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- An Optimization Analysis of Processes to Recycle Phosphorus from Sewage Sludge

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Abstract

Phosphorus is a limited resource and for countries like Sweden without domestic mines, it becomes increasingly important to recycle this resource. Sewage sludge is rich in phosphorus and has traditionally been used as a fertiliser via direct application to farmland. There are many technologies that have been developed to recover P at the wastewater treatment plant or from sludge ashes, but the adaption of these technologies is slow. In Sweden the most common method of utilisation is still recycling through direct application to farm land, but this still only encompasses 25% of the produced sewage sludge. The Swedish EPA has suggested the objective to recycle 40% of the phosphorus in sewage sludge should be recycled to farmland by 2018, without risk of harming people or environment. Along with this target, new regulations have been suggested, which means that stricter limit values for residue in sludge is to be expected. Thus it will become more difficult to apply sludge to farmland. This makes it important to consider the effects of sludge quality when making strategic decisions. It is thus relevant to investigate which is the least costly processes with potential for recycling phosphorus from sewage sludge, under the suggested new regulations. This study compares the effect of four processes using linear programming to estimate the lowest cost operation, with Kungsängsverket as a case plant. The processes include two wastewater treatments, EBPR and conventional treatment with AS and chemical P precipitation, plus two additional processes; upstream management (Revaq) and recovery from ashes (CleanMAP). EBPR in combination with Revaq was found to be the optimum process combination. It was however rather difficult to make a reliable estimation of construction costs and therefore the results ought to be viewed with caution.

Sammanfattning

Fosfor är en ändlig resurs och för länder som likt Sverige saknar egna gruvor, blir det allt viktigare att återcirkulera denna resurs. Avloppsslam är rikt på fosfor och har traditionellt sett använts som gödselmedel genom direkt spridning på åkermark. Det har utvecklats många tekniker för att återvinna fosfor vid avloppsreningsverk eller från slamaskor efter förbränning. Implementeringen av dessa processer har dock dröjt och direkt spridning på åkermark är fortfarande det största användningsområdet för avloppsslam i Sverige. Ändå sprids bara 25 % av slammet. Naturvårdsverket har föreslagit ett etappmål att 40 % av fosforn ur avloppsslam ska återföras till åkermark senast 2018. Samtidigt har de föreslagit en ny författning med striktare gränsvärden för resthalter i slam vid åkerspridning. Det blir således svårare att återföra slammet. Därmed blir det viktigare att ha slamkvalitén i åtanke vid strategiska beslut. Det är därför relevant att undersöka vilka processer som är de minst kostsamma med potential att producera ett slam eller utvunnen produkt som kan återföras till åkermark med den nya förordningen. Denna studie omfattar fyra processer och använder linjär programmering för att minimera kostnaden. Optimeringen utförs med Kungsängsverket som fallstudie. Processerna som jämförs är två processer för rening av avloppsvatten (biologisk fosfor avskiljning, s.k. Bio-P och konventionell rening med kemisk fosforfällning), samt två ytterligare processer; uppströmsarbete (Revaq) och utvinning av fosfor ur aska (CleanMAP). Bio-P i kombination med Revaq visade sig vara den optimala process-kombinationen. Dock visade det sig vara problematiskt att göra en tillförlitlig uppskattning av konstruktionskostnaden, varför resultaten bör tolkas med försiktighet.

Table of Contents

Explained expressions

Effluent: Treated water which is released to a recipient (receiving body of water)

EBPR: Enhanced biological phosphorus removal (Bio-P). A modification of the activated sludge treatment at a WWTP. Usually a plant with this configuration uses no or little chemical addition as it inhibits bacterial growth and thus the biological P-uptake

Operation vs activity: These two expressions generally mean the same and could be used interchangeably in most contexts. The reason for using the two expressions is that they appear in different bodies of theory. The expression activity is more common and broader. It is applied in most theories to any sort of economic activity, while operation more specifically refers to a production set and is used mainly in management theory/operations research.

Water Treatment Plant vs Wastewater Treatment Plant: The former used to be used to describe a wastewater treatment plant (WWTP), but as it could also refer to facilities treating drinking water, it has been replaced by the more specific term WWTP.

Wastewater: In this thesis the expression wastewater refers to the water received by municipal WWTP:s. This may include wastewater both from households and industries.

Abbreviations

BOD_7 = Biological oxygen demand (measured over 7 days)

COD = Chemical oxygen demand

CPI = Consumer price index

DAP =Di-ammonium phosphate

DM = Dry matter

EBPR = Enhanced biological phosphorus removal

EPA = Environmental protection agency

IFDC = International Fertilizer Development Centre

KSEK = Kilo (thousand) SEK

LP = Linear programming

MAP = Mono ammonium phosphate

MSEK = Million SEK

NPV = Net present value

PAH = Polycyclic aromatic hydrocarbons

PCB = Polychlorinated biphenyl

PE or pe = Person equivalent

PPI = Producer price index

PR = Phosphate rock

SEK = Swedish krona

TOC = Total organic carbon

tot = Total

TSP = Triple superphosphate

UNEP = United Nations Environment Programme

WAP = Wet process phosphoric acid

WWT = Wastewater treatment

WWTP = Wastewater treatment plant

Chemical Symbols:

Ag = Silver
Ca = Calcium
Cd = Cadmium
Cr = Chrome
Cu = Copper
Hg = Mercury
K = Potassium
Mg = Magnesium
Mn = Manganese
N = Nitrogen
Ni = Nickel

P = Phosphorus
Pb = Lead
Zn = Zink

NH_4 = Ammoniac
NO_2 = Nitrite / Nitrogen dioxide
NO_3 = Nitrate
P_2O_5 = Phosphorus pentoxide

1 Introduction

This is a study of processes for wastewater treatment and reuse of the phosphorus (P) in resulting waste material, sewage sludge. The aim is to provide a cost comparison of different ways to recycle P from wastewater in a Swedish context. Data is obtained through a combination of literature and personal communication with trade organisations, recycling companies and existing WWTP:s in Uppsala, Helsingborg and Borås. The data is applied to Kungsängsverket (Uppsala), in a case study. The objective is to optimise the choice of treatments in order to minimise costs. The studied treatments include two different wastewater treatments, additional strategic up-stream management (Revaq-certification) and incineration and extraction of phosphorus from ashes using the Clean-MAP technology.

1.1 Problem background

The research is motivated by two separate, yet intertwined problems. One being the scarcity of phosphorus, which is an absolute necessity for food production. This is a need that increases with a growing population. The other problem is dealing with sewage sludge, a waste product that is constantly and inevitably produced in large volumes at our waste water treatment plants (WWTP:s). This problem is also growing with the growing population. At the same time, it is becoming increasingly difficult to recycle it. A large part of the nutrients we harvest (including P) eventually end up in sewage sludge. However, the sludge can serve as an alternative source for P. By recirculating the phosphorus in sewage sludge and thus re-looping the production chain (which historically used to be a cycle but has become all too linear), the two problems may be partially solved as one. The Swedish environmental protection agency (SEPA) has suggested the introduction of a national target to recycle at least 60 % of the phosphorus from sewage to productive land, whereof half must be utilised on farmland (Naturvårdsverket, 2013, 1).

1.1.1 Why is phosphorus scarcity an issue?

Phosphorus is an irreplaceable building block in all living cells. It is also finite and acts as a bottle neck for life and food production (Cordell *et al.*, 2011; Ott & Rechberger, 2012). Together with nitrogen and potassium, it is one of the key nutrients in agriculture. The Haber-Bosch process for producing nitrogen may be energy intensive, but the supply is inexhaustible and potassium is the 7th most abundant element on earth, making up 2,6 % of the earth crust it is mined as potash. Phosphorus on the other hand, is far less abundant. Only a handful of countries have the majority of the world’s phosphate rock (PR) mines and their stocks are diminishing. This poses an enormous problem for the agricultural sector, which uses 90 % of the phosphorus produce. In time, farmers will experience increasing problems procuring the phosphorus they need to run their business (Cordell, 2010).

Seyhan and fellow writers (2012) suggest that the known reserves will be depleted in 50-100 years, while Ott and Rechberger (2012) more optimistically state that it is the high-grade reserves are depleted within 50-120 years. Cooper and colleagues (2011) describe that 70% of the global production originates from reserves that will run out within 100 years. But there are also higher estimates, suggesting that the reserves will last another 350 years. These exclude the usual assumption of increased demand (due to increased population and consumption). Many estimates refer to what is economically accessible today, but The International Fertilizer Development Center, IFDC assumes that technological advance will make more phosphorus available so that PR reserves pure enough to produce fertiliser will last another 300-400 years (IFDC, 2010). They argue that the amount of P that can be produced is based on its value to the agricultural system (and other users). More can be made available, depending on the price.

Though the estimated time frame varies, there is no doubt that the high grade P-resources will eventually be depleted. As the high grade phosphate mines are emptied, the quality of remaining assets decreases. This leads to increased production costs (Cordell *et al.*, 2009; IFDC, 2010). The IFDC points out that while efforts are made to increase the efficiency of mining processes, only the techniques that are economically, logistically and technically feasible will be adapted. On the other hand, Seyhan with co-writers (2012) state that phosphorus has no choke price due to its irreplaceability.

1.1.2 Phosphate rock: Sources and quality

Phosphate rock varies widely in mineralogy, texture and chemical properties, though it commonly contains some form of apatite (phosphate mineral). Igneous deposits often contain intrusions and typically produce low grade phosphate ores. These have to be upgraded through further processing from <5% P_2O_5 to 35-40%. The igneous PR is mainly mined in Russia, South Africa, Brazil, Finland and Zimbabwe. The bulk of the sedimentary deposits have formed on offshore continental shelves. Their composition vary greatly, though most sedimentary deposits contain an apatite that can at best be upgraded to 42 wight-% P_2O_5 (IFDC, 2010). Many high grade deposits are already depleted and the quality of PR has decreased. There are issues with both cadmium and uranium content which to a large extent end up in the fertilisers (Cohen, et. al).

The IFDC (2010) write that the search for PR reserves became a global effort in the 20th century and the mining now results in about 160 million tonnes of PR yearly. The PR is primarily obtained through open-pit mining and requires advanced technology and transportation systems to move vast volumes of overburden and phosphate rock, from which phosphoric acid is produced for use in fertilisers. When todays mines are mined out, more expensive underground mining methods may become more attractive. It may also become necessary with vertical integration of PR mining and the further processing of fertiliser products to be able to compete on the future phosphate fertiliser market (ibid.).

