and preliminary purification are lower compared to the brownwater unit. This is because greywater does not contain as much organic matter as brownwater.

Greywater treatment

The first component of the greywater treatment plant, as depicted in figure 3, is an intermediate storage tank, where a 3mm screen is installed to hold back materials such as hair other bigger particles before greywater enters in the tank. At the bottom of the tank, a device for sediment discharge is installed. As within the brownwater unit, sediments are withdrawn by suction automatically. The greywater in the intermediate storage tank is not stirred but simply aerated, which is sufficient due to less organic matter compared to brownwater. The lower impurity of greywater is also the reason why the tank surrounding the membrane module only contains one flush air device. The lower amount of organic matter compared to the brownwater MBR requires less oxygen. To avoid the MBR module from blocking, also here there is a flush air input underneath which provides constant aeration and keeps the greywater in the tank mixed. Additionally the greywater unit consists of a storage tank where the processed permeat is kept.

(comp. WINKER, M. et al., 2012, p.16f)

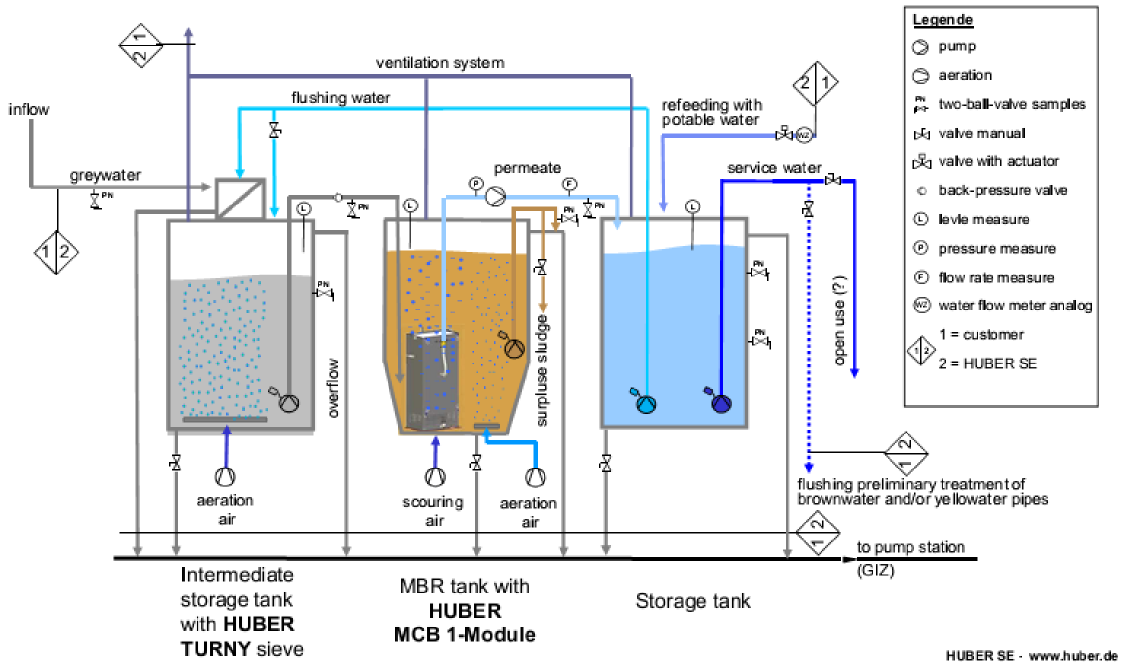


Figure 3 - Grey Water MBR (HUBER Grey Water Treatment, 2011)

The difference in size also applies for the MBRs that have been chosen in the upscaled scenario for 651 users. Because there are more users assumed as in the current system, the amounts of brown- and greywater had to be adjusted. Regarding the brown water MBR, the model MCB 4x3-1 with a treatment capacity of 7.5 m^3 per day was chosen. Regarding the grey water MBR the model MBC 3x2-2 with a treatment capacity of 3.75 m^3 per day were picked. Both MBRs are products of Huber SE, a mechanical engineering company and the project partner who provided the plant technology within the project.

2.1.3. Urine treatment

Urine which is separated through the urine separating toilets is treated in a struvite reactor to precipitate struvite from urine. The occurring urine is collected in four big PE-tanks that capture approximately 2000 l of urine each. The reactor has a maximum treatment capacity of 400 l per day and can treat up to 40 l per cycle. Each batch of treated urine consists of 800 liters and contains 20 cycles. (WINKER, M., SAADOUN, A., 2012, p.2) With a urine production of approximately 360 l a day the actual installed reactor is capable of treating the higher amount of urine in the upscaled scenario (comp. figure 16, appendix). This leads to a required time of about 2.5 days per batch of urine.

One liter of urine contains about 0.8 g of struvite (comp. figure 16, appendix). To start the precipitation the urine is led into the precipitation-reactor, where struvite is gained by adding 14 g of magnesium-oxide (MgO) to 40 l of urine. The MgO is contained in a small vinyl alcohol bag, which dissolve when being put in the urine. Mixing urine and MgO activates the precipitation process. 95% of the precipitation process takes place within the first 30 to 90 min after the MgO has been added and the mixture has been stirred three times for 30 sec each with a 30 sec break after each stirring interval (comp. WINKER, M. et al., 2012, p.20f). After the stirring, a sedimentation time of 90 min is allowed, where the struvite precipitates from the urine. Since the main part of precipitation happens within the first 90 min, it would be inefficient to admit a longer time span for this process.

To gain the precipitated struvite, the mixture is filled in needle felt filter bags in which the struvite remains as the urine passes through. There are five rotating filter bags placed in the struvite reactor, which are sufficient to filter the urine of one batch, which contains 800 l. After the processing of each cycle, which consists of 40 l of urine, the treated urine is filled in two filter bags. After the urine has run trough, the next two filter bags rotate to filter the urine of the upcoming cycle. This leads to the fact that each filter bag filters the amount of four cycles in sum.

After the processing of one batch, the filter bags are taken out of the reactor and remain in a drying box for three days, so the struvite can start drying. After those three days the bags are put in a drying oven for up to five days in the summertime and up to ten days in the wintertime until it is dried sufficiently for storage (personal information, HEYNEMANN, J., WINKER, M., 2012).

The dried struvite is separated from the needle felt filter bags by beating of the bags. This procedure leads to a loss of struvite due to the fact that approximately 12%-37% of the struvite that is contained in the filter bags sticks to those and cannot be removed (comp. apprendix, figure 18). For calculations of the amount of struvite that can actually be gained, an average loss of 24.5% of the precipitated struvite has been assumed, which leads to the circumstance that approximately 0.6 g of struvite per liter urine can be gained in the end of the precipitation process. This means that 0.2 g of the amount 0.8 g of struvite which is contained in one l of urine cannot be gathered although precipitated.

In the gained struvite, no residues of pharmaceuticals can be detected. Hence, it can be used as fertilizer without concerns from this point of view (comp. WINKER, M. et al., 2012, p.32).

Unlike the MBRs there was no need to design the struvite reactor larger in the upscaled scenario, since it is perfectly able to treat the fictitious amount of urine, 360l per day, produced by 651 people. An illustration of the struvite reactor can be found in figure 15 in the appendix.

Concerning the economic calculation, the possibilities of urine usage were split up in two different alternative sanitation systems (A1/A2). *First* it was assumed that urine could be used directly for fertilization (A1). For this scenario, no struvite reactor is needed but urine storage tanks with a capacity of approximately 8 m^3 would have to be retained. This is the amount of urine that occurs approximately during one month. *Second* the production of struvite was considered (A2). For the production of this, only two small intermediate storage tanks would be needed, with a capacity of 0.8 m^3 each, since the urine would be led directly in the struvite reactor after a batch of 800 liters has been collected. Those different scenarios lead to different investment and running costs, which were investigated separately in further calculations. The conventional sanitation system is referred to as system B. For detailed information on those three scenarios see chapter 2.1.5.

Regarding the legal permission of the usage of urine and struvite as fertilizers in agriculture, there are no clearly defined regulations yet. So far both substances can only be applied two cases. Either they can be used in agriculture by an exceptional rule if they are subject to research projects. Or struvite and urine can be declared as waste product and applied if the federal waste management agency of a state approves this.

(comp. DWA, 2008, p.194)

Further, the German regulation concerning the usage of fertilizers states that every substance can be used for fertilization, as soon as it is applied in another European country or member of the EFTA-states, which has happened for neither struvite nor urine so far (comp. §3, Abs 1, Satz 2, Nr.1,2 DÜNGG, 2012).

2.1.4. Problems within the current system

Whereas both MBRs and the struvite-reactor were found to run stable and reliable, there have been certain limitations in the interference-free operation of the urine separating toilets. The main problem turned out to be a constantly occurring blockage of the valves, which enable the urine separation process, whereby the valves need to be replaced rather frequently. This blockage is caused by the deposit of urine scale which could not have been avoided in the past, even though a monthly additional cleaning procedure with citric acid was performed. This leads to high additional spare part costs which make the running of the SANIRESCH system very expensive.

In addition it is also necessary to replace the odor-stop rubber ring, which is embedded in the urinals, once a year. Those costs are much lower than the replacement costs for the broken valves but they still occur and cannot be avoided, for if the rubber rings are not replaced a noticeable odor is exuded from the urinals. An omission of the replacement does not affect the performance of the urinals though.

One further detail which ought to be mentioned is that the running costs of the struvite reactor is high due to the high amount of manual labor which is needed for operation. This is mainly caused by the fact that the struvite reactor in the SANIRESCH project is a pilot plant and therefore does not have a high scale of automation implemented. Both this aspect and the purchase price would most likely change noticeably if those plants were fabricated in serial production. Nevertheless, a decreasing purchase price of the reactor would not influence the overall outcome noticeably, since it does not have a high impact compared to running costs such as manual labor or required spare parts.

Those problems will be subject to further investigation in the sensitivity analyses performed in chapter 3.5.

2.1.5. Systems which were subject to further investigation

The systems which were investigated in this thesis are two specifications of alternative sanitation systems (A1/A2) and one conventional sanitation system (B).

Alternative sanitation *system A1* assumes that the wastewater streams greywater, brownwater and urine are separated. Grey- and brownwater are treated by membrane bioreactors (MBR) as to gain process water for toilet flushing. The urine which accumulates in the building is gathered in a big PE-tank in the basement of the building and collected with a pump-trolley by a farmer once a month. The collection of the urine by the farmer is assumed to happen free of charge whereas the farmer has the tradeoff to receive fertilizer without charge. This system's realization presumes that the application of urine as fertilizer will become legal in the future although this is not the case at the moment, as mentioned in chapter 2.1.2. Due to the fact that urine needs to be stored a certain while before being used as fertilizer safely, the collecting farmer must ensure a proper storing which he or she carries out. Investigating feasible storage scenarios is not part of this thesis though. The system boundary is drawn when the fertilizing substance is being picked up. Costs for transport and storage are therefore not taken into account. This also counts for the produced struvite in scenario A2.

In the alternative sanitation *system A2* brown, grey and yellow water are separated as well but urine is treated in a struvite-precipitation reactor as to gain struvite as a fertilizer. After the precipitating process the urine is led into the sewage system. This leads to a slightly higher amount of waste water in system A2 than in system A1. Precipitating the struvite from the urine makes it easier to store the valuable element compared to the storage of large amounts of urine. The storage of struvite only requires a small amount of space and demands no special circumstances other than a dry environment. Sure enough, struvite as fertilizer cannot cover all of the plants' nutrient demands, but as phosphor is one of the major nutrients, plants need for growing, a phosphor-based fertilizer such as struvite can form a proper base feed. It has to be remarked that the use of struvite as fertilizer in agriculture is not yet legal.

The situation concerning the alternative fertilizer struvite is comparable to the use of urine in agriculture as mentioned in 2.1.2. This means, such fertilization cannot be implemented yet. Additionally the sales price of struvite cannot be determined safely as there is no traded yet on global markets but the element is only traded on spot markets. The price of one ton of struvite can be assumed as approximately 300€ (personal information according to ARNOLD, U., 2012/07/10)

The conventional *system B* acts on the assumption that regular toilets and urinals are installed. The whole waste water which accrues in the system is supposed to be led in a conventional sewer system. In this scenario, water is neither recycled, nor reused. The treatment of the waste water takes place in a regular sewage purification plant. Due to simplification with respect to the limited time given for this thesis, it is not taken into account that phosphor can be recovered from sewage sludge or sewage sludge ashes.

2.2. LAWA-methodology

To compare the differences and analyze the cost structures of the SANIRESCH system in contrast to the conventional sanitation system, the guidelines of the *Dynamic Cost Comparison Method 2005*, elaborated by the Working Group of the Federal States on Water (LAWA), were used.