The phosphate in PR needs to be processed to become available to plants. Through different processes the phosphate is commonly turned into wet process phosphoric acid (WPA), from which mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP) or triple superphosphate (TSP) can be obtained. Other forms are also produced, but MAP, DAP and TSP make up half of the world’s phosphate based fertilisers.

Almost 80 % of the world’s known reserves are found in Morocco and West Sahara (Cohen *et al.*, 2011). The second greatest national reserve contains over 5 % of the world reserve and is found in China. Other large deposits are found in Syria, USA, Jordan, South Africa, Russia, Brazil, Egypt and Israel. Less than 5 % of the world reserves are found in other countries. While Morocco and West Sahara have the world’s largest deposits, the US still surpasses them in production. However, exports from the USA ceased in the early 2000’s and China introduced high tariffs on the export of fertilisers in 2008, in order to safeguard their domestic supply. The tariffs have since been decreased due to domestic over-supply. In 2008, 72 % of the world production came from the USA, Morocco, West Sahara and Russia.

1.1.3 Recirculation offers a partial solution

As an alternative to mining virgin materials, phosphorus can be recycled from a number of different waste fractions, achieving various quality at varying costs (as with mining). A lot of research has gone into recycling of phosphorus in the last few years and concerns have been raised over the sensitive geopolitical situation, which arises when the entire world is dependent on only a handful of countries that hold the vast majority of the world’s accessible phosphate rock (Cordell, 2008). To reduce dependence on foreign supply, countries like Sweden with no or little domestic assets need to increase the recirculation of already imported resources. Increased recirculation will not evade depletion of accessible high-grade phosphate rock, but can significantly delay it (Seyhan, *et al.*, 2012).

Both Sweden and the EU have a positive phosphorus balance, meaning that the total mass of phosphorus in imported products is greater than that in exported products (Linderholm, 2012; Ott & Rechberger, 2012). This means that the resource accumulates in different areas. Currently only a small portion is being recycled, so there is great potential for increased recirculation. According to Cohen with colleges (2011) the phosphorus that is removed from the field through harvest ends up in either the fodder cycle, the food cycle or industrial cycle. These cycles result in wastes such as sewage sludge, manure and other bio wastes, which could all serve as alternative sources for P.

1.1.4 Swedish objectives for sustainable recirculation of phosphorus

One of the wastes from which P can be recycled is sewage sludge, the inevitable by-product of today's sewage systems. In Sweden, sewage sludge is traditionally applied to farmland as a fertiliser. When used as a fertiliser, sludge could potentially supply all necessary nutrients, except for potassium. But sludge does not only contain wanted nutrients. It also contains unwanted substances. To avoid recirculating pollutants, stricter regulations have been long in the making and are expected to be introduced within a near future, making it increasingly hard to apply sludge to agricultural land. At the same time, sludge cannot with today's regulations be disposed of in landfills (Schipper *et al.*, 2001).

The Swedish Environmental Protection Agency (Swedish EPA or SEPA) has ben assigned by the government to suggest targets and legislation regarding recirculation of phosphorus in accordance with the national environmental objectives. The SEPA concluded that sewage sludge is the waste fraction with the greatest potential for increased recycling in a short-term perspective. Only 25% of the P in sewage sludge is currently being recycled. That leaves a potential for another 4000 tonnes. There is however a conflict between the goals for phosphorus recycling and the generational goal of a toxic free environment, due to residue of pathogens and heavy metals that can be found in sewage sludge. To limit the output of these substances, new and stricter regulations regarding the content in recycled sewage fractions have been suggested. These include limit values for eight heavy metals and five organic compounds (Naturvårdsverket, 2013, 1). These restrictions will make recycling safer, but will also make it increasingly hard to make use of sewage sludge as a fertiliser.

1.2 Problem statement

Many processes have been developed to recover phosphorus from sewage sludge, sludge ashes or reject water from the anaerobic digestion at WWTP:s. Yet the SEPA expresses that it has not seen the development for the centralised phosphorus mining from sludge that it had expected. It seems that the reason for this is not primarily a shortage of technological development, but a lack of commercialisation of developed technologies. Thus, there is assumed to be a need for introducing economic management tools (Naturvårdsverket, www, 2013). The United Nations Environment Program (UNEP; 2011) sees a need for information on new technologies. As phosphorous has not received much attention from economic analysts in the past, there is still a need to evaluate how different technologies compare to each other from an economic perspective (Seyhan *et al.*, 2012; Cordell *et al.*, 2011; Molinos-Senante, *et al.*, 2011).

Previous research on P-recovery from WWTPs has primarily focused on technological aspects and there is little empirical research on process costs (Friedler & Pisanty, 2006). Studies with an economic focus usually take on a broad socio-economic perspective, using cost-benefit analysis or life cycle analysis to asses a specific process or sometimes comparing phosphorus removal from wastewater to no phosphorus removal (Molinos-Senante, *et al.*, 2011; Paul, *et al.*, 2001; Linderholm, *et al*., 2011). The analysis of environmental costs is highly relevant, but micro-economic theory suggests any entity, including WWTP:s, is likely to strive for maximising profits or minimising costs. Tsagarakis and colleagues (2003) write that water management strategies are to a great extent governed costs of construction and operation and maintenance. Yet little attention has been given to profitability and cost minimisation. The reason for this might be that phosphorus recovery at WWTP:s is not usually associated with profits and costs are simply covered by tariffs.

According to Cordell *et al.*, (2011), there is a gap between the development of technologies and frameworks that support the best technology for recovering nutrients. There is currently no technology for recovery that is accepted as the best available on the market. Researchers also see a need to determine sustainable ways of recovery in a given context. This includes economic sustainability, as costs have a great impact on wastewater management strategies (Friedler & Pisanty, 2006).

1.3 Aim & objective

Aim: This is a study of how an effective fertiliser with acceptable pollution can be produced at a minimum cost. The research is aimed at comparing existing processes for phosphorus recycling from sewage sludge in terms of costs in a specific context (a mid-sized Swedish WWTP, with plant specific conditions based on a Kungsängsverket in Uppsala). The costs of four treatments are minimised in three scenarios based on different quality requirements; current limit values (LV), expected new LV as suggested by the SEPA, or yet stricter LVs.

Objective: The objective is that the comparison may serve as a guide for WWTP:s when making strategic decisions about process-set up. Results may not interest the end user of the phosphorus, i.e. the farmer. The extent of recycling and quality of recycled products may however affect the future availability of alternatives to today's commercial fertilisers.

1.4 Research question

- How is phosphorus from sewage sludge recirculated to farmland at a minimum cost, using existing wastewater treatments and recovery processes?

1.5 Delimitations

This a strictly business economic problem, taking only the costs for one entity (the WWTP) into account. It is not a cost-benefit analysis and does not include any estimated environmental or socio-economic values of recycling. The study is also limited to processes applied to wastewater or sewage sludge. This is because sewage sludge has a high content of phosphorus and because recycling is becoming increasingly problematic with the expectation of stricter regulations for farmland application. The comparison of treatments only regards the quality of the resulting sludge in terms of metal-residue. The compared methods are, for the purpose of this study, assumed to be equal in attaining a good water quality or adjusted so that the same assumption can be made. This study focuses on the economics of the studied processes. It is not meant to give comprehensive insights on the total environmental impacts of these processes. It merely considers their ability to meet certain environmental criteria (i.e. not exceed limit values).

It is impossible for any single study to cover all possible methods of recirculating phosphorus. Thus, this study will focus on only 4 processes, where two are actually wastewater treatments, one is continuous work to reduce pollution upstream in order to achieve a cleaner sludge, and one is a process for extracting phosphorus from sludge-ashes. The processes in this study show potential to live up to Swedish environmental regulations. The technologies described in the literature do not, as Cordell et alia (2011) state, address the inefficiencies of today's commonly centralised waste water treatment systems. These inefficiencies will not be taken into account in this study either. Instead the processes are chosen because they are applicable to Swedish wastewater treatment. This means that processes based on source separation were ruled out as likely alternatives to be implemented on a large scale.

Different qualities of the phosphorus in terms of solubility and availability to plants cannot be analysed in the mathematical model and is only briefly touched upon in the discussion. This is however a potentially important aspect. Another aspect that would make an interesting research topic, is how scale of production affects the economics of different recirculation options. This is not a part of this project, as data could not be obtained at a level of detail where scaling could be done with any level of preciseness.

2 Literature review

This chapter is somewhat condensed, as some of the findings from previous research are described in other chapters. This is to facilitate the reading process and avoid repetition. At the end of the chapter an overview is presented of some of the reviewed literature (table 1).

2.1 Recycling technologies and applicability in Sweden

Development of technologies to recycle phosphorus from wastewater treatment (WWT) has been substantial around the world. These include processes for recovering P from different streams at the WWTP or from ashes from incinerated sludge. Technologies that recover P from reject water from anaerobically digested sludge (see empirical background on WWT) are found to be cheaper and produce a cleaner product compared to recovery directly from sludge. Recovery from the sludge does however allow more efficient recycling (Carlsson, *et al.*, 2013). Many of the existing technologies are based on crystallisation or struvite precipitation which can only be achieved at plants using enhanced biological phosphorus removal. Levin with colleagues (2014) summarise the development of processes for recycling phosphorus from sludge and related materials. Based on cost estimates previously published by Pinnekamp et alia (2011), Nieminen (2010) and Carlson with colleagues (2013), they suggest that technologies to recover P vary in cost from between, 17 and 400 SEK per kg P.

Linderholm and others (2012) studied four different processes through life cycle analysis. In this study, the environmental impacts were compared for certified sludge (Revaq), struvite-precipitation (Ostara), recovered magnesium-ammonium phosphate from ashes (ASH DEC) and of mineral fertiliser. They found that struvite and recovered P from ashes had a lower content of cadmium, but that recovery also used more energy and produced more greenhouse gases. In terms of energy and greenhouse gases, direct application of sewage sludge to farmland was more efficient. But if only looking at the cadmium content, recovery from ashes is preferable. Struvite precipitation was found not to be suitable in Sweden due to costs and technical reasons. Jonsson (2015) evaluated a number of existing technologies for P recovery from ashes for Fortum, concluding that ASH DEC and CleanMAP are the most promising for implementation in Sweden. ASH DEC is run commercially in Germany and at pilot scale in Austria. CleanMAP is a new technology which is not yet commercialised.