Those LAWA guidelines serve the purpose to find the most cost-efficient result on a relative cost comparison base, while considering certain additional criteria concerning the special characteristics of water projects. The cost comparison method is the simplest method to compare different alternatives economically. Other than methods such as the utility analysis or the cost effective analysis for example, the dynamic cost comparison method must be regarded to as the minimum of economic information that is necessary to make a decision on water management activities. Solely a comparison of the monetary costs is part of the calculation, not the use or the sustainability of a system though. (comp. LAWA, 2005, p.1-2)

Making special assumptions is important due to the fact that water infrastructure projects are always long term investments and many long term developments cannot be foreseen clearly. The long operating time of water infrastructure can be taken into consideration by making a dynamic cost comparison. This means that real interest rates and real costs are used for calculations, which make it possible to pay respect to changes, which will most likely occur during the time. (Comp. LAWA, 2005, p.1 ff)

Further, there are three fundamental constrictive conditions. *First*, one must aim at a normative target, which has to be achieved. This has to be the main goal of each alternative scenario. *Second*, there has to be equality of benefit for each solution, because calculations such as a cost-benefit-equation are not made within the LAWA-approach. *Last*, monetarily not ratable effects of costs must be equivalent, since they cannot be considered in this method of cost-comparison. They should be discussed verbally in the overall assessment though.

(comp. LAWA, 2005, p.1-2)

Additionally, one has to be aware of the fact that all outcomes of the calculations only allow a statement on the *relative* advantage of each scenario. This means that only the information regarding the fact if one scenario is cheaper or more favorable than the other one can be obtained, but not if a scenario is absolutely advantageous, meaning that the benefits of this scenario are higher than its costs. (Comp. LAWA, 2005, p.1-2)

With respect to the character of water infrastructure investments, this has to be taken into account while making calculations regarding the different scenarios.

The analysis in this investigation is based on a comparison of the economic feasibility of the SANIRESCH system's costs and those of a conventional sanitation system. For that purpose, the annual costs (AC), the total project costs based on the gross present value (TPC) and the dynamic project costs (DPC) were determined. A further explanation of these costs' character will be given in chapter 2.2.3.

To detect factors, which influence the cost structure noticeably, various sensitivity analyses were made for both sanitation systems in their upscaled design (SANIRESCH/conventional). In those, different parameters were undergone increasing magnitudes of change for each system, to carve out sensible factors. Hence, the systems' reactions which were caused by those changes could be monitored. The comparison of the results found happened by the comparison of the systems' DPCs. Their outcomes are presented in chapter 3.5.

2.2.1. Framework of the LAWA-approach

The framework of the LAWA-methodology is composed of two main workflows, which are diagrammed in figure 4.

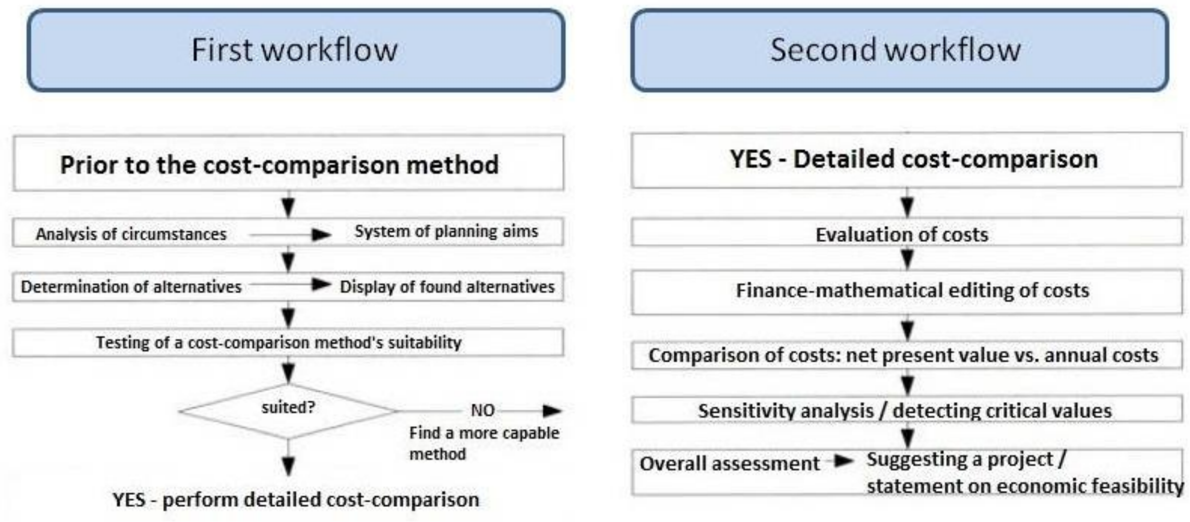


Figure 4 - According to LAWA, 2005, p.2-1

First workflow within the LAWA-approach

The first workflow involves three steps, which have to be done prior to the actual cost comparison. Their intention is to figure out whether the limited power of the LAWA-methodology is adequate to solve the problem of analyzing a chosen scenario. If not, other methodologies have to be considered. The LAWA methodology is suitable if a relative cost-comparison is sufficient in order to compare the alternatives which ought to be investigated and if the alternatives are equal regarding their benefits.

For the comparison of the SANIRESCH system and a conventional system, the application of the LAWA-methodology could be affirmed because the three fundamental constrictive conditions mentioned on page 18 were met. *First*, the normative target of both a systems is to handle and treat waste water as good as possible. *Second*, equality of benefit on a simple level is the same, since both solutions lead to a disposal of waste water and a supply of fresh water and potable water. *Third*, monetarily not ratable effects of costs, meaning negative effects that are put forth by a system which are not ratable in monetary units, are the same. For example, a broken treatment system would have the same negative consequences for the users in both cases. Thus, the LAWA-methodology was judged as suitable for a cost-comparison.

Second workflow within the LAWA-approach

The second step consists of the actual collection of relevant data and the preparation of this data for further calculations. This includes structuring the contents and grouping them according to the cost-groups recommended by LAWA.

In this thesis, it has been found adequate to structure the occurring costs by investment, reinvestment and running costs. This cost structure makes changes in assumptions easier realizable than a grouping according to machinery, construction and electro technological costs, which can be done alternatively.

Figure 5 - Structure according to LAWA, 2005, p.3-1 ff

"Investment costs"

Those costs occur only once, most likely in the beginning of a project, when machinery and other equipment are bought or installations are necessary. They might also occur in a further stage, for example when new equipment is bough to enhance the already installed system. Investment costs include the following costs:

- Costs of purchase (MBRs, struvite-reactor, toilets, urinal, pipes, further equipment)
- Costs of installation (either documented or as percentage of purchase costs)

“Running costs”

These costs can be assigned directly to the operation of a machine or other parts of the system where costs occur on a regular basis. Running costs are composed of:

- Costs for personnel (e.g. maintenance work, inspection, supervision)
- Energy costs (e.g. electricity, water, fuel)
- Material costs (e.g. spare parts, wear parts)
- Consumables (e.g. needle felt filter bags, MgO)
- Reinvestment costs of parts with a live span of five years or less

“Reinvestment costs”

Costs of this type accrue for parts of the system which are to be replaced within the investigation period of the whole system if their economic service life is shorter than the service life of the main system components.

Appropriate parameters were chosen according to LAWA where needed and economic assumptions were made where information was not provided. Those assumptions and parameters will be shown and explained in the following sub-chapter 2.2.2.

2.2.2. Basic parameters

First of all it is necessary to determine an overall timeframe for the study which is reasonable. According to LAWA, the project time span of 30 years has been chosen since this is the most common timeframe when investigating the service life of wastewater treatment projects (Comp. LAWA, 2005, p.4-2). General information to the most relevant parts of the system is given in table 1 and table 2.Further information can be found in table 19 in the appendix.

Table 1 - Service life of most relevant parts of the SANRESCH project

ITEM	SERVICE LIFE [YEARS]
Project's overall service life[1]	30
Toilets, urinals and other sanitary devices[2]	15
Membrane bioreactor[3]	15
Struvite reactor[4]	25
Urine tanks[5]	35
Pipes[5] (wastewater/freshwater)	35/45

1 LAWA, 2005, p.4-2

2 Own assumption. According to Prager, J., 2002, p.186, toilets in private households are supposed to have a service life of 25 years. Due to a more frequent usage in office buildings, the service life is reduced here.

3 Huber SE, 2012, provided data within project

4 Huber SE, 2011, provided data within project

5 Prager, J., 2002, p.186

One further aspect to be mentioned is the unitary yearly interest rate of 3% which is recommended by LAWA as the most reasonable interest rate for long term investments concerning water infrastructure. Since projects which try to investigate this kind of infrastructure always are afflicted with a high rate of uncertainty, no exact specifications can be made. Nevertheless an investment rate of 3% has shown to be a good estimation corresponding to investigations made by the federal road transport infrastructure planning. This value can also be used for water infrastructure planning. (Comp. LAWA, 2005, p.4-3).

Table 2 – Most important parameters for CCM

PARAMETER	AMOUNT
Fresh water fee[1]	1.99 €/m³
Waste water fee[1]	2.66 €/m³
Electricity costs[2]	0.25 €/kWh
Yearly interest rate[3]	3%
Hourly wage of maintenance personnel[4] (working at struvite reactor)	34 €
Struvite value[5]	300 €/t

1 WU, Y., 2011, p.60

2 LÖW, K., 2011, p.48, discounted

3 LAWA, 2005, p. 4-3

4 Braum, C., 2011, excel sheet as base for calculations

5 Ute, A., 2012, personal information

Also LAWA makes the recommendation, to leave real price increases or price increases of single parts of the system out of consideration and only refer to those as part of the sensitivity analyses. This simplifies the procedure. (Comp. LAWA, 2005, p.3-9)

2.2.3. Cost comparison

There are different parameters which can be used to compare the costs of the SANIRESCH and the conventional installation. In order to compare the value and the cost of each part of the installations properly, the numbers have to be referred to a unitary base year. In this thesis the year 2010 was chosen as the struvite reactor, which is a core unit for the whole system, has been implemented in this year. All occurring costs whether cost rows or costs which occur once, were based on the year 2010. To meet this goal, cost which occurred before 2010 were accumulated and costs which arose later were discounted with respect to the LAWA guidelines. Furthermore, all costs presented are gross costs (including taxes). This makes it possible to compare each systems's costs on the same base.

First of all, the total project costs (TPC) of each alternative can be opposed to each other. These costs include all accruing costs whether investment, reinvestment or running costs, calculating them regarding the same base year, including taxes and therefore having their GPV (gross present value) as outcome. Costs, which occur once, are simply discounted or accumulate to the base year. Cost rows (e.g. running costs) were transformed in costs occurring once, along the LAWA guidelines.

Second, also the annual costs (AC) of each alternative can be compared. For that reason, the running costs which occur each year were discounted to 2010. Further the investment and reinvestment costs were transformed in cost rows with the character of AC according to the rules of LAWA.

Last, there are the dynamic project costs (DPC), which represent a unit other than a simple monetary unit. This is necessary to pay respect to many of each system's advantages and potentials. The unit chosen for this analysis was [€/use]. It was found more significant to display the costs which occur as costs per toilet use rather than costs per cubic meter. This was done because an alternative and a conventional waste water system produce a different amount of waste water and use a different amount of potable water but the number of uses stays the same in both scenarios. Most likely, an alternative sanitation system will lead to higher installation and running costs, than a conventional system. However, with the installation of such an alternative system, less water will be used and therefore a smaller amount of money has to be spent on the usage of drinking water. Especially in areas with high water prices, it may make a major difference in the result of an economic analysis if a comparison based on the unit of [€/use] instead of [€/m³] is chosen.

3. Economic analysis

3.1. SANIRESCH System A1

The SANIRESCH system A1 is supposed to deal with the scenario that urine, which accumulates in the building, is collected and used as fertilizer in agriculture. Furthermore grey- and brownwater are treated in a MBR and reused as process water. A summary of all investment costs (IC), reinvestment costs (ICR) and running costs (RC) is given in table 3. More detailed information about the evolving of costs can be found on the excel sheet which is part of the appendix.

Table 3 – SANIRESCH system A1: IC, ICR, RC

	IC[1]	ICR [1]	RC[1]
GREY WATER MBR[2]	19,700 €	12,700 €	2,900 €/a
BRONW WATER MBR[2]	26,000 €	15,500 €	4,000 €/a
TOILETS[3] AND URINALS[4]	205,300 €	123,100 €	59,800 €/a
WATER PIPES[4]	385,700 €	-	-
URINE TANK[5]	4,900 €	-	-
WATER[6]	-	-	3,300 €/a

1 Costs rounded to thousand

2 Costs acc. to Huber SE

3 Costs acc. to Roediger Vacuum

4 Costs acc. to LAZO PAÉZ, A., 2010, p.78, including conecction of U1-U2

5 Own calculation due to bid

6 Amount determined by retroactive accounting by GIZ, 2012

The machinery investment, which has to be done for this system includes one brown water membrane and one grey water membrane with a sedimentation tank and a puffer tank each. The gross price of the grey water MBR adds up to 19,700€ gross, including all purchase and installation costs. The gross price of the brown water MBR sums up to 26,000€ gross and also includes all costs. The price difference between the two MBRs evolves from the different amounts of water that has to be treated. The brown water MBR has to handle approximately 7.6 m^3 per day whereas the grey water MBR is only configured to treat about 2.9 m^3 per day.

The installation of urine diversion toilets and waterless urinals requires a three line waste water pipe installation on the constructive side, which leads to higher costs for the piping compared to the conventional system. The investment costs for toilets and urinals add up to 205,300 € gross, the reinvestment costs add up to 123,100 € gross and for the three line piping system the costs amount to 385,700 € gross (for details see table 3). The investment costs for the piping system also include the costs for connecting the tanks and reactors with the piping system. Since the wastewater pipes are supposed to have a service life of 35 years and freshwater pipes of 45 years, their reinvestment costs are not taken into consideration (comp. PRAGER, J., 2002, p.186).

The same applies to the service life of the PE-tanks in which the urine is stored. Furthermore, a big PE-tank for the collection of urine has to be purchased. The size of the tank should not be smaller than 8m^3 since this is the approximate amount of urine which accrues in the building during one month if a daily amount of 0.36 m^3 is assumed. Due to the fact that the scenario plans that the gathered urine is picked up by a farmer, it was found reasonable that the farmer would come once a month to collect the urine. An amount of 8 m^3 can be picked up with a normal pumping wagon most farmers have for the transportation of water or manure. The price for a tank of this size and of tolerable quality was estimated at approximately 4,900 € gross, including installation. This price was found by a comparison of the costs for smaller and bigger tanks, where the price was known. The corresponding calculation can be found in the appended excel-sheet.

The required amount of fresh water in this scenario adds up to 2.88 m^3/d. Fresh water is used for hand washing, in the kitchnettes and in the dish washers of the building. The discharged amount of waste water amounts to 2.88 m^3 as well. This is caused by the fact that the amount of produced brow water is exactly the amount of water needed for flushing, thus this amount of water is reused within the system and additionally, the amount of urine is drawn out of the waste water system and stored in a tank. These amounts lead to water costs of about 3,300 € gross each year.

One finding that stands out is the high amount of running costs regarding urinals and toilets. The corresponding costs are extraordinary high because they include two major expense components, the cleaning costs of the toilets and the spare parts of the urine diversion toilets and the waterless urinals. With an amount of 1,172,000 € of total costs, the running costs regarding toilets and urinals are responsible for about 43% of the total project costs.

3.2. SANIRESCH System A2

The SANIRESCH system A2 is subject to almost the same circumstance as system A1. The difference in this system is that the urine is not collected but treated in a struvite precipitation reactor with the goal to gain struvite as fertilizer. This means there are costs occurring additionally for the struvite reactor, a collection tank and a tank which leads the urine in the reactor, an oven and a drying box to dry the precipitated struvite and a rain barrel to store it. A summary of IC, ICR and RC is listed in table 4.

In this system's installation, costs regarding the machinery investment for the grey and brown water MBRs stay the same as in SANIRESCH system A1. The costs for toilets, urinals and pipes remain the same a well.

Thus, there are higher investment, reinvestment and running costs for the machinery costs and also higher costs in waste water disposal in this system since there is slightly more waste water to be disposed. Nevertheless, the amount of struvite precipitated and dried can be sold. On detailed information how the struvite amount is estimated, see chapter 2.1.3.

The extractable amount of struvite in this system sums up to approximately 60 kg per year (for calculations see appendix, excel-sheet). With its value of about 300 € per ton (comp. table 2), this makes earnings of 18 € per year. The gathering of urine, which is done in system A1 does not bring forth any earnings.

Table 4 - SANIRESCH system A2: IC, ICR, RC

	IC[1]	ICR[1]	RC[1,9]
Grey water MBR[2]	19,700 €	12,700 €	2,900 €/a
Bronw water MBR[2]	26,000 €	15,500 €	4,000 €/a
Toilets[3] and Urinals[4]	205,300 €	123,100 €	59,800 €/a
water pipes[4]	385,700 €	-	-
Struvite reactor[2]	22,500 €	10,700 €	-
Urine tanks[5]	2,500 €	-	-
Dirt Filter[6]	700 €	900 €	-
Drying Box[7]	1,300 €	800 €	-
Drying oven[7]	1,200 €	700 €	2,600 €/a
Rain Barrel[7]	40 €	-	-
Water[8]	-	-	3,600 €/a
Struvite production	-	-	21,100 €/a

1 Costs rounded to thousand

2 Costs according to Huber SE

3 Costs according to Roediger Vacuum

4 Costs according to Lazo Paéz, A., 2010, p.78, including also conecction of U1-U2

5 Own calculations due to bid

6 personal information, Winker, M., 2012

7 Braum, C., 2011, excel sheet used for struvite storage

8 Amount determined by retroactive accounting by GIZ, 2012

9 Costs for maintenance personnel according to Braum, C., 2011, excel sheet

The investment costs of the struvite reactor already include the installation costs. It has to be mentioned at this point that the struvite reactor referred to in this analysis is a prototype and therefore more expensive than a comparable reactor would be when produced in serial production. The service life of the reactor can be assumed longer than the MBRs, because it is made of extremely durable material. A service life of 25 years can be assumed therefore. (Personal information Schlapp, C. (Huber SE), E-Mail, 2011/02/03)

3.3. Conventional sanitation system B

Other than in both SANIRESCH systems, the conventional system requires no special equipment. The costs which occur here can be limited to toilets, urinals and waste water pipes as well as running and reinvestment cost regarding those positions.

Table 5 gives an overview of the cost in system B.

Also in this scenario, it is obvious that the running costs are somewhat high but still distinctly lower than in both alternative sanitation systems. The high amount is again caused by the fact that the cleaning of the restrooms is taken into account but the fact that sum is noticeably lower, gives an impression of the impact of spare part costs, which accrue in the SANIRESCH systems.

Table 5 – Conventional system B: IC, ICR, RC

	IC[2]	ICR[2]	RC[2]
TOILETS AND URINALS[1]	98,200 €	63,100 €	34,900€/a
WATER PIPES[1]	256,900 €	-	-
WATER[3]	-	-	13,200 €/a

1 According to LAZO PÁEZ, A., 2010, p.78

2 All costs rounded to thousand

3 Calculated with amount determined by retroactive accounting by GIZ, 2012

As a result, it can be stated that the running costs due to fresh water consumption and wastewater production are much higher than in both alternative sanitation systems.

3.4. Cost comparison

The costs of all scenarios were grouped according to the guidelines suggested by LAWA (2005), using total project costs (TPC [€]), which are based on the gross present value of all expenses, annual costs (AC [€/a]) and dynamic project costs (DPC [€/use]). A brief overview of these results can be found in table 6. Detailed information on the evolving of all occurring costs and on which factors those costs depend on can be found in the appendix. In this sheet e.g. a grouping of machinery costs or running costs is listed with their value according to TPC, AC and DPC.

Table 6 - Summarized presentation of TPC, AC and DPC

	TPC[1,2]	AC[1,2]	DPC[2]
SCENARIO A1	2,166,000 €	110,000 €	12.68 €-Cents/use
SCENARIO A2	2,713,000 €	139,000 €	15.88 €-Cents/use
SCENARIO B	1,361,000 €	69,400 €	7.96 €-Cents/use

1 Costs were rounded to thousand

2 Costs given are gross costs, base year 2010

As a first view on the summarized costs, table 6 shows clearly that both alternative sanitation scenarios are noticeably more expensive than the conventional sanitation system. For a graphical impression, this is depicted in figure 6. In this graphic it becomes evident that the running costs are accountable for a high amount of total project costs for all sanitation systems.

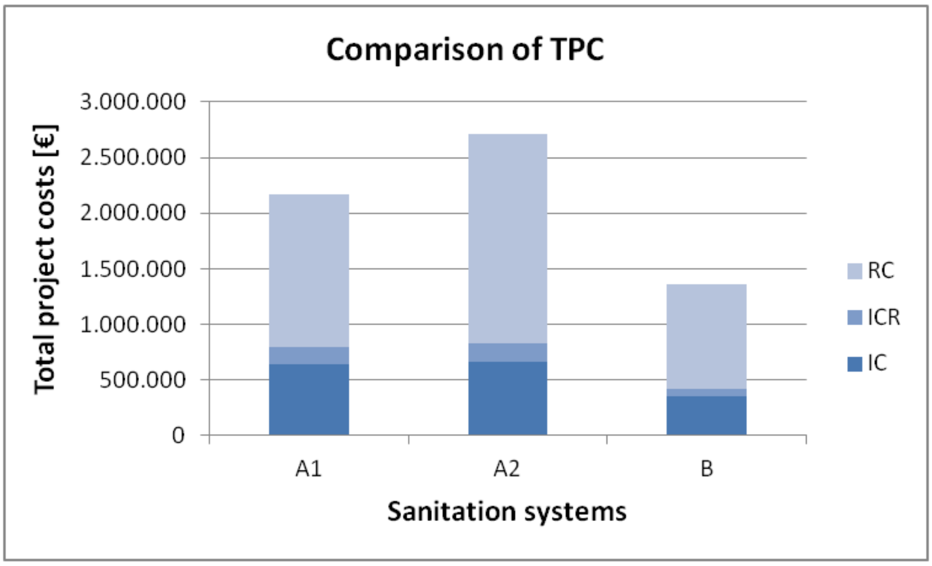


Figure 6 - Distribution of systems' TPC (total project costs)

For both alternative sanitation systems one cause for this can be found in the higher investment, reinvestment and running costs of the alternative sanitation systems' toilets and urinals. When comparing the values depicted in tables 4 and 5, it can be seen that the IC for the alternative sanitation systems' toilets and urinals are 107,100€ higher than those for conventional sanitation installations. The same regards to the ICR and the RC, which are 60,000€, respectively 24,900€/a more expensive.

Additionally, alternative system A2 works with a struvite precipitation reactor, which causes further investment, reinvestment and running costs together with the needed equipment. As table 4 displays, the struvite precipitation generates costs in the amount of 33,200€ for IC and ICR, which do not occur in the conventional system. Further 21,100€/a evolve as RC from the struvite precipitation process.

When comparing system A1's and system B's DPC in table 5, it can be seen that the alternative system is about 1.6 times more expensive than the conventional system. Sanitation system A2 is even close to twice as expensive as B. Parameters that lead to a change in feasibility will be examined in the sensitivity analysis.

3.5. Sensitivity Analyses

In order to find parameters which influence the costs of the systems, the most probable changes of circumstances have been taken into account. Those changes include a rise of water fees and of the energy price and price decreases concerning certain equipment of the SANIRESCH system. The parameters of the alternative sanitation system towards which the system was thought to be potentially sensitive were the amount of manual labor required for struvite production, the service life of the spare parts that are necessary in running the urine separating toilets and the waterless urinals and the investment price of such toilets and urinals.

An overview of all scenarios and the corresponding assumptions which have been made can be found in table 7.

Table 7 - Overview of scenarios

SCENARIOS	ASSUMPTIONS
I	Increase of automation
II	Increase of service life of urine separation toilets' spare parts
III	Decreasing investment costs of urine separating toilets and waterless urinals
IV	Increase of fresh and waste water fees
V	Combination of I and II
VI	Combination of I, II and III
VII	Combination of I, II, III and IV
VIII	Combination of II and III
IX	Combination of II, III and IV
X	Increase of energy price

3.5.1. Sensitivity analysis I

The first scenario assumes an increase of automation within the struvite production as base for the analysis. Hence, it has an impact on all sanitation system designs where the alternative A2 is taken into consideration.