2.2 Economic assessment of wastewater treatment

Most studies on wastewater treatments focus on process technological aspects, such as removal efficiency. Less attention has been given to economic feasibility of different recycling methods (Molinos-Senante, *et al.*, 2011). There are few studies on costs for recycling phosphorus from sewage sludge, but none have been found that use investment calculation or directly compare the cost of implementing different processes at a specific plant. Research has however showed that the cost of wastewater treatment vary with different levels of treatment and depending on the size of the plant in terms of design flow. The level of treatment will depend on the quality of the raw sewage and the requirements on the effluent.

The two major cost categories are cost of construction and cost of operation and maintenance (O&M). Tsagarakis with colleagues (2003) also describe cost of land as a separate major cost category. With a rising level of treatment, the relative size of construction costs tend to decrease and subsequently the costs of O&M tend to increase proportionally (Friedler & Pisanty, 2006). There is no abundance of openly accessible documents that describe construction costs in any detail. Cost break downs are only rarely available (ibid.), which of course limits the ability to draw more specific conclusions from the clumped information.

2.2.1 Capital and construction Costs for Municipal WWTP:s

Costs depend on the value that is to be depreciated (that is the initial investment, in this case construction costs plus land costs), the depreciation period and the method of depreciation. Huang (1980), Tsagarakis with colleagues (2003) and Friedler & Pisanty (2006) have gathered statistical data to formulate cost functions for WWTP:s with different levels of treatment. The construction costs are generally expressed as

$$C = a\,x^{b} \qquad (1)$$

C is construction costs
a is a cost coefficient (costs * $(m^3 * d^{-1})^{-b}$ or costs * pe^{-b})
x is the design flow ($m^3 * d^{-1}$ or pe)
b is a power coefficient,

b is usually less than 1 to express an economy of scale effect on total costs (Tsagarakis *et al.*, 2003 & Friedler and Pisanty 2006). The cost coefficient can describe costs in relation to design flow (x), which can be expressed either as cubic meters per day or the number of person equivalents, pe, which the plant can treat.

This function was first estimated by Huang in 1980, in a USEPA study using data from over 700 American WWTP:s. Huang (1980) states that the functions he presented can be used for preliminary estimation of construction costs for a facility or individual process, but also stresses that the results are statistical averages and should be used with caution. Site specific conditions can dramatically alter the costs, also this cost equation does not always incorporate the same components (Friedler and Pisanty, 2006; Tsagarakis *et al.*, 2003).

Friedler and Pisanty (2006) found that the treatment costs were lower than those found by the USEPA. The differences may be ascribed to reductions in technology specific cost, increased process efficiency over the decades, but also to differences in living standard, construction regulations and building specific costs in the two countries. To be able to analyse costs for investments made over several years, the costs can be normalised by multiplying the historical cost of the investment to the change in CPI or PPI (ibid.):

$$PV_t = HC_{t0} * (I_t / I_{t0}) \qquad (2)$$

PV_t is the present value at year t,
HC_{t0} is the historical cost at year t0
I_t is the PPI or CPI (producer- or consumer price index) for year t
I_{t0} is the index for the year of the investment, t0.

Capital costs are annuitized by multiplying the PV with a capital recovery factor (Tsagarakis, *et al.*, 2003):

$$CRF = \frac{r(1 + r)^t}{(1 + r)^t - 1} \qquad (3)$$

Huang (1980) found that non-construction costs such as planning, administration, engineering fees and contingency allowance accounts for 33-65% of total costs for construction of a new plant, with a national average of 50%. For upgrading or enlarging existing WWTP:s the non-construction costs range from 18-45% instead. The same report describes costs for different treatment levels, one of which is a tertiary treatment described as “advanced wastewater treatment” including nitrogen and phosphorus removal. For this treatment he found a strong correlation with the function

$$C = 2{,}41 * 10^{6} * Q^{0{,}92} \qquad (4)$$

where Q is the design flow in million gallons per day (MGD). The study also presents a breakdown of total costs for construction components and unit costs for secondary treatment through activated sludge. The breakdown includes unit costs that are generally not applicable to Swedish treatment plants, such as drying beds and aerobic digestion (the common practice in Sweden is mechanical dewatering and anaerobic digestion).

Similarly the Israeli practices included in Friedler and Pisanty's study (2006) differ from Swedish practices, except perhaps for the advanced treatment category which includes chemical precipitation. For which they derived the below function:

$$C = 1934 * Q^{0.87} \tag{5}$$

Where Q is defined as cubic meter per day and the cost is expressed in US$. An interesting find they made is that the power coefficient gets closer to 1 with more advanced treatment, suggesting that the economy of scale is less. The relative proportion of engineering costs tend to decrease with increasing design flow, and thus the proportional cost of electro mechanical equipment tend to increase. However, the costs of electricity and control were found to be fairly insensitive to design flow, which according to the authors implies shorter depreciation time for larger plants and thus higher capital costs.

2.2.2 Costs of operation and maintenance

Operation and maintenance (O&M) costs include different things in different studies, but in general O&M includes costs of personnel; energy; chemicals; and maintenance. Tsagarakis with colleagues (2003) include major repairs and replacements that would have been regarded as capital cost, except for that they are normally not possible to distinguish and are thus incorporated with maintenance. The sludge treatment costs cannot usually be separated from the costs of wastewater treatment. Tsagarakis with colleagues (2003) state that in many cases the disposal costs only include transportation to a landfill. As the landfill is usually owned by the municipality itself, there is no additional cost.

The proportion of O&M costs tend to rise with an increased design flow. Friedler & Pisanty (2006) found that for secondary treatment with nutrient removal and filtration, the O&M costs represent about 56% of annual costs at a daily flow of 50 000m^3, compared to 46% at 10 000 m^3/day. Larger flows were not included in the analysis due to lack of data. The percentage of O&M costs vary greatly in different studies (ibid.).

Huang (1980) uses the same formula ($a\ x^b$) for describing O&M as for construction costs. Hernandes-Sancho with colleague (2011) point to the weakness of such functions, that they only describe how costs vary with plant size. In order to include more information, they developed more or less process-specific functions that describe costs as a function of plant size, where the power coefficient is a function of the age of the plant and removal rates for COD, N and P.

2.2.3 Assessing treatment costs in a Swedish context

Tagesson (2001) researched accounting practices at municipal WWTP:s in Sweden, and found that there is no ruling set of principles for how investments or transactions are accounted. He concluded that this causes comparisons to give an untrue view. A decade later Balmér & Hellström (2011) discussed performance indicators for WWTP:s and found that it is difficult to make meaningful comparisons of total costs for WWTP:s, because investments have usually been made at different times and sometimes at different interest rates. Less than half the studied plants (24 in total) were willing or able to provide data including amortisation and interest expenditures. It appears that only a few WWTP:s account for personnel costs at cost centres that show whether or not the cost has arisen from work within the core business.

The most common method of depreciation used by Swedish WWTP:s is linear depreciation

(Tagesson, 2001). Applied depreciation schedules in the industry badly match the economic life time of investments. Guidelines from local authorities recommend using a 25 year depreciation period, though both the economic and technical life time is generally considered to be longer. This results in a skewed representation of costs over time.

Tagesson (2001) describe that in accordance with the cost principle it has been accepted to use actual interest rates on long term loans in the calculation, rather than a rate that better reflects market risk. The industry guidelines suggest using the rates of 5 year government bonds. There is however a great variation in the required rate of return in different municipalities, which do not always reflect actual rates and thus make cost comparisons misleading. Also reinvestments and general repairs are not always clearly separated. Reinvestments may be periodised and depreciated and treated as a direct cost. The practices affect the proportion of costs referred to capital contra operations and maintenance. Capital costs constitute an average of thirty percent of total costs for municipal WWTP:s in Sweden, though they may make up as much as half of the yearly costs.

Table 1: Overview of reviewed articles

Previous research of WWT and sludge recycling				
	Main topic	Method	Process/System studied	Geographical context
Balmér & Hellström (2011)	Discussion & suggestion of performance indicators & exergy indices for WWTP:s		Process indicators & benchmarking of Municipal WWTP:s	Sweden
Borglund (2004)	Process technical optimisation at käppalaverket (w short mention of O&M costs)	Full scale, on-site case study.	EBPR	Sweden
Carlsson, et al. (2013)	Treatments for phosphorus recovery	Literature review	Recovery at WWTP or materials originating from WWT	Sweden
Friedler & Pisanty (2006)	How cost elements relate to design flow for diff. levels of treatments	Developing regression equations from empirical data for cost elements	ST, Advanced ST, Advanced WWT, Nitrification, Phosphate removal	Israel
Gustavsson (2005)	Efficiency of hydrolysing mixed primary & secondary sludge (mentions pros and cons of EBPR)	Computer simulation and laboratory tests	EBPR & VFA hydrolysis	Sweden
Huang (1980)	Construction & O&M costs of WWTP:s with different levels of treatment in the USA	Developing regression equations from empirical data for construction and process costs respectively	Secondary treatment (ST), ST w P removal, Advanced ST (AST), AST w nitrification, AST w P removal, AST w nitrification & P removal, different stabilisation ponds and lagoon systems	USA
Jansen, et al (2009)	Summary of experiences from start up and O&M of EBPR-plants in Sweden	2 full scale case studies of VFA hydrolysis+ laboratory tests (FISH)	EBPR w VFA hydrolosis	Sweden
Jonsson (2015)	Prospects of technologies for P recovery from ashes	Literature review	Recovery from ashes	Sweden
Levin et al. (2014)	Review of existing methods for phosphorus recovery	(literature review?)	29 recovery processes. Costs estimated for Ashdec, Berlin/AirprexSeaborne, Crystalactor, Fix-Phos, Ostara, Pasch, P-Roc, Phosnix,Phoxnan, SesalPhos	Sweden
Mattson et al. (2012)	Revaq: reduction from upstream involvement at Gryab WWTP	Case study, applying own model to predict reductions of metals based on previous levels and already taken measures	Revaq	Sweden
Norstrom et al. (2008)	Environmental impact and costs of connecting developing areas to existing WWTP or constructing on-site systems	Substance flow analysis, energy analysis	On-site systems compared, connection to central system	Sweden
Molinos-Senante, et al. (2011)	Economic feasibility of P recovery from wastewater	CBA of P recovery	Struvite recovery	Spain
Tagesson (2001)	Common practices for Swedish WWTP:s to report capital costs	Survey	Municipal WWTP:s	Sweden
Tsagarakis et al. (2003)	Systems comparison (construction + O&M costs)	LCA	Reed beds, Waste stabilisation ponds, conventianal activated sludge treatment (AS), AS with extended aeration (EA) and mechanical dewatering, AS with EA and air drying	Greece
Wei (2013)		Optimisation, evolutionary programming		

2.3 Commentary on findings in the literature

No study has been found that use mathematical programming to directly compare processes for a specific plant. Comparisons are usually made in a broader context. There appears to be a greater focus in current research on processes for extracting P from sludge or else concentrating it, rather than improving practices at the wastewater treatment plant to achieve a cleaner sludge. One must however not forget that the purpose of a WWTP is not sludge production, but the production of clean effluent water. The sludge is thus purposely containing as much of the contaminants from the incoming wastewater as possible (personal comment).