Due to the fact that the actual struvite reactor is a prototype, which has not been completely optimized to meet to customers' demands yet, it requires a high amount of manual labor, since almost none of the processes work automatically. This includes the manual production of the polyvinyl alcohol bags which contain the MgO that is added to the urine, which requires about 60 min per batch. Each batch contains 800 l of urine from which a total of 0.48 kg of struvite can be gained (for detailed information on the size of a batch and parameters regarding struvite, see chapter 2.1.3). The needle-felt filter bags and MgO bags have to be inserted in and taken out of the reactor manually, which requires roughly 15 min per batch. Further, the gained struvite is beaten out of the needle-felt filter bags manually after those have been dried in the drying oven. This process of beating again requires 100 min per batch. Additionally, the storage tank is cleaned manually after every other batch of urine has been processed, which takes about 30 min per batch and the filter which is installed between urine storage tank and struvite reactor is cleaned after every batch, which takes approximately 20 min. Further 36 min must be considered as general set-up and reactor chamber cleaning time. This leads to an overall demand of 4.35 h of manual labor per processed batch of urine, which cause 148€ (rounded) as wage for maintenance personnel with an hourly wage rate of 34€ as listed in table 2. The sum of manual labor, needle-felt filter bags, MgO and the energy which the oven requires for drying the struvite lead to 190€ of running costs per kg struvite. A detailed listing of costs can be reviewed in the excel sheet in the appendix.

(GIZ, 2012, personal information)

Those costs of 190€ per kg are much higher than the current value of MAP, which can be approximated with 0.3 € per kg (compare table 2).

The assumption made in this thesis is, that an increase of automation will happen if the struvite reactor's supplier detects a certain potential that the reactor will be demanded on the market. This gives reason to him to pursuit further enhancement of the reactor, because an improvement regarding the automation would be absolutely necessary due to user-friendliness and only a user-friendly system will be successful on the market. An increasing demand will develop if there is a stronger willingness to use struvite in agriculture or as fertilizer in general and if the precipitation of struvite from urine is accepted as gaining process. Reasons for an increasing need of struvite as fertilizer were mentioned in chapter 1.1. Those motives are e.g. the increasing phosphor price due to phosphor's finite character and the possibility to lower the phosphor load in wastewater in general.

A greater demand would also lead to an increasing number of produced reactors. One can imply that if reactors were produced in serial production, this would result in a decreased price based on scaling effects.

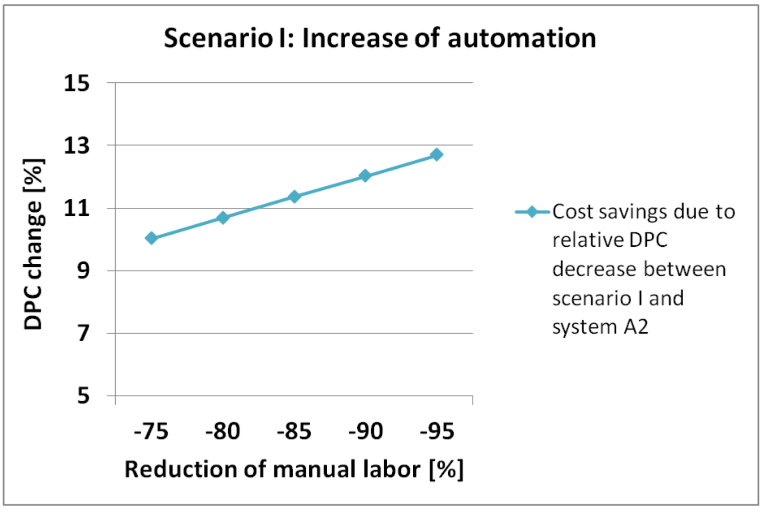


Figure 7 - Curve's progression of DPC for Scenario I

For the execution of this sensitivity analysis, a cost reduction of 75% up to 95% regarding the costs for manual labor has been found reasonable. This can be justified, as 148€ of the 190€ that have to be assessed as running costs within struvite production, come from manual labor. The biggest part of the required manual labor evolves from the beating of the filter bags (100 min per batch), the production of the MgO bags (60 min per batch) and the cleaning, respectively the rinsing of reactor and filter (50 min per batch together). Those processes are all subject to potential automation. If they were automated, a high amount of manual labor time would fall away. The time required for general set-up will decrease automatically if the other activities are not longer required.

The other running costs such as expenses for needle-felt filter bags and MgO have remained unchanged in the calculation.

Figure 7 demonstrates the trend with witch cost savings can be realized due to increasing automation.

Table 8 - Change in DPC for Scenario I [€-Cents/use]

	-75%	-80%	-85%	-90%	-95%
DPC I[1]	**14.29**	**14.18**	**14.07**	**13.97**	**13.86**
System A2					
DPC difference[2]	- 1.59	- 1.70	- 1.81	- 1.91	- 2.02
DPC change [%][3]	- 10.02	- 10.69	- 11.36	- 12.02	- 12.69

1 DPC of scenario I (based on system A2)

2 DPC difference between scenario I system A2

3 Relative DPC change between scenario I and system A1(A2)

As can be demonstrated in table 8, cost reductions on the alternative A2's running costs will lead to an overall cost reduction of 12.69%. Changes of this magnitude can be called significant for the system in any case. Even if only a small degree of automation is reached, for example if the needle felt filter bags were beaten automatically, already a cost reduction of more than 10% could be realized. Hence, a cost reduction in this part of the system is not only desirable but essential to reach a marketable product.

3.5.2. Sensitivity analysis II

This analysis treats the assumption of a longer service life of the toilets' spare parts. In the beginning of this scenario's description, one must mention that the increase of service life refers to a longer service life of the valves and other technical components which enable the mechanical urine separation process in the toilets. Because those components only last a rather limited time and are quite expensive, they account for about 190 €/year per toilet, which sums up to the high amount of running costs of 19,900 € per year for the whole building, only for spare parts (comp. appendix, excel-sheet). An increase in the spare parts' service life time will lead to a decrease of running costs in both SANIRESCH systems.

The only spare parts used in the waterless urinals are rubber odor stoppers, which are taken out and cleaned by the cleaning personnel once a week. Those odor stoppers are not part of the investigation.

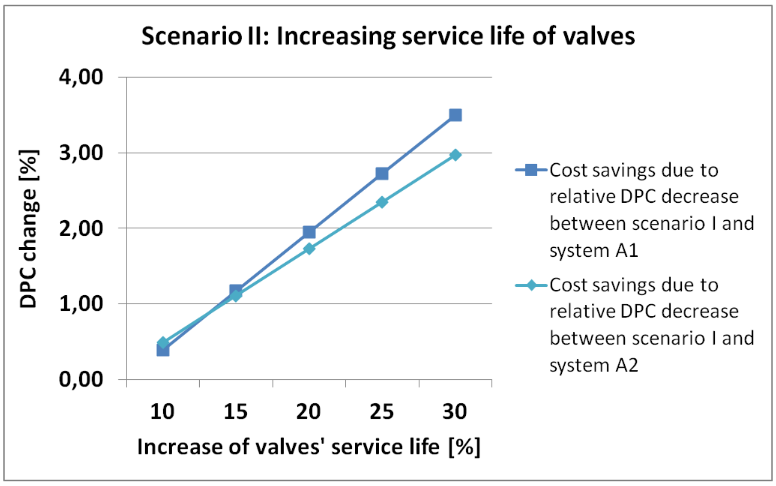


Figure 8 - Curves' progressions of DPC for Scenario II

A cost reduction of the spare parts can either happen due to a rising demand for NoMix toilets or better quality. An increasing demand of those parts will happen if there is a rising motivation to separate yellow and brown water. As the number of toilets and urinals becomes bigger, it will cause a correlated higher demand of spare parts. As for the changes regarding the price of those spare parts, they could either become cheaper due to the increased demand and the related potentials of mass production or their quality could improve, respectively they could become more suitable in design for the toilets. Since it is quite difficult to make an appropriate estimation on the cost reduction potential and additionally it cannot be foreseen if an increasing demand will occur, a decrease of price was estimated regarding an improvement in quality which results in a longer service life.

An extension of service life has been chosen carefully, since the spare parts are stressed mechanically. Additionally, it cannot be clearly estimated which effect a potential enhancement in component quality or suitability would have on the extension of the service life.

After discussion with experts at the SANIRESCH project meeting it could be found out about the fact that compared to other alternative sanitation systems that run with the same type of urine separating toilets under similar conditions, there is an increased number of broken parts to be registered in the SANIRESCH system. The reasons could not be determined, but due to this information and the statement that spare parts are required much less frequently in other sanitation systems, equipped with the same type of NoMix toilets, a maximum longer service life of 30% was assumed as reasonable. Changing steps of 5% were chosen in investigation, starting at a change value of 10%.

Table 9 - Change in DPC for Scenario II [€-Cents/use]

	+ 10%	+15%	+20%	+25%	+30%
System A1					
DPC II[1]	**12.28**	**12.16**	**12.05**	**11.94**	**11.82**
DPC difference[2]	- 0.40	- 0.52	- 0.63	- 0.74	- 0.86
DPC change[3] [%]	- 3.15	- 4.10	- 4.97	- 5.84	- 6.78
System A2					
DPC II[1]	**15.48**	**15.37**	**15.25**	**15.14**	**15.03**
DPC difference[2]	- 0.40	- 0.51	- 0.63	- 0.74	- 0.85
DPC change[3] [%]	- 2.52	- 3.21	- 3.97	- 4.66	- 5.35

1 DPC of scenario II, based on system A1 (respectively system A2)

2 DPC difference between scenario II, based on system A1 (A2) and system A1 (A2)

3 Relative DPC change between scenario II (based on system A1 (A2)) and system A1(A2)

When evaluating the graph in figure 8, it is evident that a cost reduction due to longer service lifes also leads to a noticeable change in project costs. Even though the slopes of both graphs indicate significance in demonstrating that there is an effect, the overall consequences for the project costs are only moderate to medium. The steeper slope of the scenario on A1 results because the TPC of A1 is lower than the one of A2. Therefore the same amount of monetary change leads to a higher impact. Evidence of the impact through a comparison of percentaged changes can be found in table 9. The maximum DPC change taking place for scenario II based on system A1 is 6.78%, whereas the maximum DPC change of scenario II based on system A2 is only 5.35%.

It has to be pointed out though that there is quite a potential in cost reduction if it can be managed to achieve even a longer components' service life.

3.5.3. Sensitivity analysis III

The assumption of this scenario is that there will be a decrease in the price of urine diversion toilets and waterless urinals. This development will lead to lower investment and therefore also lower reinvestment costs. Such a tendency could be caused by a series of changes. First the demand of such toilets and urinals must increase. This could be either caused by a stronger readiness to fertilize with urine based products, or by a stronger ambition to save water through the use of service water. In the first case, the aim is to substitute conventional fertilizers by urine based fertilizers. The urine needs to be separated before processing or storing it. For this purpose, urine separating toilets are needed. In the second case, if the aim is to gain process water, the waste water has to be cleaned before reusing it. Those are the two circumstances that both would lead to a higher demand of separating toilets.

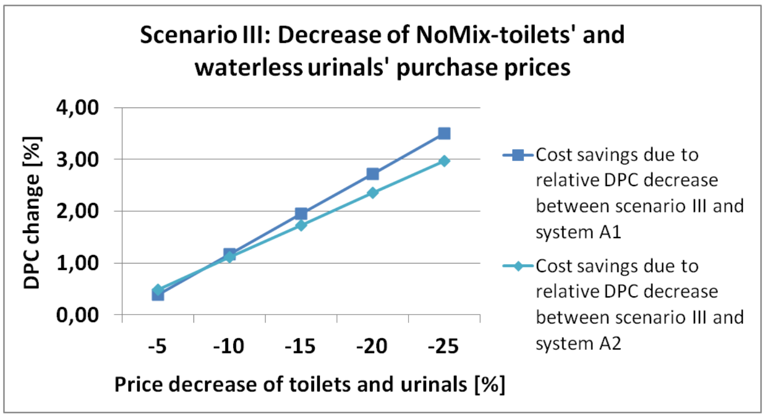


Figure 9 - Curves' progressions of DPC for Scenario III

Regarding the slope of A1 and A2 the same applies in this sensitivity analysis as in analysis II. Because the TPC of A1 are lower than the one of A2, a decrease of investment and reinvestment costs affects the DPC of A1 stronger than it does for A2. This is graphically depicted in figure 9.

A look at table 10 shows that there is a change detectable but it does not account for a big difference in the DPC because the maximum cost saving is 3.50% for A1, respectively 2.97% for A2.

Table 10 - Change in DPC for Scenario III [€-Cents/use]

	- 5%	- 10%	- 15%	- 20%	- 25%
System A1					
DPC III[1]	**12.63**	**12.53**	**12.43**	**12.33**	**12.23**
DPC difference[2]	- 0.05	- 0.15	- 0.25	- 0.35	- 0.45
DPC change[3] [%]	- 0.39%	- 1.17%	- 1.95%	- 2.72%	- 3.50%
System A2					
DPC III[1]	**15.80**	**15.70**	**15.60**	**15.50**	**15.41**
DPC difference[2]	- 0.08	- 0.18	- 0.28	- 0.38	- 0.47
DPC change[3] [%]	- 0.49%	- 1.11%	- 1.73%	- 2.35%	- 2.97%

1 DPC of scenario III, based on system A1 (respectively system A2)

2 DPC difference between scenario III, based on system A1 (A2) and system A1 (A2)

3 Relative DPC change between scenario III (based on system A1 (A2)) and system A1(A2)

Due to the fact that small changes, such as a price reduction of 5% only lead to an overall cost reduction of less than 1%, it has to be stated that the system is potentially sensitive to price reductions of investment costs in toilets and urinals but only if the price decrease is considerably. It cannot be foreseen if or under which probability this will happen. For that reason the sensitivity towards price changes of toilets and urinals under the assumptions made for the SANIRESCH system has to be negated.