3 Theoretical framework & economic models

This chapter describes the theoretical framework applied in developing the model and performing the analysis. The theoretical concepts dictate the choice of quantitative methods used for solving this problem. The first three sub-headings describe general microeconomic theories and the last section describes theories more specific to wastewater treatment.

3.1 Microeconomics: Resource allocation & cost minimisation

Microeconomics provide concepts and models for understanding the process of allocating resources and for understanding the roles that prices and markets play in the allocation decision (Gravelle & Rees, 2004). Basically, a firm can be described through a set of production possibilities. An entity (such as a business firm, government, economy or other organisation or person) has a given quantity of different factors of production to its disposal and this limitation of resources directly limits the production possibilities (Dorfman, *et al.*, 1958). This makes the allocation of scarce resources the fundamental problem of any firm. The problem consists of finding the optimum solution to the objective function, that is the line of production which allows the firm to attain its objectives within the scope of available resources (Intriligator, 2002). An entity is assumed to make production decisions aimed at minimising costs and/or maximising profits (Kreps, 1990).

Cost minimisation is essentially straight forward, though it is complicated by environmental factors over which the company has no or little control, such as prices, availability of inputs or regulations. These factors tend to add restrictions to the problem. Though prices change over time, they can usually be assumed to be unaffected by the firm’s own actions. Prices are determined by the market, which is said to be perfectly competitive if there are enough actors that no single buyer or seller can have a significant impact on the price. On the other hand, there are markets with only a few sellers where a single firm or cartel of firms acting as one may have a distinct impact on prices. These are considered non-competitive. Many markets are competitive enough to be treated as perfectly competitive for the sake of aiding analysis (Pindyck & Rubinfeld, 2009).

Resource allocation is a choice between alternative uses, so called trade-offs. For a firm, this trade off means that choosing a line of production requires it to focus its available input factors into that activity, rather than another. Whether it is monetary assets, land or available labour that is the limiting factor, a firm has varying ability to relocate its assets depending on the time horizon (Pindyck & Rubinfled, 2009). In a short term perspective a company's assets tend to be locked into a specific production system. There will be less available for alternative use than there will be in a long term perspective, when for example a line of production can be dropped to free inventory or additional labour can be hired. The time perspective thus decides whether costs are treated as fixed or variable. Over a long enough time period all costs are variable, though at a given moment most of them are better considered to be fixed.

3.2 Decision making through operations research

There are so called single-criterion decision problems, but most problems are multi-criteria decisions. If the problem of phosphorus recycling was a single-criterion problem, the only criterion might be to recirculate the maximum amount of phosphorus and the method for recycling would be the one that produces most phosphorus with no regards to costs or residue in the product. However, in most real world situations there are many criteria, such as limited budget and maximum emissions. This makes the decision more complex because there is seldom one alternative that is the best in regard to all criteria. This is where the methods used in operations research come in handy to help make the decision.

Operations research, also called management science, is the body of knowledge used to facilitate decision-making. It commonly makes elaborate use of quantitative methods. Anderson and colleagues (2000) list seven steps in problem-solving, where the first five make up the decision process:

1. Identifying & defining the problem at hand
2. Determining a set of alternative solutions
3. Determining the criteria for evaluating the alternatives
4. Evaluation of alternatives
5. Choosing an alternative
6. Implementing the chosen alternative
7. Evaluating results

Andersson (2013) describe the same process leading up to the decision, with a heavier focus on the use of data and calculation method:

1. Defining the decision situation
2. Identifying calculation data
3. Evaluating standard calculation costs
4. Choosing or developing calculation model
5. Compute calculation results and add to other decision basis information
6. Make the decision

The decision can be based on either qualitative or quantitative analysis of the alternatives. A quantitative evaluation is especially useful if the problem is complex (Anderson, 2000). It is also useful if the problem is of special importance, if it is a new problem for the decision-maker or if it is repetitive and quantitative procedures save time. The analyst then develops a mathematical expression, describing the objective/-s, constraints and other aspects of the problem. It is important when using a quantitative approach that the management scientist and the manager agree on the structure of the problem before developing a calculation model. The purpose of which is to structure the data on which the decision is based (Andersson, 2013). Models can also be either descriptive or normative. The descriptive method has the strength of providing an image of the consequences of different decisions and highlighting differences in alternative scenarios. The normative model on the other hand, finds the best outcome from a number of different alternative actions. Operations research typically uses a normative approach.

The mathematical model allows for an assessment, without having to use trial and error. It is a representation of a situation, where the problem is simplified and described by the necessary symbols and mathematical expressions (Andersen *et al.*, 2000). Provided that the mathematical model represents the problem well enough, the solution to a profit maximisation model will be close to the actual profit that would be obtained in a test-production. If the model is ill defined it will give misinformation that can lead to deciding on the wrong cause of action and thus lead to high losses or default profits. The decision therefore depends on an accurate representation of the real problem. Models for production planning usually describe the relationship between profits and produced volumes, costs and revenues. When deciding which production process to invest in, it is important that the model depicts both fixed and variable costs. It is also important to only include separable costs that are specific to the examined operation/-s and exclude all joint costs that are independent of the outcome.

3.2.1 Applied operations research: linear programming

Different activities (operations) in the process of phosphorus recovery can be analysed using linear programming (LP). LP is a method of analysis for finding the optimum (maximum or minimum) solution to a linear function. LP differs from classical programming and non-linear programming, in that it is subject to linear inequality constraints as well as non-negativity constraints (Intriligator, 2002).

The programming-model, uses the following objective function to solve the problem of choosing the optimum process combination:

$$\min Y = \sum P_i C_i \tag{6}$$

Written out the long, but perhaps easier way, the function in this case looks like:

$$Y = P_1C_1 + P_2C_2 + \ldots + P_7C_7 + P_8C_8 \tag{7}$$

With the assumption that all processes (P_1-P_8) are binary, the total cost (Y) would equal P_iC_i, where the i:t process combination is the one with the lowest cost. All other P*C would equal zero, with the assumptions that all control variables P_i = [0,1] and $\sum P_i = 1$. This means that only one combination is possible. C_i is the total cost of P_i , including fixed annual costs and variable costs for water and sludge treatment, such that

$$C_i = (FC_i + VC_i). \tag{8}$$

Where FC is fixed costs and VC is variable costs. VC is decided by the volume, which in this case is fixed, so from a computational perspective, all costs may be considered as fixed, but being able to separate different variable costs aid the analysis and traceability of data.

The restrictions used in this case, are that each P_i is binary, the treated water volume (w) equals the annual flow at the WWTP and that residue are under the limit value (LV). The inequalities that restrict the optimum solution are generally defined as (Dorfman, *et al.*, 1958):

$$a_{i\,j}\, x_i < c_j\,. \tag{9}$$

Adjusting the above formula to the case at hand, with the control variable P_i instead of x_i and constraints consisting of limit values, this becomes

$$\sum_{i=1}^{8} \left(a_{ij}P_i\right) < C_j \tag{10}$$

This function describes constraints r_1-r_8. Where a is the residue level of the j^th^ unwanted substance in the sewage sludge, and c_j is the limit value (LV) for the same substance. The substances (specified by j) in this case are the 8 regulated metals.

$$j = \{1..8\} = \{ Pb, Cd, Cu, Cr, Hg, Ni, Ag, Zn\} \tag{11}$$

In conclusion, the sum of residues in sludge or sludge products must not exceed the limit values. The next set of constraints determine that each process is either applied fully or not at all. This means that the control variable P for each process combination equals one if applied and zero if not. Thus the binary constraints, $r_9 - r_{16}$, use the function

$$P_i = \{0,1\}\,. \tag{12}$$

The objective function is also constrained by the assumption that only one process combination can be applied. This is controlled by restriction r_{17}:

$$\sum_{i=1}^{8} \left(P_i\right) = 1 \tag{13}$$

The final restriction, r_{18}, expresses that the WWTP needs to treat all received wastewater, so that

$$w = 19\,500\,000. \tag{14}$$

3.3 Comments on above mentioned theories

Some argue against the assumption that a firms simply strive for profit-maximisation, though few question that it is an inherent part of decision making. Kreps (1990) mentions the case of shareholders participating in markets that are affected by the firms operations. For example, the shareholder might be a consumer of the firm’s product and might be hurt if the firm maximises profit through high prices. Similarly if a shareholder is also a shareholder in a second firm that produces factor inputs to the first firm, this person is unlikely to prompt profit-maximisation for the factor-production as it reduces profits for the first company. Thus the assumption does not always hold true.

4 Methodology

Let us repeat the research question:

- How is phosphorus from sewage sludge recirculated to farmland at a minimum cost, using existing wastewater treatments and recovery processes?

To answer this question, there is a need to review existing technologies and choose those relevant to investigate. The treatments included in this study are found through a literature review and are then analysed based on an investment appraisal of each possible combination. As recirculation has to be conducted in compliance with Swedish regulations, the result of the appraisal is analysed in relation to limit values in different scenarios.

This is a case study. There will be no large sampling and no development of statistics. The results are highly contextual and very much influenced by the quality of the input data, which is based on data from a limited number of sources. These results are not to be generalised.

This research process has roughly followed the first four steps for problem solving as outlined by Andersson with colleagues (2000; see theory chapter):

1. Identifying & defining the problem at hand (literature review)
2. Determining a set of alternative solutions (literature review)
3. Determining the criteria for evaluation (literature review)
4. Evaluation of alternatives (case study, operations research)
5. Choosing an alternative (case study, operations research)

The choice of alternative in this case is simply a presentation of the result provided as the optimum choice by the mathematical model. This result is analysed and discussed, in relation to the context. Actually making a decision for the WWTP on which the case is based is not the objective. The objective is simply to evaluate the alternatives in relation to each other.

4.1 Literature review provides context & general figures

A review of previous research helped to define the problem, outline the background and give a necessary understanding of the context. It also helped identify possible operations/treatment processes and to determine the decision criteria. While there is much research on different methods for recycling phosphorus and related topics, there proved to be fewer publications available on costs or profitability of different options. There has been a greater focus on technical efficiency than on economic efficiency, yet costs are an important aspect (Hernandez-Sancho, *et al.*, 2011).

The literature review performed within this study include publications on phosphorus, wastewater treatment, costs of wastewater treatment and economic literature. Microeconomic theories have been reviewed to provide the theoretical framework, but relevant articles on the economics of WWT and phosphorus recycling was surprisingly scarce. There also proved to be a case of international costs and conditions not being readily applicable to Sweden, as the requirements on the level of purification and other legislation differ widely.

The economic theories are found in course literature, while the bulk of publications on WWT and sewage sludge is found online, mainly using the search engines Google, Google-scholar, Science Direct and Web of Science. A list of used search words and phrases can be found in appendix 1. Many papers and articles have been found through snowball referencing and suggestions of related articles on the journal home-pages. Recommendations of articles have also been received from field experts from the Swedish Water and Wastewater Association, the bio-P network, Kungsängsverket, Öresundsverket, Borås Energi & Miljö (wastewater treatment plants) and Ragn-Sells (waste management & recycling). In some cases publications that were found or suggested have been excluded due to price. This study almost exclusively include open access literature or literature that can be accessed through SLU. Some articles have also been disregarded for being written in other languages, even though the English abstract suggested that they might be relevant. Sometimes useful documents without clearly defined sources were found. These are also excluded.

The literature review has been supplemented with personal communication with trade experts (mostly e-mail and phone calls). To improve understanding of the studied processes, visits were made to Kungsängsverket, Easy Mining and Ragn-Sells. The visits and interviews have served to inspire and create a better understanding of how different treatments work, which ones appeal to the market and why, as well as why other techniques are unfavourable. A visit with Swedling at Kungsängsverket also helped to clarify which information is applicable to the case at hand. The personal communication has also helped to know when a lack of results in the literature search is due to an actual lack of relevant research or to insufficient search.

Interviews were performed in a semi-structured manner, applying the Delphi method which strives to obtain a reliable consensus from a group of experts by interviewing them individually and then returning to the interviewee with controlled opinion feed-back (Dalkey & Helmer, 1962). This method allows the researcher to return to the same expert and draw the attention to factors that were previously not considered and thus give the expert the opportunity to look at the problem from another angle and perhaps revise his or her opinion in light of new information. Questions are designed to bring out reasoning. The contacted experts are interviewed separately to avoid interaction with one another. Hence this method avoids the drawbacks with interactive methods like the round-table discussions where individuals may be prone to stick to preconceived opinions or else be swayed by a persuasively stated argument (ibid.). In this case, statements given by the interviewed experts were rephrased and repeated to another in order to validate, reject or further develop an opinion. The interviewees were presented with alternative views on matters where it was deemed plausible that further discussion could change the outcome, lead to a deeper understanding of the result or consensus where expert statements initially contradicted each other.

4.2 The case study

In previous economic assessments of WWT:s and sludge treatments, it has been stated that costs are calculated differently by different municipalities and are thus seldom comparable. A comparison is also made difficult because most processes can be implemented in various ways. The required rate of removal of key substances also varies depending on the quality of incoming water and different limits for residue in the effluent; not just on a national level, but between municipalities. This is why a case study is useful to facilitate a comparison of different processes under the influence of a fixed set of environmental factors. A case study is described by Robson (2011) as a strategy which allows the researcher to make empirical investigations of a contemporary phenomenon in its real life context. It involves using multiple methods, primarily of a qualitative nature, such as interviews and observations (ibid.).

In this case study, the cost of four different processes are compared, in eight possible combinations and under three different scenarios. The scenarios include different limit values that determine which process combinations are possible. This means that the least costly treatment might be preferable in scenario 0 which, where all treatments can produce a sludge that is approved for field application under today’s regulation. However, in a stricter scenario the restrictions imposed by the limit values may lead to the same treatment combination to be discarded in favour of a more costly process set-up, which produces a sludge with less residue.

4.2.1 The case plant

The case plant is based on Kungsängsverket in Uppsala. It can treat up to 200 000 person equivalents (pe; one pe is set to 70 g BOD_7 per 24 hours). It is assumed to treat on average 19 500 000 m^3 per year and produce over 10 000 tonnes of sewage sludge yearly. The plant is designed to treat up to 84 000 m^3 per day (Uppsala Vatten, 2015, 2). Like Kungsängsverket (whose recipient is Fyrisån), the case plant has limits for phosphorus and nitrogen in the effluent, and a guideline value for BOD_7 . These are summarised in table 2.

Table 2: Current limit values plus levels in incoming & effluent water (source: Uppsala Vatten, 2015, 1)

	content in effluent mg/l	content in incoming water mg/l	degree of purification %	**Limit/ Guideline value mg/l**
BOD_7	<3	210	98%	**10**
total P	0,085	5,8	98%	**0,25**
total N	11	50	76%	**15**

The sludge resulting from the wastewater treatment is treated through anaerobic digestion and dewatered to 28-29% dry matter. The distance, by road, to sludge storage is assumed to be the same as for Kungsängsverket today (13,5 km) and the distance to receiving farms 27,5 km, based on a simple calculation of available farmland in the region and assumptions that one out of four or five farmers might receive sludge and apply it to part of their land.

Kungsängsverket currently has a process setup with chemical precipitation of phosphorus, dosing ferric chloride before and after the biological treatment with an activated sludge (AS) process. The blocks used for mechanical and biological treatment were built in the 1940s-1950's (Uppsala Vatten, 2013). The initial mechanical treatment uses grids and aerated sand catchments. There is also an addition of ferric chloride and then removal of primary sludge. Next follows the AS process. After the biological treatment, the sludge is allowed to settle. The majority of this sludge from the pre-sedimentation is recycled to the first step of biological treatment and a smaller part is removed from the process. Part of the recycled sludge is treated anaerobically to remove P.

In the following chemical treatment, the remaining phosphorus and rests from the biological treatment are removed by dosing ferric chloride. The water passes through flocculation basins with mechanical stirring before the final sedimentation. The water goes through final polishing in chlorination basins before the effluent is released into Fyrisån.

Before stabilisation, the primary sludge and the chemical sludge from the final sedimentation are mixed together. The sludge is dewatered mechanically under the aid of an added flocculation chemical before it is stabilised through anaerobic digestion, which according to Henriksson *et al.*, (2012) is standard at larger WWTP:s. The digestion process produces biogas, which is partly used to run the local city buses and partly to supply the plant with heat and energy. The digestion residue (the sewage sludge) is again treated with a polyelectrolyte and centrifugation until it the dry matter-content (dm) is about 28%.

4.2.2 Three different scenarios

The treatments are compared in three scenarios with different limit values regulating the use of sewage sludge as a fertiliser. These are based on scenarios described by the Swedish EPA in its report 6580 (Naturvårdsverket, 2013, 1) and summarised in table 3 on the next page.

Table 3: Scenarios for case study

Scenario 0 current regulations			Scenario 1 suggested regulations from year				Scenario 2 stricter limits scenario		
		mg/kg dm			mg/kg dm	mg/kg P			mg/kg dm
Pb	<=	100	Pb	<=	25	900	Pb	<=	20
Cd	<=	2	Cd	<=	0,8	30	Cd	<=	0,4
Cu	<=	600	Cu	<=	475	17000	Cu	<=	350
Cr	<=	100	Cr	<=	35	1200	Cr	<=	20
Hg	<=	2,5	Hg	<=	0,6	20	Hg	<=	0,5
Ni	<=	50	Ni	<=	30	1000	Ni	<=	15
			Ag	<=	3	100	Ag	<=	2
Zn	<=	800	Zn	<=	700	25000	Zn	<=	550

The first scenario uses today's regulations. The second scenario applies the same regulations as suggested by the Swedish EPA and in the third scenario even stricter regulations are applied to the use of sewage sludge for fertilisation. The LV's constitute constraints r_1-r_8, defined as by function 10 on page 12. This study will not include scenarios for partial goals, but will look only on the potential of living up to the limit values as suggested to be effected in 2030. This is in order to provide a fixed time frame for making estimations of possible reductions in unwanted substances.

The suggested new limit values also include five organic substances that are not considered in this study. Those are excluded due to lack of research on how the substances may be reduced by upstream involvement. There are thus no grounds for assumptions made in relation to these limit values. There are also limits for how much of these substances may be spread per hectare of farmland, but limits for content in sludge are deemed to be more relevant and also more manageable. Thus the scenarios used in this case study are based solely on limits for heavy metals in milligram per kilo dry matter sludge. This is considered to give a sufficient indication of which processes are preferable.

4.2.3 Processes for WWT and phosphorus recycling

Though some research has been made attempting to asses different processes from an economic perspective, none have directly compared EBPR and conventional treatment with chemical precipitation in the context of a Swedish WWTP to see which has the potential to produce a sludge suitable for field application at the lowest cost. The literature review also showed no previous research on whether the extra cost of the quality certification Revaq can be motivated by a need to meet future requirements for residue in sludge (rather than by a general assumption that it is better for the environment to work against pollution).

This study is limited to covering four treatments. As the wastewater treatment process determines the sludge quality, two types of WWT:s are included in the study. These are chemical precipitation and EBPR (Bio-P). The other treatments are additional upstream management (Revaq-certification) and a treatment for P-recovery from sludge ashes (CleanMAP). These treatments are chosen for their potential for low cost and high quality output. They have been identified through the literature review and are all described in chapter 6, empirical background. In the mathematical model these are labelled T_1-T_4. An overview of the treatments can be seen in the figure below.