Nevertheless sensitivity analysis VIII was made as analyses II and III correlate to the same development regarding an increasing demand of urine separation toilets (comp. chapter 3.5.8)

3.5.4. Sensitivity analysis IV

In this analysis rising water fees are taken into consideration. Because the waste water production and fresh water consumption in the conventional scenario B are responsible for higher running costs, it was assumed that it would also lead to a significant cost change in system B if those fees were supposed to rise. The SANIRESCH systems are characterizes by low fresh water consumption and low waste water production. In system A1 3,300€ per year have to be spent on waste and fresh water, 3,600€ per year in system A2 whereas in system B the water consumption and waste water production accounts for 13,200€ per year.

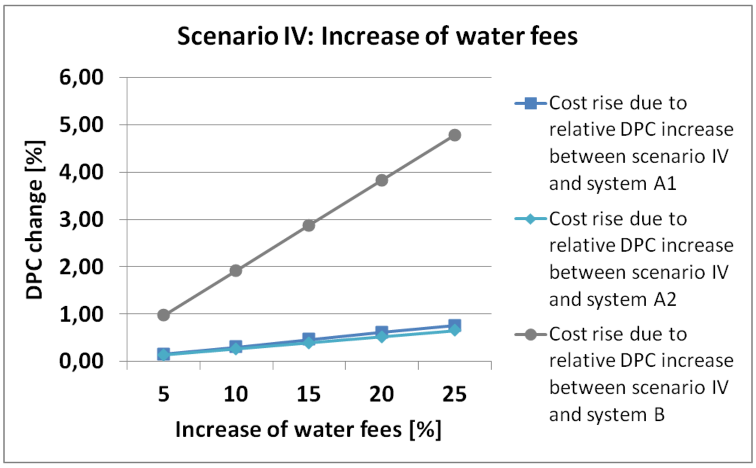


Figure 10 - Curves' progressions of DPC for Scenario IV

As can be seen in figure 10 the assumption that the DPC would be much more affected in system B than in either A1 or A2 was correct. This leads to the conclusion for this scenario that the higher the water price, the more economically reasonable both A1 and A2 are. Nevertheless, it has to be remarked that system B is still cheaper than both alternative systems under these circumstances.

Table 11 demonstrates that whereas the DPC of both A1 and A2 are not even affected by 1%, the change in DPC is noticeably bigger for system B, close to 5%. Even though the absolute water costs are higher in A2 than in A1, the impact of rising water fees is slightly bigger on A1 due to the fact that this alternative's DPC is lower. The DPC of system A1 is affected by a maximum of 0.76%, whereas the DPC of A2 only rises by 0.65%.

Although an additional charge of 0.38 €-cents per use in the conventional system B, which is caused by a water fee increase of 25%, is not very much, it has to be kept in mind that this is the increase under German water cost circumstances. In countries where water is generally more expensive, the changes will be rather tremendous since the cost gap between systems B and either A1 or A2 becomes larger the higher the water fee rises.

Table 11 - Change in DPC for Scenario IV [€-Cents/use]

	+ 5%	+ 10%	+ 15%	+ 20%	+ 25%
System A1					
DPC IV[1]	**12.69**	**12.71**	**12.73**	**12.75**	**12.77**
DPC difference[2]	+0.01	+0.03	+0.05	+0.07	+0.09
DPC change[3] [%]	+0.15	+0.30	+0.46	+0.61	+0.76
System A2					
DPC IV[1]	**15.90**	**15.92**	**15.94**	**15.96**	**15.98**
DPC difference[2]	+0.02	+0.04	+0.06	+0.08	+0.10
DPC change[3] [%]	+0.13	+0.26	+0.39	+0.52	+0.65
System B					
DPC IV[1]	**8.04**	**8.12**	**8.19**	**8.27**	**8.34**
DPC difference[2]	+0.08	+0.16	+0.23	+0.31	+0.38
DPC change[3] [%]	+0.97	+1.92	+2.87	+3.83	+4.78

1 DPC of scenario IV, based on system A1 (respectively system A2, respectively system B)

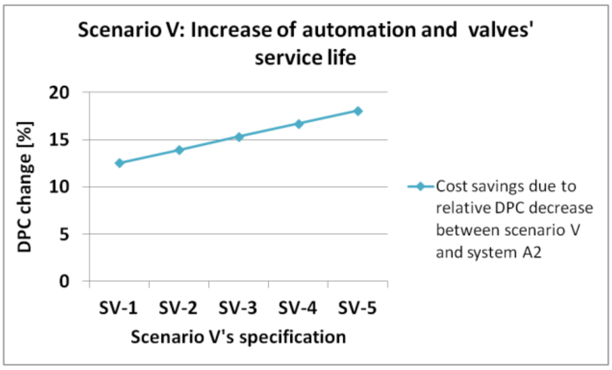
2 DPC difference between scenario IV, based on system A1 (A2, B) and system A1 (A2, B)

3 Relative DPC change between scenario IV (based on system A1 (A2, B)) and system A1(A2, B)

3.5.5. Sensitivity analysis V

Sensitivity analysis V combines scenarios I, an increasing automation, and II, a longer service life of spare parts. Hence it provides more complete information for all scenarios corresponding to system A2. Certainly, it does not give any new knowledge of the system's reaction towards the changing of those costs from scenario I and II, but it makes a statement on how much can be saved if both circumstances occur at the same time. The combination of I and II is supposed to happen as I-1+II-1 which present V-1 and I-2+II-2 which present V-2 and so on. This means that a 75% cost reduction regarding manual labor is combined with a longer spare parts' service life of 10%, whereas an 80% cost reduction regarding manual labor is combined with a longer spare parts' service life of 15%. Combining the scenarios in this way implies a change from a *little bit* more favorable to *much more* favorable.

This is because a further development of the struvite reactor and an enhancement of the spare parts are assumed to have the same trigger – an increasing motivation to separate waste water streams which also cause a higher demand of urine separation toilets.



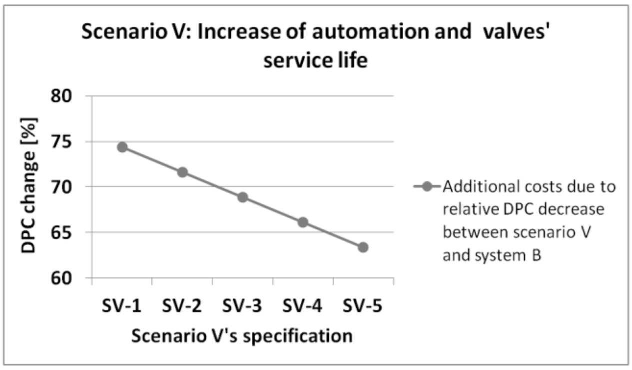


Figure 11 - Curves' progressions of DPC for Scenario V

Figure 11 illustrates the finding of analysis V. The slopes of both curves are steeper compared to the curves of the individual scenarios (figures 6 and 7). This means that lowering two costs post leads to higher savings if scenario V is compared to the original system A2 and less cost rise if scenario V is compared to the original system B.

Table 12 depicts in more detail that the change is significant. A cost reduction of more than 18% can be reached compared to the regular system A2. Also a comparison between analysis V and the conventional system B shows that the system in analysis V is “merely” about 63% more expensive than B, if most favorable circumstances occur, other than additional costs of 99% when comparing the original system A2 with system B. This leads to the conclusion that scenario V's DPC is only 5.05 cents more expensive than system B.

Even if only rather small amounts of costs reductions can be achieved, such as the case for V-1, the DPC cost reduction still accounts for noticeable savings of close to 13%, which are already significant.

Table 12 - Change in DPC for Scenario V [€-Cents/use]

	V-1	V-2	V-3	V-4	V-5
DPC V[1]	**13.89**	**13.67**	**13.45**	**13.23**	**13.01**
System A2					
DPC difference[2]	- 1.99	- 2.21	- 2.43	- 2.65	- 2.87
DPC change[3] [%]	- 12.53	- 13.91	- 15.30	- 16.68	- 18.06
System B					
DPC difference[2]	+5.93	+5.71	+5.49	+5.27	+5.05
DPC change[3] [%]	+74.39	+71.63	+68.87	+66.11	+63.63

1 DPC of scenario V, based on system A2

2 DPC difference between scenario V and system A2 (respectively system B)

3 Relative DPC change between scenario V and system A2(B)

3.5.6. Sensitivity analysis VI

In this sensitivity analysis the conditions of analysis V are given and additionally a decreasing price of urine diversion toilets and waterless urinals (scenario III) is assumed. This means that e.g. scenario VI-1 represents a combination of I-1+II-1+III-3. In detail, scenario VI-1 assumes that manual labor costs decrease by 75% (I-1) and the spare parts' service life increases by 10% (II-1) and additionally the IC and ICR of water separation toilets and waterless urinals decrease by 5% (III-1).

This analysis implies the most favorable circumstances which could occur for the alternative sanitation system A2. Again, VI is only relevant for scenarios related to struvite precipitation, as it contains a cost reduction of manual labor required for the operation of the struvite reactor.

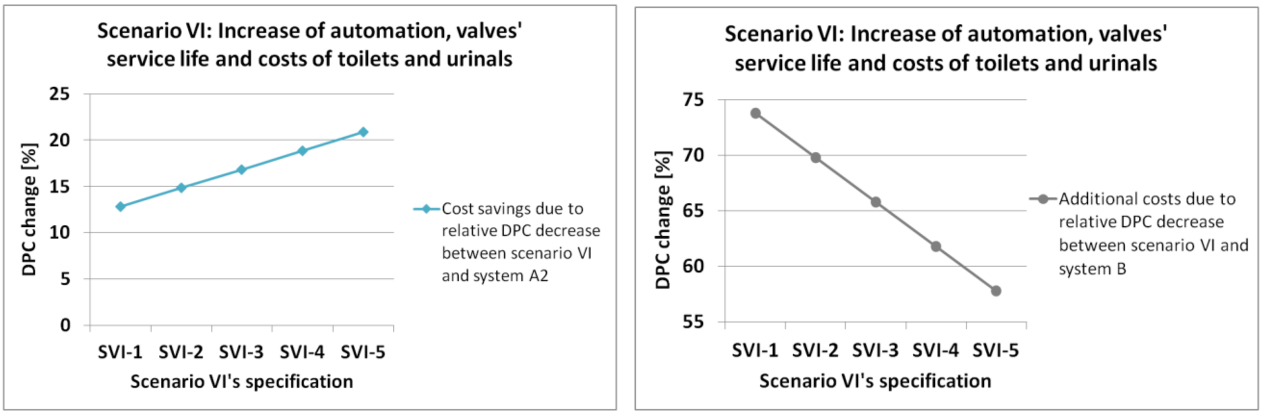


Figure 12 - curves' progressions of DPC for Scenario VI

A direct comparison of the curves' of scenarios V and VI (figures 11 and 12) shows that again the trend of both curves is steepened in this analysis, meaning that again the savings can be extended when compared to the original scenario A2 and further the additional costs compared to the conventional sanitation system B can be made smaller.

Table 13 - Change in DPC for Scenario VI [€-Cents/use]

	VI-1	**VI-2**	**VI-3**	**VI-4**	**VI-5**
DPC VI[1]	**13.84**	**13.52**	**13.20**	**12.89**	**12.57**
System A2					
DPC difference[2]	2.04	2.36	2.68	2.99	3.31
DPC change[3] **[%]**	12.83	14.84	16.84	18.85	20.85
System B					
DPC difference[2]	5.88	5.56	5.24	4.93	4.61
DPC change[3] **[%]**	73.78	69.78	65.78	61.79	57.79

1 DPC of scenario VI, based on system A2

2 DPC difference between scenario VI and system A2 (respectively system B)

3 Relative DPC change between scenario VI and system A2(B)

A look at table 13 proves that in this "best case scenario" a cost reduction of over a fifth can be realized compared to the original A2 if the most favorable circumstances were to occur. The additional costs of an alternative sanitation system with costs assumed as in analysis VI would only be about 58% of a conventional sanitation system which is a great achievement regarding the fact that the original system A2 was almost twice as expensive as the conventional system B, as can be recalled in table 6.