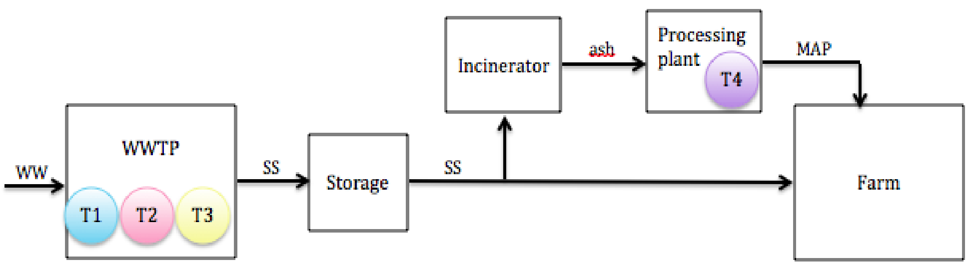


Figure 1: Processes included in the analysis. In the figure ww stands for wastewater and ss for sewage sludge

At first glance, one might think that T_3 (Revaq) which is primarily a quality management system directed at influencing stakeholders upstream, ought to be depicted to the left of the WWTP in this image. The work is however carried out by personnel at the plant, though it includes working both upstream (outside the depicted system) and all the way “downstream” to the farm with quality assurance of the sludge.

The wastewater treatments T_1 and T_2 are treated as mutually exclusive. However the water needs to be treated, so one of these must be applied. These can be used by themselves or in combination with additional treatments. Originally the four treatments included in this study were evaluated by themselves with the intention for the model to present the optimum treatment or combinations of treatments. But in order to linearize the constraints, the data had to be restructured. Instead of assuming that each treatment, (T_i) is an activity that can be combined with others in different combinations provided by the model, these combinations were identified and are each treated as an activity. These combinations are called P_1-P_8 and are generally referred to as process combinations to separate them from the individual treatments. Of course, a treatment is a process and there may be exceptions to this. The possible combinations of treatments are shown in the figure 2 below:

P1	P2	P3	P4	P5	P6	P7	P8
T_1	T_2	$T_1 + T_3$	$T_2 + T_3$	$T_1 + T_4$	$T_2 + T_4$	$T_1 + T_3 + T_4$	$T_2 + T_3 + T_4$

Figure 2: Overview of different process combinations (operations) available to the WWTP.

4.3 Optimisation through mixed integer linear programming

The method of linear programming was chosen because, as Doucet & Sloep (1992) state, linear systems tend to allow for a more explicit and complete analysis than non-linear systems. There are also solid computational and solution methods developed for solving this type of problem, such as the simplex method which is used in this case. It is true that the linear model, like any conceptualisation of a real problem, is not a strictly accurate representation of the situation it deals with. What it does is to seize strategic relationships in the problem described and thereby allows for manipulation of it (Dorfman *et al.*, 1958).

As wastewater treatment is a complex process, it is not easy to properly model the operations with classical mathematical or physics-based models. Wei (2013) argues that one of the problems when modelling WWT is that data is often incomplete or inconsistent. Much of the data is also coupled, as the total need for treatment depends on incoming quality and a part of the treatment depends on the efficiency of another. Data may therefore need much pre-processing. Another problem is that models for optimising the process are often non-linear and dynamic. However, it is often the case that non-linear programming problems can be reduced to LP-problems (Charnes *et al.*, 1978; Dorfman *et al.*, 1958). While it may seem violating to apply a strictly linear model to economic problems, it can be done, and often so with the advantage of bringing on a new perspective to the problem that has had to be rewritten into linear form.

4.4 Capital investment appraisal

In operations research, an important aspect of the fixed costs for every option is the investment cost necessary to perform that particular operation. Thus financial evaluation of investments is often part of the early stages of decision-making (Alkaran & Northcott, 2007). Strategic investments such as installing new manufacturing processes are associated with risk, due to the long-term impact on the company’s performance and the difficulty in quantifying the outcome. There are many aspects that need to be considered, though basically the evaluation can be broken down into three parts: Choice of evaluation method and determination of necessary data; estimation of the investment's life span; and the choice of an appropriate discount rate (ibid.).

The investment calculation is essentially a cash flow prediction. This means that the decision-maker must examine actual expected payments instead of costs and revenue. There are three types of cash flow resulting from an investment, normally depicted as in figure 3 below. These are initial investment, current payments and residual value (Greve, 2003). If the investment is a new machine or something other that requires transport, installation or education on how to use it, these costs are all part of the initial investment. Current payments include all interim payments such as maintenance, fees or costs for additional labour needed due to the investment. Current payments also include revenues resulting from the investment.

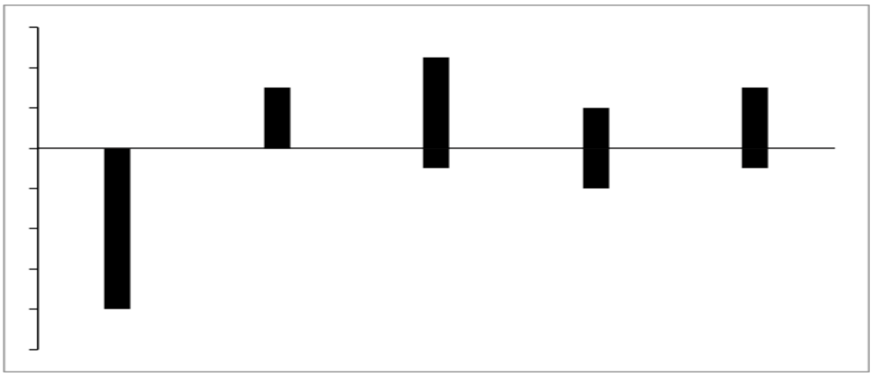


Figure 3: Cash flows resulting from an investment

The positive and negative payments occurring under one year are usually added up and depicted with one column at the end of the year. The figure above shows the sum of negative payments as well as the sum of positive payments each year. By subtracting negative payments from the positive, one receives the net payment of that year. At the end of the investments economical lifespan there is usually a residual value. This can be negative if there is close down expenses. If the technical lifespan is still longer than the economical lifespan the investment may still be of use, in which case it may be sold or still used to postpone replacing investments. In the investment calculation, any residual value is treated as a payment in the last year of the economic lifespan. The investment will be profitable if the net income (i.e. net current payments) exceeds the initial investment (ibid.).

4.4.1 Cost of capital and interest rates

Profitability calculations for investments are made by relating expected cashflows to a required rate of return, usually most often referred to as the discount rate or interest rate. An investment is considered profitable if it meets the company's demands for return on capital. The interest rate needs to exceed the cost of capital, and not just the capital invested, but the company's average cost of total capital. The interest rate consists of:

- Real interest rate
- Inflation correction
- Risk replacement

The interest rate should reflect the average risk on total assets. Thus it is theoretically supported for a firm to use the same interest rate in all investment calculations, unless the particular investment is subject to a very different risk. Opportunity cost and expected inflation are also reflected in the interest rate. The opportunity cost corresponds to the return on capital that would be expected from the best alternative placement. Expected inflation is usually already covered by the rate of return on the market. Inflation is thus more problematic when calculating expected cash flows than when determining the interest rate (Greve, 2003).

The interest rate is often calculated as a weighted average cost of capital (WACC), taking into consideration the costs of equity and debt. Another option is to use the company's actual rate of return on total assets in the investment calculation. When doing this, the rate of return is influenced by the accounting practices of the firm and may then not give an accurate representation of the risk associated with the investment. Another practice is to use the rate at which the firm can borrow money or make alternative placements. Though this may lead to the risk being under-appreciated as bank loans usually have a lower risk than most other business activities. The choice of interest rate will differ depending on if one is calculating the profitability before or after taxes. The most common practice in Sweden is to calculate profits before taxes, though it may sometimes be meaningful to calculate profits after taxes (ibid.).

4.4.2 The annuity method

The most common calculation methods are net present value, annuity, payback and internal rate of return. Generally, capital investment calculations aim to make payments at different times comparable through discounting. The exception is the payback method (Andersson, 2013). For a good simulation, it is of course important to choose the method one believes best describe a correct value of the investment. It is also important to apply the same method and general assumptions to each alternative investment.

The annuity method divides the capital investment's net present value into equal yearly payments, so called annuities. An investment's annuities do not have to contain the same requirements for rate of return or the same costs. Dividing the initial investment into annuities can be useful when wanting to know what prices to set to cover the yearly cost in order for the investment to break even. Any current payments need to be forecasted, discounted and added to the initial investment before multiplying the present value with an annuity factor to receive the correct annuity (Greve, 2003). If current payments are equal in size, the annuity is calculated by dividing the sum of initial investment and residual value into annuities and adding that to the yearly payment. If current payments are unequal in size, it is a more tedious process. Net payments must be discounted separately before the PV of the investment can be calculated and multiplied with the annuity factor (Andersson, 2013).

As the present value of operations and maintenance costs (current payments) for a WWTP can be assumed to be somewhat constant, the annuity method is especially suitable here. The annuity calculation can be performed either by dividing the present value (PV) of the investment with a present value sum (PVS), or more commonly by multiplying the PV with the annuity factor ANN, which is the invert of the PVS.

The annuity is calculated as (Andersson, 2013, p 244):

$$\text{Annuity} = PV * ANN_t^i \tag{15}$$

$$ANN_t^i = \frac{i}{1 - (1 + i)^{-t}} \tag{16}$$

i is the interest rate
t is the investments economic lifetime in years.

In this case, as the yearly payments for WWTP are considered to be constant, only the initial investment and residual value need to be annuitized, so the function used in this case, more specifically looks like:

$$\text{Annuity} = (C_c + R) * ANN_{25}^{5\%} + VC \tag{17}$$

C_c is the construction cost for the WWTP
R is the residual value of the investment

The initial investment is considered to equal the construction costs (C_c) and the residual value (R) is assumed to be zero. There may be a sizeable saving of future payments after the investments economic lifetime, due to a much longer technical lifetime, but there are also substantial costs associated with deconstruction and restoration if the WWTP is no longer to be used. The estimation of a residual value was thus deemed too uncertain to include in the model. The economic lifetime is assumed to be 25 years, based on recommendations for depreciation times from Svenska kommunförbundet (now part of the Swedish Association of Local Authorities and Regions, Sveriges Kommuner och Landsting) as published by Svedin in 1996 (Tagesson, 2001). The standard discount rate 5% is used. VC are simply the present value of the variable costs, O&M. The calculations of C_c and VC are described in chapter 5. The annuity calculation described here gives the value of C_i in the objective function described in the theory chapter.

4.5 Sensitivity analysis

A sensitivity analysis (SA) aims to give the decision maker an understanding of how the capital value of an investment depends on different factors. In the analysis different variables are changed to see how a marginal change of that variable changes the capital value. A SA can also test at what value for any variable two different investments are equally profitable. By identifying which variables are critical for the appraisal and at what changes the ranking of alternatives will shift, the decision maker can easier appreciate the risk (Greve, 2003).

The sensitivity analysis may include all input variables; prices, volumes, residual value, economic lifetime and interest rate. However, they can only be analysed ceteris paribus, that is each at a time with all other variables treated as constants. In this case, the costs are not provided at the level of detail where prices per unit of any specific input variable is defined. Thus the sensitivity analysis of variable costs test variation in total costs of different variables, which may correspond to either a change in price or used volume.

5 Data collection and treatment

The input-data is obtained from wastewater treatment plants (Kungsängsverket, Öresundsverket, Borås Energi & Miljö) and publications of previous research. Some data is also obtained from the Swedish Water and Wastewater Association, Ragn-Sells and Easy Mining.

5.1 Cost parameters

Cost parameters are based on Kungsängsverket for conventional treatment. Estimates for EBPR are based on data from Öresundsverket and Sobacken WWTP which is currently under construction.

5.1.1 Estimating the cost of construction (fixed costs)

The fixed cost for each treatment is the annuity of the construction cost. The crux in this case is estimating the cost of construction. Only the wastewater treatments (T_1 and T_2) are assumed to demand a capital investment, as these are the only two treatments with an investment that directly cost the WWTP. T_3 demands no capital investment and T_4 is assumed to be an external service bought by the WWTP, so that any capital investment associated with that process is taken care of by the service provider and indirectly by the WWTP through the price of the service. Hence it is already included in the variable costs of that treatment.

The construction costs for a conventional plant with chemical precipitation as the main treatment for phosphorus removal, is based on estimates that Kungsängsverket have made for a potential new plant for 300 000 pe. This is not just a very relevant source, it is also the only relevant source found. There are very few WWTP:s in a relevant size category being constructed in Sweden in recent times. The most recent plant that uses conventional treatment to 100% was constructed in 1995 for 95 000 pe, less than half the size of the case plant. Using historical costs to estimate present investment costs as recommended by Tsagarakis et alia (2003) and Friedler & Pisanty (2006) is not easily done in Sweden. This is because most WWTP:s operating today are old and have been subject to several reconstructions and adaptions. This means that costs are generally depreciated, unknown or unrepresentative of a modern new investment. Looking for relevant sources of cost data abroad is not easy either since the effluent requirements and thus the design of WWTP differ. Fransson (personal communication, 2015) says that benchmarking against foreign plants proved to be of little use when calculating the cost of investing in a new WWTP.

The construction cost for an EBPR plant is estimated based on Sobacken (150 000 pe), which is currently being constructed by Borås Energi & Miljö (Borås E&M). Sobacken is basically the only plant designed to treat all wastewater with EBPR that has been (or more correctly, is being) constructed at once in Sweden. The other relevant EBPR plant to base assumptions on is Östersundsverket, which is used to estimate current payments, that is O&M, for an EBPR plant. This plant has however been upgraded and the design changed and adjusted over decades. It is thus difficult to determine what the construction cost would have been for the plant as it is today based on their historical investment. This is also the case for Kungsängsverket, whose historical costs could not give an accurate representation of what a new plant would cost if built in one go, as the existing plant has had large extensions made four times, plus other smaller adaptions. The older reconstructions are already more than 70 and 60 years old.

The calculated costs for Sobacken and a possible new Kungsängsvärket have been recalculated for a WWTP of 200 000 pe, assuming a linear correlation between pe-load and construction costs. The cost of EBPR has also been recalculated to use the same percentage of uncertain costs as was used for Kungsängsverkets estimate. Attempts to use the function suggested by Huang (1980) and the scale of economics suggested by Friedler & Pisanty

(2006) showed that the cost of an EBPR plant would be a mere 42% of the cost of a conventional plant. As the general belief seems to be that an EBPR plant would be more expensive, it was decided that a linear pe-based estimation is the more realistic one, although it still suggests a much lower costs for EBPR. With a low level of insight into how these estimates have been derived, the reliability of these estimates cannot be validated. Holmström (personal communication, 2015) argues that EBPR needs larger basins for the biological treatment and if EBPR is applied, the case plant still needs a chemical addition after the biological treatment to achieve the low effluent values required.

5.1.2 Estimation of O&M costs (variable costs)

The operation and maintenance costs for the different treatments are based on a relevant main source but have then all been adjusted more or less for various reasons. The main sources are described in table 4 below and the collection and treatment of data is then described for each treatment.

Table 4: Sources of cost data

Treatment	Main source (facility, organisation)	Main source (person)
Conventional, T_1	Kungsängsverket, Uppsala Vatten	Swedling, E-O.
EBPR, T_2	Öresundsverket, NSVA	Lindquist, H.
Revaq, T_3	Svenskt Vatten	Finnson, A.
CleanMAP, T_4	Ragn-Sells	Kihl, A.

T_1: The operational cost of conventional treatment (chemical precipitation) is based on the running costs for Kungsängsverket. The costs are sorted into categories as quoted by Swedling (personal communication, 2015). The costs have been adjusted by addition of the extra chemicals that are assumed to have been reduced for the line of wastewater (less than 20%) which is today treated with an EBPR process. The estimation for the cost of chemicals is the amount needed is based on standards suggested by Holmqvist at Uppsala Vatten (personal communication, 2015). The costs for transporting storing and utilising the sludge have been replaced with transportation and storage costs suggested by Wigh at Ragn-Sells (personal communication, 2015). This is to both standardise the costs between treatments and to compensate for most sludge not being used for field application but for landfill coverage as it is today. Costs that are today caused by the Revaq-certification have been deducted.

T_2: The operational costs for the EBPR treatment are based on cost data for Öresundsverket sent by Lindquist (personal communication, 2015) and sorted into the same categories as those given by Swedling for Kungsängsverkets costs. Also the sludge related costs have been adjusted in the same manner as for T_1 and costs for an assumed chemical polishing step currently not being used at Öresundsverket is added, based on the same standards for costs and volumes as used for T_1: To be sure to reduce phosphorus in the water from 0,3 to under 0,25 mg/l, one must aim at 0,1 mg/l. To achieve this, one needs to add 40ml PIX-111 (ferric chloride), with a density of 1,42g/ml. PIX-111 contains 13,8% iron and each added gram of iron generates about 3,5 grams sludge. This gives a total addition of 528 tonnes of sludge (dm) and 1.9 MSEK.

T_3: All costs for the Revaq-certification are considered to be variable costs. These include a certification-fee, a yearly fee per connected person equivalent and extra personnel. These costs are all based on statistics provided by Finnson at the Swedish Water and Wastewater Association (personal communication, 2014). These costs are also deducted from T_1 as the source of the costs for chemical precipitation is Kungsängsverket who became certified 2 years ago.

T_4: The cost for CleanMAP is considered to be variable. It is assumed that the WWTP buys this service from an external entity. Thus the cost of the capital investments for incineration and extraction plants are included in the full service price. It is assumed that sludge is burnt separately (so called mono-incineration).

5.2 Quality parameters (residues)

Limit values for residue in sludge are taken straight from report 6580 (Naturvårdsverket, 2013, 1) and applied as restriction values for the different scenarios. Residue levels in sludge for T_1 are taken from Kungsängsverkets environment report (Uppsala Vatten, 2015). The residues in sludge from T_2 are based on the levels for T_1 but with the addition from chemicals subtracted based on figures from the same report. The residue in sludge from T_3 is calculated as a reduction in mg based on the same input data and the assumption of 2% yearly reduction. The residue level is then calculated for year 2030 when the new limit values are suggested to be fully implemented. Residue is the extracted phosphorus from T_4 is based on statement by Jonsson (2015) that it produces a 100% clean ammonium phosphate.

5.3 Production volumes

The volumes of sludge produced from different processes are based on the production at Kungsängsverket as described in the Environment report (Uppsala Vatten, 2015). This volume has been adjusted for more or less chemical addition. This is of course a simplified calculation, assuming that the difference in production volume between conventional treatment and EBPR equals the difference in sludge formed from the chemical additions. In reality there may be differences in the sludge production from the biological treatment of T_1 and T_2, which are not included here due to uncertainty.

5.4 Explanation & motivation of assumptions

All assumptions are listed here. For further information and motivation, see the following subsections.

- Fixed production volumes
- 100 % utilisation as fertiliser
- Processes are binary
- Residue levels in sludge from T_1-T_4 are assumed as fixed averages
- Discount rate 5% (interest rate)
- 25 year economical life span

5.4.1 Production volumes

For simplicity, the volume of water and the BOD-load is assumed to be constant. Population is likely to increase and with it the load on the WWTP. This is not accounted for in the model. There is basic cost data available that can be applied to the treatments for a plant with the assumed volumes, but when calculating costs for greater volumes assumptions have to be made on how to scale up O&M costs which makes the solution less reliable.

The assumed production of sludge with different processes is based on todays production for Kungsängsverket and numbers from the environmental report (Kungsängsverket, 2014, 1). The sludge production in a facility with chemical precipitation would be the same as today but with the addition from another 20% of the water flow being treated chemically before the biological stage. The added volume is based on the average amount of chemicals per cubic meter for the two other streams and the assumed DM 28%. The sludge production from a

EBPR process is estimated in the same manner, but this time with a reduction of the chemicals currently added prior to the biological treatment.

The Revaq-certification is assumed to have no effect on the produced sludge volume. The volume MAP produced through CleanMAP is not needed for the cost calculation, it is however calculated based on the input volume (sludge from T_1 or T_2). It is assumed that the sludge is treated through mono-incineration and standard percentage of DM, ash- and phosphorus content and rate of extraction is applied in the calculation.