3.5.7. Sensitivity analysis VII

This sensitivity analysis is only done as a brief insight as how changing water fees would influence the development of costs in case that the most favorable circumstances for an alternative sanitation system based on A2 (depicted by scenario VI) have arrived.

Table 14 - Change in DPC for Scenario VII [€-Cents/use]

	VII-1	VII-2	VII-3	VII-4	VII-5
DPC VII[1]	**13.86**	**13.56**	**13.27**	**12.97**	**12.67**
DPC diffrence[2]	+0.02	+0.04	+0.07	+0.08	+0.10
DPC change[3] **[%]**	+0.14%	+0.30%	+0.53%	+0.62%	+0.80%

1 DPC of scenario VII

2 DPC difference between scenario VII and VI

3 Relative DPC change between scenario VII and scenario VI

As sensitivity analysis IV already pointed out, an increase in water fees is a rather small contributor for increasing costs within the alternative sanitation system. This is because the water consumption in this system is quite low in general

As table 14 demonstrates, rising water fees from 5% up to 25% in five percent steps only account for not even one percent price increase in the DPC. Thus, an increase in water fees can be neglected as insignificant parameter for sanitation system A2. It cannot be neglected whatsoever for the conventional system B, as it has a bigger impact within the conventional sanitation system, as analysis IV has already shown.

3.5.8. Sensitivity analysis VIII

For investigations on how the SANIRESCH sanitation system A1 responds to changing costs, sensitivity analysis VIII combines analyses II, extended spare parts' service life, and III, a decrease in investment and reinvestment costs for urine separating toilets and waterless urinals.

Within this analysis, e.g. scenario VIII-1 forms, as II-1 and III-1 are combined (a longer spare parts' service life of 10% for II-1 and decreasing IC and ICR by 5% of urine diversion toilet and waterless urinals). VIII-2 evolves by combining II-2 and III-2 and so on.

This analysis cannot be compared directly to analysis VI for system A2, since that analysis also takes an increasing automation into account. It has to be noted that decreasing costs, such as assumed here, have a stronger impact on system A1 than scenario VI has on system A2 because the TPCs in general are lower here. This means that the same amount of monetary change leads to a stronger percentaged change in system A1. Figure 13 depicts the impact of decreasing costs for scenario VIII graphically.

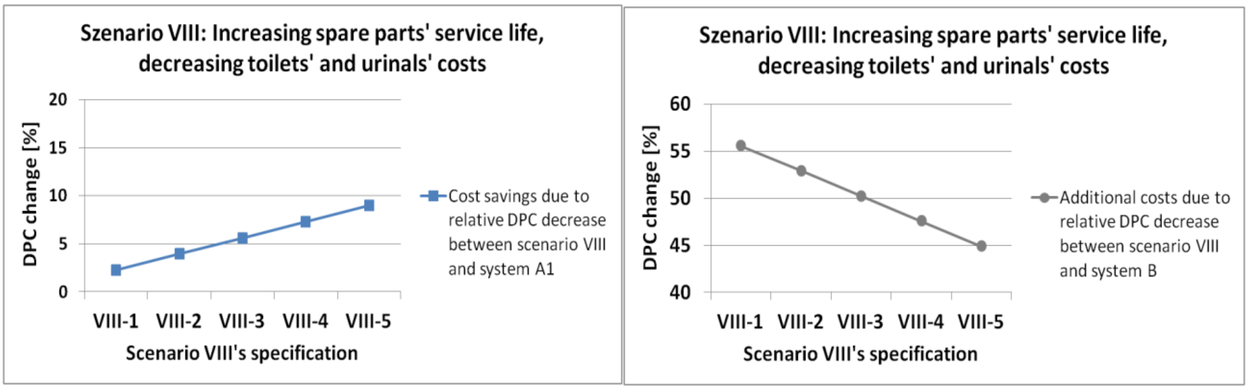


Figure 13 - Curves' progressions of DPC for Scenario VIII

Table 15 illustrates that a combined cost reduction of the two components can lead to a cost saving of more than 8% compared to the original A1 system.

The cost gap between the enhanced scenario VIII and the original system B can be lowered to 46.13% coming from a cost gap of 60% when comparing the original system A1 and system B. Especially compared to B it is evident that Scenario A1 becomes much less expensive, if advancements take place.

Table 15 - Change in DPC for Scenario VIII [€-Cents/use]

	VIII-1	VIII-2	VIII-3	VIII-4	VIII-5
DPC VIII[1]	**12.39**	**12.18**	**11.96**	**11.85**	**11.64**
System A1					
DPC difference[2]	- 0.29	- 0.50	- 0.72	- 0.83	- 1.04
DPC change[3] [%]	- 2.26	- 3.93	- 5.61	- 6.51	- 8.18
System B					
DPC difference[2]	+4.43	+4.22	+4.00	+3.89	+3.68
DPC change[3] [%]	+55.55	+52.89	+50.22	+48.79	+46.13

1 DPC of scenario VIII, based on system A1

2 DPC difference between scenario VIII and system A1 (respectively system B)

3 Relative DPC change between scenario VIII and system A1(B)

3.5.9. Sensitivity analysis IX

This sensitivity analysis has the same function for system A1 as scenario VII has for system A2. It is supposed to demonstrate which impact rising water fees would have on an alternative system A1 when the more favorable circumstances of scenario VIII have occurred. In table 16 is becomes apparent that rising water fees have an even lower impact on scenario IX than they had on scenario VII, which was already negligible. It can be seen that rising water fees cause not even 1% higher costs.

Table 16 - Change in DPC for Scenario IX [€-Cents/use]

	IX-1	IX-2	IX-3	IX-4	IX-5
DPC IX[1]	**12.41**	**12.22**	**12.02**	**11.93**	**11.73**
DPC difference[2]	+0.02	+0.04	+0.06	+0.08	+0.09
DPC change[3] [%]	+0.16	+0.33	+0.50	+0.67	+0.77

1 DPC of scenario IX

2 DPC difference between scenario IX and scenario VIII

3 Relative DPC change between scenario IX and scenario VIII

This is because system A1 has a lower waste water production than system A2 because urine is not discharged in the sewage water line but collected separately with the aim to use it as fertilizer.

3.5.10. Sensitivity analysis X

Analysis X implies that there is an increase in energy prices. This sensitivity analysis was done separately because high energy consumption is always one of the major points criticized in context with the operation of MBRs. Due to this, scenario X was run to show the magnitude of impact for alternatives A1 and A2 if energy prices increase and which consequences this development brings along for the SANIRESCH system. The scenario where X is run on the base of system A1 was called Xa. The scenario where X is run on the base of system A2 is called Xb. The impact of increasing energy pices is illustrated in figure 14.

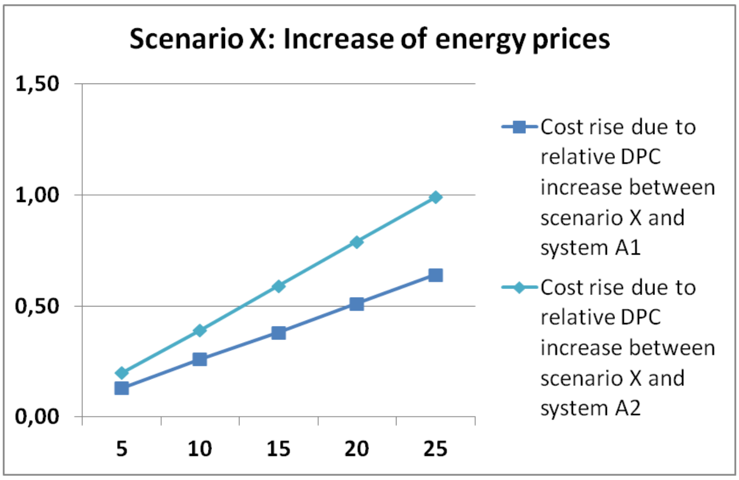


Figure 14 - Curves' progression of DPC for Scenario X

In the SANIRESCH sanitation systems A1 and A2, the analysis showed that energy consumption takes regard for such a small amount of generated costs that a rise of those contributes to only a small amount of higher expenses. The A2 system is affected slightly stronger because in this system the precipitated struvite must be dried in a drying oven, which is not needed in system A1. Table 17 displays that the maximum change for both systems would not even sum up to a rise of 1% of the total costs.

When comparing tables 17 and 11 directly, it stands out that an increase in energy prices only accounts for a comparable increase of costs as in case of the water fees' increase. Due to the fact that reaction of the systems towards increasing water fees is not regarded to as sensitive, this also cannot be the case for an increase of energy prices.

Table 17 - Change in DPC for Scenario X [€-Cents/use]

	+ 5%	+ 10%	+ 15%	+ 20%	+ 25%
System A1					
DPC X[1]	**12.69**	**12.71**	**12.72**	**12.74**	**12.76**
DPC difference a[2]	+0.01	+0.03	+0.04	+0.06	+0.08
DPC change a[3] [%]	+0.13	+0.26	+0.38	+0.51	+0.64
DPC difference b[4]	+4.73	+4.75	+4.76	+4.78	+4.80
DPC change b[5] [%]	+59.42	+59.67	+59.80	+60.05	+60.30
System A2					
DPC X[1]	**15.91**	**15.94**	**15.97**	**16.00**	**16.03**
DPC difference a[2]	+0.03	+0.06	+0.09	+0.12	+0.15
DPC change a[3] [%]	+0.20	+0.39	+0.59	+0.79	+0.99
DPC difference b[4]	+7.95	+7.98	+8.01	+8.04	+8.07
DPC change b[5] [%]	+99.87	+100.25	+100.63	+101.01	+101.38

1 DPC of scenario X, based on system A1 (respectively A2)

2 DPC difference between scenario X (based on system A1 (A2)) and system A1 (A2)

3 Relative DPC change between scenario X (based on system A1 (A2)) and system A1(A2)

4 DPC difference between scenario X (based on system A1 (A2)) and system B

5 Relative DPC change between scenario X (based on system A1 (A2)) and system B

One most frequently put forth objection against systems run with the use of MBRs, sensitivity towards this parameter can be negated in the special case of the SANIRESCH implementation. Although a rather high energy consumption of MBRs compared to other ways of waste water treatment can be criticized, it does not stick out as a major issue in the SANIRESCH system.

If the systems in scenario X are compared to system B, it becomes evident that an energy cost increase by 25% only leads to an increase of DPC by 1% for system A1 and roughly 2% for A2. This impact demonstrates that energy prices cannot be regarded to as sensitive factor within the two alternative sanitation systems.

4. Conclusion and Summary

The outcome of the analyses made can be split up in two statements regarding the economic feasibility of the complete SANIRESCH system.

Regarding the gaining of struvite, the sensitivity analyses demonstrate that the greatest cost saving potential lies in an increasing automation (scenario I) for system A2, followed by an increase of the spare parts' service life (scenario II). For system A1 the spare parts' service life is the most important component to undergo optimization.

Decreasing costs of urine diversion toilets and waterless urinals (scenario III) led to no particularly significant cost reduction, although they are more expensive than conventional sanitation installations.

Increasing water fees (scenario IV) had almost no impact, neither on system A1 nor system A2. However, it can be demonstrated that increasing water fees do have an impact on conventional system B and the more expensive water becomes, the more meaningful it is to consider alternative sanitation.

As the cost comparison in chapter 3.4 and the sensitivity analyses in chapter 3.5 have proven, that investment, reinvestment and running costs of the urine separation toilets and the struvite precipitation reactor are the major components responsible for a high amount of costs within both alternative sanitation systems A1 and A2. In contrast, the extracted amount of struvite, respective the fertilizer value of urine which can potentially be gained under these circumstances do not give economical reason to follow the precipitation of struvite any further.

All this leads to the conclusion that the costs for the separation of urine and the following struvite precipitation account for most of the cost difference between the SANIRESCH and a conventional sanitation system. Regarding the amount of struvite which can be gained, the evolving costs are disproportionally high. Precipitation of struvite from urine is not economically reasonable in the context of this system.

However, to the fact that the favorability of the alternative sanitation systems investigated is mainly determined by the saving of water, this can lead to the conclusion that it does make sense to consider the installation of an MBR for service water recycling.

As a comparison of the running costs due to fresh water consumption and waste water production given in tables 3, 4 and 5 adduces, it is sensible to run an MBR. The operation of an MBR does not need special sanitary equipment other than additional pipes for the greywater stream. Hence an MBR can be combined with a conventional waste water system. This avoids the disadvantages of an alternative sanitation system run with different waste water lines due to high costs caused by special sanitary installation but still provides the potential to take advantage of cost savings due to water recycling.

Nevertheless, it must be mentioned that in the SANIRESCH context the installation of a brownwater MBR as well as a greywater MBR is superfluous. This is because the brown water MBR solely treats the amount that is needed for toilet flushing. Service water treated by the greywater MBR cannot be reused because there is no need for additional service water in the planned system. In fact, costs caused by this MBR could be left out of consideration in further investigations. The processed greywater could be used though if new demands such as water for air conditioning or a green area sprinkler system arose.

5. Outlook

It has been shown in this thesis that the major limitation concerning a reasonable precipitation of struvite from urine can be found in the costs of sanitary devices that are necessary to enable the separation of brownwater and urine. Additionally, the state of technology does not allow efficient plant operation yet.

Still, the need of alternative phosphor resources due to reasons illustrated in chapter 1 is still there. Whereas the single stream treatment of urine has proven to be uneconomic, other solutions such as the gaining of struvite from sewage sludge or sewage sludge ashes have already shown to be more reasonable. The price of phosphor, which is extracted from those sources in sewage water treatment plants, is approximately 1.5 to 5 times as high as the price for conventionally gained phosphor. In other words, each user connected to the sewage water system would have to pay an increase of 1% of the waste water fee to enable to process of gaining struvite from sewage sludge or sewage sludge ashes. Compared to the precipitation from urine, this process is reasonable.

(comp. Cornel, P., 2006, p.7).

Together with the finding that the operation of MBRs is cost-effective due to potable water savings, even though they consume energy, a sustainable approach towards water management can be designed. E.g. based on a decentralized approach in which the use of MBRs is planned to lower the wastewater and the freshwater demand in areas where new housing development is planned, it could be either prevented to increase the size of an existing sewage water treatment plant or it could be possible to choose a plant of smaller scale if one has to be built. Additionally phosphor from local sources could be used for example in agriculture, if this element extracted from the occurring sewage water. Scenarios as this would need further investigation.

Though there are certain economical limitations at this point of time, it is necessary to think over alternative ways of gaining or saving resources because the shorter in supply they become the more valuable they are.

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7. List of abbreviations

MBR	Membrane bioreactor
MgO	Magnesium oxide
MAP	Magnesium ammonium phosphate
SANIRESCH	SANitary REcycling Eschborn
LAWA	Länderarbeitsgemeinschaft Wasser
TPC	Total project costs [€]
DPC	Dynamic project costs [€/toilet use]
AC	Annual costs [€/a]
GPV	Gross present value [€]
IC	Investment costs [€]
ICR	Reinvestment costs [€]
RC	Running costs [€/a]
l	Liter
mg	Milligram
min	Minute
sec	Second
e.g.	example given
kWh	Kilowatt hour
t	ton

8. List of figures

9. List of tables

10.Appendix

The excel sheets were handed in as part of a separate document

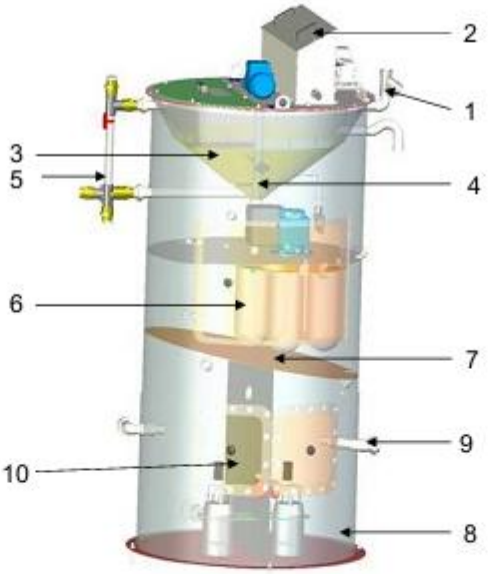

Figure 15 - Struvite Reactor

(according to HUBER Precipitation Reactor, 2010)

1	Filler
2	Dosing unit
3	Precipitation tank (trough-shaped)
4	Stirrer
5	Level probe
6	Filter
7	Collecting tray for process water
8	Chamber for process water
9	Outlet
10	Inspection opening

Table 18 – Occurring amounts of wastewater and urine

Occurring amounts of wastewater and urine	
Users	651
Thereof women	335
Thereof men	316
Working days per year	250
Number of urinations per day and user	3
Percental handwashing after urination	67%
Number of defecations per day and user	0.5
Percental handwashing after urination	100%
Flushwater demand defecation	10.26 l per flush
Flushwater demand urination (women)	3.9 l per flush
Water used for handwashing	1.5 l per handwashing
Water use in kitchenettes	240 l/d
Water use of dish washers	192 l/d
Greywater amount	2.88 m^3/d
Brownwater amount (system A1)[1]	7.26 m^3/d
Brownwater amount (system A2)[1]	7.62 m^3/d
Urine amount	0.36 m^3/d

1 The difference in brownwater amounts is caused by the fact that the total urine is collected in system A1, whereas the urine in system A2 is processed and after that led to the brownwater stream for purification.

Table 19 – Sevice life parameters

ITEM	LIFE SPAN [YEARS]
Project's overall service life[1]	30
Toilets, urinals and other sanitary devices[2]	15
Membrane bioreactor[3]	15
Struvite reactor[4]	25
Urine tanks[5]	35
Pipes[5] (wastewater/freshwater)	35/45
Urine tanks[6]	35
Other sanitary accessories[6]	25
Membrane bioreactor[7]	15
Struvite reactor[7]	25
Drying oven[8]	25
Drying box[8]	25
Rain barrel[9]	10
IBC[8]	10
Filter[10] (before MAP-reactor)	10

1 LAWA, 2005, p.4-2

2 Own assumption. According to Prager, J., 2002, p.186, toilets in private households are supposed to have a service life of 25 years. Due to a more frequent usage in office buildings, the service life is reduced here.

3 Huber SE, 2012, provided data within project

4 Huber SE, 2011, provided data within project

5 Prager, J., 2002, p.186

6 Lazo Páez, A., 2010, p. 17

7 personal information by Huber SE

8 Braum, C., 2011, excel sheet for further calculations

9 own assumption comparing service life of rain barrel to service life of IBC

10 own assumption

Table 20 – SANIRESCH system A1: detailed TPC

SANIRESCH ALTERNATIVE A1	TOTAL PROJECT COSTS [€]
Sorted by cost types	
Investment costs (machinery, sanitary devices, pipes)	641,600 €
Reinvestment costs (machinery, sanitary devices)	151,300 €
Running costs (machinery, sanitary devices, water)	1,373,000 €
Sum (rounded to thousand)	**2,166,000€**
Sorted by cause of costs	
Machinery	214,100 €
Sanitary devices	1,500,500 €
Pipes	385,700 €
Water	65,600 €
Sum (rounded to thousand)	**2,166,000 €**

Table 21 - SANIRESCH system A2: detailed TPC

SANIRESSCH ALTERNATIVE A2	TOTAL PROJECT COSTS [€]
Sorted by cost types	
Investment costs (machinery, sanitary devices, pipes)	664,300 €
Reinvestment costs (machinery, sanitary devices)	165,500 €
Running costs (machinery, sanitary devices, water)	1,883,400 €
Sum (rounded to thousand)	**2,713,000 €**
Sorted by cause of costs	
Machinery	756,700 €
Sanitary devices	1,500,500 €
Pipes	385,700 €
Water	70,300 €
Sum (rounded to thousand)	**2,713,000 €**

Table 22 – Conventional system B: detailed TPC

CONVENTIONAL ALTERNATIVE (B)	TOTAL PROJECT COSTS [€]
Sorted by cost types	
Investment costs (sanitary devices, pipes)	355,100 €
Reinvestment costs (sanitary devices)	63,100 €
Running costs (sanitary devices, water)	942,800 €
Sum (rounded to thousand)	**1,361,000 €**
Sorted by cause of costs	
Sanitary devices, pipes	845,400 €
Pipes	256,900
Water	258,700 €
Sum (rounded to thousand)	**1,361,000 €**

Table 23 – SANIRESCH system A1: detailed AC

SANIRESCH ALTERNATIVE A1	ANNUAL COSTS [€]
Sorted by cost types	
Investment costs (machinery, sanitary devices, pipes)	32,800 €
Reinvestment costs (machinery, sanitary devices)	7,500 €
Running costs (machinery, sanitary devices, water)	70,000 €
Sum (rounded to thousand)	**110,000 €**
Sorted by cause of costs	
Machinery	10,800 €
Sanitary devices, pipes	96,300 €
Water	3,300 €
Sum (rounded to thousand)	**110,000 €**

Table 24 - SANIRESCH system A2: detailed AC

SANIRESCH ALTERNATIVE A2	ANNUAL COSTS [€]
Sorted by cost types	
Investment costs (machinery, sanitary devices, pipes)	33,900 €
Reinvestment costs (machinery, sanitary devices)	8,200 €
Running costs (machinery, sanitary devices, water)	96,100 €
Sum (rounded to thousand)	**139,000 €**
Sorted by cause of costs	
Machinery	38,400 €
Sanitary devices, pipes	96,300 €
Water	3,600 €
Sum (rounded to thousand)	**139,000 €**

Table 25 – Conventional system B: detailed AC

CONVENTIONAL ALTERNATIVE (B)	ANNUAL COSTS [€]
Sorted by cost types	
Investment costs (sanitary devices, pipes)	18,100 €
Reinvestment costs (sanitary devices)	3,200 €
Running costs (sanitary devices, water)	48,100 €
Sum (rounded to thousand)	**69,000 €**
Sorted by cause of costs	
Sanitary devices, pipes	56,200 €
Water	13,200 €
Sum (rounded to thousand)	**69,000 €**

Table 26 - SANIRESCH system A1: detailed DPC

SANIRESCH ALTERNATIVE A1	DYNAMIC PROJECT COSTS [€-CENTS/USE]
Sorted by cost types	
Investment costs (machinery, sanitary devices, pipes)	3.76 €-Cents/use
Reinvestment costs (machinery, sanitary devices)	0.89 €-Cents/use
Running costs (machinery, sanitary devices, water)	8.03 €-Cents/use
Sum	**12.68 €-Cents/use**
Sorted by cause of costs	
Machinery	1.26 €-Cents/use
Sanitary devices, pipes	11.04 €-Cents/use
Water	0.38 €-Cents/use
Sum	**12.68 €-Cents/use**

Table 27 - SANIRESCH system A2: detailed DPC

SANIRESCH ALTERNATIVE A2	DYNAMIC PROJECT COSTS [€-CENTS/USE]
Sorted by cost types	
Investment costs (machinery, sanitary devices, pipes)	3.89 €-Cents/use
Reinvestment costs (machinery, sanitary devices)	0.97 €-Cents/use
Running costs (machinery, sanitary devices, water)	11.02 €-Cents/use
Sum	**15.88 €-Cents/use**
Sorted by cause of costs	
Machinery	4.43 €-Cents/use
Sanitary devices, pipes	11.04 €-Cents/use
Water	0.41 €-Cents/use
Sum	**15.88 €-Cents/use**

Table 28 – Conventional system B: detailed DPC

CONVENTIONAL ALTERNATIVE (B)	DYNAMIC PROJECT COSTS [€]
Sorted by cost types	
Investment costs (sanitary devices, pipes)	2.08 €-Cents/use
Reinvestment costs (sanitary devices)	0.36 €-Cents/use
Running costs (sanitary devices, water)	5.52 €-Cents/use
Sum	**7.96 €-Cents/use**
Sorted by cause of costs	
Sanitary devices, pipes	6.45 €-Cents/use
Water	1.51 €-Cents/use
Sum	**7.96 €-Cents/use**

Table 29 – Percentual development of DPC for Scenario I

	SI-1 (75% -)	SI-2 (80% -)	SI-3 (85% -)	SI-4 (90% -)	SI-5 (95% -)
Percental cost saving compared to A2	10.02%	10.69%	11.36%	12.02%	12.69%

Table 30 – Detailed monetary change in DPC for Scenario I [€-Cents/use]

DPC A2	15.88	15.88	15.88	15.88	15.88
	-75%	**-80%**	**-85%**	**-90%**	**-95%**
DPC Scenario I	14.29	14.18	14.07	13.97	13.86
DPC Change	1.59	1.70	1.81	1.91	2.02

Table 31 – Percentual development of DPC for Scenario II

	SII-1 (10% +)	SII-2 (15% +)	SII-3 (20% +)	SII-4 (25% +)	SII-5 (30% +)
Percental cost saving compared to A1	3.14%	4.04%	4.93%	5.83%	6.73%
Percental cost saving compared to A2	2.51%	3.22%	3.94%	4.65%	5.37%

Table 32 – Detailed monetary change in DPC for Scenario II [€-Cents/use]

DPC A1	12.68	12.68	12.68	12.68	12.68
	+ 10%	**+ 15%**	**+ 20%**	**+ 25%**	**+ 30%**
DPC Scenario II (A1)	12.28	12.16	12.05	11.94	11.82
DPC Change (II/A1)	0.4	0.52	0.63	0.74	0.86

DPC A2	15.88	15.88	15.88	15.88	15.88
	+ 10%	**+ 15%**	**+ 20%**	**+ 25%**	**+ 30%**
DPC Scenario II (A2)	15.48	15.37	15.25	15.14	15.03
DPC Change (II/A2)	0.40	0.51	0.63	0.74	0.85

Table 33 – Percentual development of DPC for Scenario III

	SIII-1 (5% -)	SIII-2 (10% -)	SIII-3 (15% -)	SIII-4 (20% -)	SIII-5 (25% -)
Percental cost saving compared to A1	0.39%	1.17%	1.95%	2.72%	3.5%
Percental cost saving compared to A2	0.49%	1.11%	1.73%	2.35%	2.97%

Table 34 – Detailed monetary change in DPC for Scenario III [€-Cent/use]

DPC A1	12.68	12.68	12.68	12.68	12.68
	- 5%	**- 10%**	**- 15%**	**- 20%**	**- 25%**
DPC Scenario III (A1)	12.63	12.53	12.43	12.33	12.23
DPC Change (III/A1)	0.05	0.15	0.25	0.35	0.45

DPC A2	15.88	15.88	15.88	15.88	15.88
	- 5%	**- 10%**	**- 15%**	**- 20%**	**- 25%**
DPC Scenario III (A2)	15.80	15.70	15.60	15.50	15.41
DPC Change (III/A2)	0.08	0.18	0.28	0.38	0.47

Table 35 – Percentual development of DPC for Scenario IV

	SIV-1 (5% +)	SIV-2 (10% +)	SIV-3 (15% +)	SIV-4 (20% +)	SIV-5 (25% +)
Percental cost rise compared to A1	0.15%	0.30%	0.46%	0.61%	0.76%
Percental cost rise compared to A2	0.13%	0.26%	0.39%	0.52%	0.65%
Percental cost rise compared to B	0.97%	1.92%	2.87%	3.83%	4.78%

Table 36 – Detailed monetary change in DPC for Scenario IV [€-Cents/use]

DPC A1	12.68	12.68	12.68	12.68	12.68
	+ 5%	+ 10%	+ 15%	+ 20%	+ 25%
DPC Scenario IV (A1)	12.69	12.71	12.73	12.75	12.77
DPC Change (IV/A1)	0.01	0.03	0.05	0.07	0.09
DPC A2	15.88	15.88	15.88	15.88	15.88
	+ 5%	+ 10%	+ 15%	+ 20%	+ 25%
DPC Scenario IV (A2)	15.90	15.92	15.94	15.96	5.98
DPC Change (IV/A2)	0.02	0.04	0.06	0.08	0.10
DPC B	7.96	7.96	7.96	7.96	7.96
	+ 5%	+ 10%	+ 15%	+ 20%	+ 25%
DPC Scenario IV (B)	8.04	8.12	8.19	8.27	8.34
DPC Change (IV/B)	0.08	0.16	0.23	0.31	0.38

Table 37 – Percentual development of DPC for Scenario V

	SV-1	SV-2	SV-3	SV-4	SV-5
Percental cost saving compared to A2	12.53%	13.91%	15.30%	16.68%	18.06%
Percental cost rise compared to B	74.39%	71.63%	68.87%	66.11%	63.63%

Table 38 - Detailed monetary change in DPC for Scenario V [€-Cents/use]

DPC A2	15.88	15.88	15.88	15.88	15.88
DPC B	7.96	7.96	7.96	7.96	7.96

	V-1	V-2	V-3	V-4	V-5
DPC Scenario V	13.89	13.67	13.45	13.23	13.01

DPC Change (V/A2)	1.99	2,21	2,43	2,65	2,87
DPC Change (V/B)	5,93	5,71	5,49	5,27	5,05

Table 39 – Percentual development of DPC for Scenario VI

	SVI-1	SVI-2	SVI-3	SVI-4	SVI-5
Percental cost saving compared to A2	12.83%	14.84%	16.84%	18.85%	20.85%
Percental cost rise compared to B	73.78%	69.78%	65.78%	61.79%	57.79%

Table 40 - Detailed monetary change in DPC for Scenario VI [€-Cents/use]

DPC A2	15.88	15.88	15.88	15.88	15.88
DPC B	7.96	7.96	7.96	7.96	7.96
	VI-1	**VI-2**	**VI-3**	**VI-4**	**VI-5**
DPC Scenario VI	13.84	13.52	13.20	12.89	12.57
DPC Change (VI/A2)	2,04	2,36	2,68	2,99	3,31
DPC Change (VI/B)	5,88	5,56	5,24	4,93	4,61

Table 41 – Percentual development of DPC for Scenario VII

	SVII-1	SVII-2	SVII-3	SVII-4	SVII-5
Percental cost saving compared to A2	12.72%	14.61%	16.44%	18.32%	20.21%
Percental cost rise Compared to B	74.12%	70.35%	66.71%	62.94%	59.17%
Percental cost rise compared to VI	0.14%	0.30%	0.53%	0.62%	0.80%

Table 42 - Detailed monetary change in DPC for Scenario VII [€-Cents/use]

DPC A2	15.88	15.88	15.88	15.88	15.88
DPC B	7.96	7.96	7.96	7.96	7.96
	VII-1	**VII-2**	**VII-3**	**VII-4**	**VII-5**
DPC Scenario VII	13.86	13.56	13.27	12.97	12.67
DPC Change (VII/A2)	2.02	2.32	2.61	2.91	3.21
DPC Change (VII/B)	5.90	5.60	5.31	5.01	4.71
DPC Change (VII/VI)	0,02	0,04	0,07	0,08	0,10

Table 43 – Percental development of DPC for Scenario VIII

	SVIII-1	SVIII-2	SVIII-3	SVIII-4	SVIII-5
Percental cost saving compared to A1	2.26%	3.93%	5.61%	6.51%	8.18%
Percental cost rise compared to B	55.55%	52.89%	50.22%	48.79%	46.13%

Table 44 – Detailed monetary change in DPC for Scenario VIII [€-Cents/use]

DPC A1	12.68	12.68	12.68	12.68	12.68
DPC B	7.96	7.96	7.96	7.96	7.96

	VIII-1	VIII-2	VIII-3	VIII-4	VIII-5
DPC Scenario VIII	12.39	12.18	11.96	11.85	11.64

DPC Change (VIII/A1)	0.29	0.50	0.72	0.83	1.04
DPC Change (VIII/B)	4.43	4.22	4.00	3.89	3.68

Table 45 – Percentual development of DPC for scenario IX

	SIX-1	SIX-2	SIX-3	SIX-4	SIX-5
Percental cost saving compared to A1	2.26%	3.78%	5.30%	6.04%	7.56%
Percental cost rise compared to B	54.30%	51.90%	49.50%	48.32%	45.92%
Percental cost rise compared to VIII	0.16%	0.33%	0.50%	0.67%	0.77%

Table 46 – Detailed monetary change in DPC for Scenario IX [€-Cents/use]

DPC A1	12.68	12.68	12.68	12.68	12.68
DPC B	7.96	7.96	7.96	7.96	7.96

	IX-1	IX-2	IX-3	IX-4	IX-5
DPC Scenario IX	12.41	12.22	12.02	11.93	11.73

DPC Change (IX/A1)	0.27	0.46	0.66	0.75	0.95
DPC Change (IX/B)	4.45	4.26	4.06	3.97	3.77
DPC Change (IX/VIII)	002	0.04	0.06	0.08	0.09

Table 47 – Percentual development of DPC for scenario X

	SX-1 (5% +)	SX-2 (10% +)	SX-3 (15% +)	SX-4 (20% +)	SX-5 (25% +)
Percental cost rise compared to A1	0.13%	0.26%	0.38%	0.51%	0.64%
Percental cost rise compared to A2	0.20%	0.39%	0.59%	0.79%	0.99%

Table 48 - Detailed monetary change in DPC for Scenario X [€-Cents/use]

DPC A1	12.68	12.68	12.68	12.68	12.68
	+ 5%	**+ 10%**	**+ 15%**	**+ 20%**	**+ 25%**
DPC Scenario X (A1)	12.69	12.71	12.72	12.74	12.76
DPC Change (X/A1)	0.01	0.03	0.04	0.06	0.08
DPC A2	15.88	15.88	15.88	15.88	15.88
	+ 5%	**+ 10%**	**+ 15%**	**+ 20%**	**+ 25%**
DPC Scenario X (A2)	15.91	1.94	15.97	16.00	16.03
DPC Change (X/A2)	0.03	0.06	0.09	0.12	0.15

Figure 16 - Struvite production, factsheet 1/4

Magnesium-Ammonium-Phosphate (MAP) reactor

1 Process principle

Simplified equation:	$NH_4^+ + Mg^{2+} + PO_4^{3-} \rightarrow MgNH_4PO_4$
Ammonium (NH_4^+):	Ammonium ion, available in excess in urine
Magnesium (Mg^{2+}):	Magnesium ion, develops in the reaction chamber of the added MgO (magnesium oxide)
Phosphate (PO_4^{3-}):	Phosphate ion, present dissolved in urine
MAP ($MgNH_4PO_4$):	Reaction product (also known as struvite)

2 Process technology

2.1 Removal of nutrients

P_{total} in influent:	180 mg/l (average)
P_{total} in effluent:	36 - 72 mg/l
P removal:	60 - 80 %
N_{total} in influent:	2700 mg/l
N_{total} in effluent:	540 – 1080 mg/l
N removal:	60 - 80 % (Probably mainly due to ventilation)

2.2 Cycle data and amount of urine

10 cycles per day	
Duration of one cycle:	135 min
Urine flow rate:	180 l/d
Per cycle:	40 l (theoretically possible: 50 l)
Amount treated:	400 l/d (theoretically possible: 500 l/d)
Usable urine storage:	7.5 m^3 (in 4 storage tanks)
Duration to process 7.5 m^3:	3 weeks if operating at 5 days per week and at full load

3 MAP recovery

MAP recovery:	
➢ with technical grade MgO	50 - 65 %
➢ with analytical grade MgO	90 - 95 % (only a few experiments in the laboratory)
Estimated recovery:	0.8 g MAP_{dried} / l urine
MAP production with technical MgO:	320 g MAP/d
	117 kg MAP/year

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Continuation of figure 16 - Struvite production, factsheet 2/4

Magnesium-Ammonium-Phosphate (MAP) reactor

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4 Operating costs

MgO bag:
- Total material costs — 0.31 €/bag
- Bag material — polyvinyl alcohol
- Bag content — 14 g MgO/bag (for cycle with 40 l urine)

Needle felt filter:
- Costs — 3 €/filter bag
- Life time — single use
- MAP loss — 37 - 12 % (remains in the filter)

Nylon filter (alternative option): (only a few experiments)
- Costs — 45 €/filter bag
- MAP loss — negligible loss

World market price MAP: approx. 480 €/t
Value of the produced MAP: 56 €/year

Theoretical costs (€) to fertilise 1 ha summer wheat for one year:[1]

Urine	MAP (Pilot plant)	NPK (Mineral fertiliser)
560	112,000,-	120

Reason for the high MAP costs: 1) at the moment there is a lot of manual labour necessary to produce MAP
2) MAP reactor was a new development, therefore very high investments cost

5 Field tests near Bonn

Soil: Supply level C (nutrient-rich soil)
Fertiliser: 100 - 140 kg N/ha for summer wheat, 40 kg N/ha for miscanthus
Urine application: 3-4 l/m² or 30-40 m³/ha (see table)

Date comparison:

	Data from Bonn	Technology Review[2]
N concentration in urine (gN/l)	2.3 – 3.9	maximum 7
Amount per area (l/m²)	3 – 4	1.5
N content per area (kgN/ha)	70 – 100	maximum 105

[1] Braum, C. (2011). Economical feasibility of using urine versus struvite as fertilizer. Using the example of GIZ in Eschborn. Bachelor thesis. Institute of Soil Sciences and Soil Conservation, Justus Liebig University Gießen, Germany
http://www.saniresch.de/images/stories/downloads/Bachelor%20Thesis%20Christina%20Braum.pdf

[2] von Muench, E., Winker, M. (2011). Technology review of urine diversion components - Overview on urine diversion components such as waterless urinals, urine diversion toilets, urine storage and reuse systems. Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Germany.
http://www.susana.org/lang-en/library?view=ccbktypeitem&type=2&id=875

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Continuation of figure 16 - Struvite production, factsheet /4

Magnesium-Ammonium-Phosphate (MAP) reactor

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