5.4.2 100% utilisation as fertiliser

It is assumed that all the sewage sludge or else extracted phosphorus is to be applied to farmland. A simplistic research into the availability of farmland suggests that there is more than enough available farmland within the surrounding region to receive the sludge produced at Kungsängsverket. With the maximum allowed application of 22 kg P/ha, a yearly production of sludge containing ca 800 tonnes P, less than 36 400 ha of available farm land is needed to utilise all sludge. There is more than 150 000 ha of arable land in Uppsala Län (Jordbruksverket, 2015).

5.4.3 Processes are binary

In reality it is not uncommon that WWTP:s have parallel lines of treatment, where the processes may differ for the different lines. One or more lines can be treated conventionally and the other line/-s with EBPR. Due to the difficulty in estimating costs of capital for different facilities, it becomes near impossible to give a reliable depiction of actual costs for a process setup with combined WWT:s. Thus it is assumed that the WWTP will have one or the other, that is they are mutually exclusive. Also it is assumed that any treatment is used for all production or not at all.

As residue values are based on averages, the model does not allow for variations over the year and any process either produces a sludge with levels lower than the limit value or exceeding it. This means that the REVAQ-certification and CleanMap process are also applied to 100% or not at all. While all sludge from a certified plant may not live up to the quality-requirements, a plant either works with the certification or not. The costs remain the same whether or not it has the desired effect. The assumption that CleanMap is either used to 100% or not at all is also necessary since the model cannot handle variations in residue over the year and thus does not allow for the (in reality plausible) scenario where some sludge parties may need to be incinerated while others could be utilised through direct field application.

5.4.4 Residue levels in sludge from T_1-T_4 are assumed as fixed averages

Variations in sludge quality and the possibility that some sludge will, and some will not, meet the requirement cannot be properly dealt with in this analysis. Thus fixed limit values can be assumed for each sludge or product resulting from the four treatments. Sludge from chemical precipitation is assumed to have the same amount of residue as todays sludge. The residue in the EBPR sludge is assumed to have the same residue minus the estimated addition through todays chemical load according to the environmental report (Uppsala Vatten, 2015, 1).

If the Revaq-certification is applied, then the residue may be reduced by a yearly 1-2% for most unwanted substances, as suggested by the findings of Mattson with colleagues (2012). In order to linearise and simplify this, the reduction due to Revaq is estimated as a reduction in mg, based on a 2% yearly reduction from todays residue levels to year 2030, when the new limit values are suggested to be fully implemented. The difference compared to if the reduction was calculated from the estimated residue level in EBPR sludge is assumed to be negligible. This is of course a questionable assumption. Estimating possible future reductions is rather uncertain and thus it seems more reasonable to assume the same reduction of all substances to get an estimated over-all quality improvement rather than to try to make projections for each substance, without sufficient support to do so. However, it is unlikely that reductions would be made for any substance that is not specifically targeted as a problem area. It is also probable that greater reductions may be achieved for those substances that are singled out as dangerously high or especially harmful. Furthermore, it is unlikely that the effect of successful upstream work would have an immediate and linear effect on the content of the corresponding substance in the sewage sludge. It is likely that the effect of any projects to reduce a substance are seen only years after the initial effort and that the effect varies over time. This cannot be considered in a simple model.

For the MAP obtained through Clean-MAP, there is no residue. In the mathimatical problem it is thus defined as the negative residue content from the other treatments. This is the process expected to be applied if the estimated effect of the Revaq-certification work does not suffice to reduce levels below the suggested limit values.

5.4.5 Financial assumptions

The calculation of cost of capital assumes a linear write off. It is assumed that the economic lifespan of a WWT facility is 25 years, although the technical lifetime can be as long 50-70 years (Borås energi & miljö, 2014; Swedling, personal communication, 2015). It is assumed that a treatment plant with EBPR and with chemical treatment have the same lifespan.

6 Empirical background

This chapter dives deeper into the background of phosphorus scarcity and the need for recycling. The structure of this chapter is such that the first section and subsections describe wastewater treatment in Sweden and the main treatment methods. The next section presents the issues of sludge utilisation, after which follows a section on technologies for sludge recovery and recirculation.

6.1 Wastewater treatment in Sweden

Since the 1920's water-based sewage systems have been the dominating practice in Swedish towns and cities (Naturvårdsverket, 2013, 2). Initially the wastewater was led away from agglomerations and released into waterways untreated, but the eutrophication and emissions had serious negative impacts on the quality of Swedish waters. This led to the development of strategic municipal wastewater treatment in the 1970's and now almost all urban households are connected to municipal treatment plants. The objective with the WWT is to be able to dispose of the effluent without any danger to human health or unacceptable impact on the environment. WWTP:s are designed to remove particles, nutrients, microorganisms and organic compounds from the wastewater. Other contaminants are not targeted in the process and much of what is in the water is thus released with the effluent and reaches the recipient and surrounding environment. Other contaminants end up in the sludge together with the nutrients. The average degree of purification at Swedish WWTP:s in 2010 was 95% for P, 59% for N, and 96% for BOD_7 (ibid.).

The requirements for phosphorus reduction from wastewater are high in Sweden, thus most WWTP:s have both chemical and biological treatment processes. This results in extensive use and transportation of chemicals. This is not just costly from an environmental perspective, but the economic cost of chemicals and treatment are also high (Jansen, *et al.*, #2, 2009). The processing of wastewater and the resulting sludge is financed by tariffs. The law does not allow the tariffs to be higher than what is reasonable to cover necessary costs. Thus the municipality determines the tariff in accordance to the absorption principle. An average Swedish household pays 400 SEK monthly for water supply and related services and around 60% of the tariff is attributable to wastewater treatment and sludge processing (Svenskt vatten, 2014).

6.1.1 Conventional treatment: with chemical P-precipitation

There is great variation in the technical solutions for treating wastewater. Most commonly there is tertiary treatment with a combination of chemical and biological processes. This is what is referred to in this study as conventional treatment. A simple process schedule of what this process may look like is presented in figure 4.

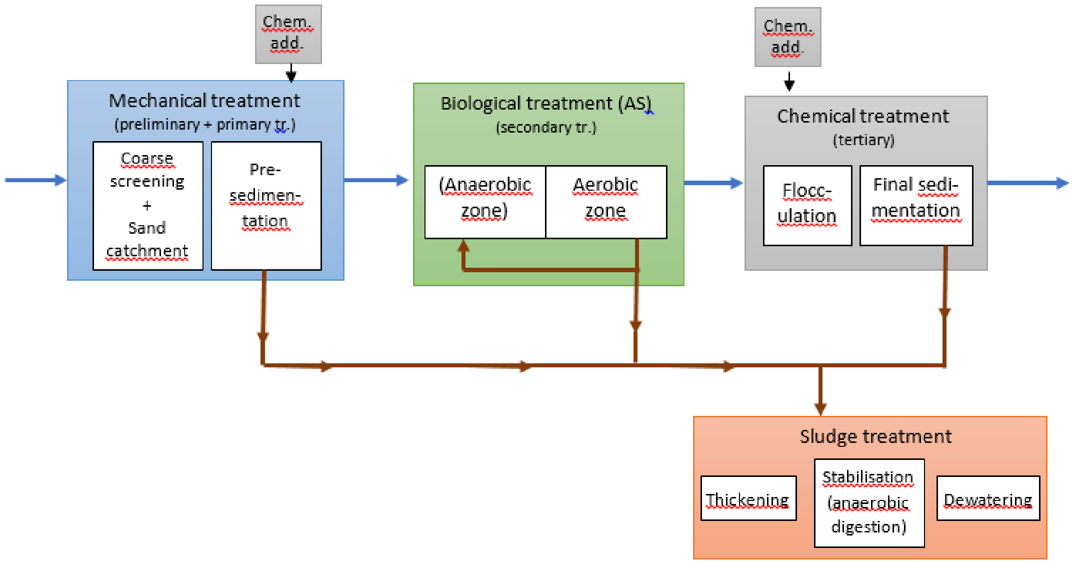


Figure 4: Conventional treatment with an activated sludge process and pre-precipitation

The first stage in a WWTP is always mechanical (Naturårdsverket, 2013, 2). First a grid catches bigger contaminants. This is followed by a sand catchment, where particles with a density higher than water (basically everything the size of a grain of sand or bigger) sinks to the bottom. Then follows the primary sedimentation, where most remaining particles are allowed to settle and form the primary sludge.

The mechanical stage is followed by chemical treatment, where iron- or aluminium-based chemicals are added. The chemicals cause phosphorus to precipitate. The phosphorus flocculates and form a sludge together with other contaminants such as metals. The sludge is usually separated through sedimentation.

In the following biological treatment, the bacteria and microorganisms in the water are used to consume organic materials. A common method for this is an activated sludge (AS) process, where the majority of the sludge is recirculated from the following sedimentation, to use the active bacteria for continued treatment. At larger WWTP:s or plants with sensitive recipients, this process also uses alternatively aerobic and anaerobic stages to favour nitrification and denitrification bacteria to enhance nitrogen removal. In aerobic conditions, ammonium is converted to nitrate. In the anaerobic stage, the nitrate is converted into nitrogen gas. This allows for removal of 50-75% of N.

Many treatment plants add a second dose of chemicals to further reduce the P content after the biological treatment. In many cases the water is also filtered as a last stage. The whole process takes between 10 and 24 hours, depending on the water flow. The sludges that have been removed from the process usually has a very low percentage of dry matter (DM) and thus needs to be dewatered through different processes. The reject water is pumped back to the first treatment stage. The sludge usually contains about 90% of the phosphorus from the water (Naturvårdsverket, 2013, 2). The common practice is to have anaerobic digestion of the sludge and produce biogas.

6.1.2 Enhanced Biological Phosphorus Removal, Bio-P

Enhanced biological phosphorus removal (EBPR) is often referred to in Sweden as bio-P. The Swedish Water and Wastewater Association describe it as an ecological method (Svenskt Vatten, www, 2014). It is a well-established method for removing phosphates from wastewater, developed from observing conditions that sometimes spontaneously occur the biological treatment at WWTP:s where natural phosphorus consuming microorganisms thrive.

The process has been further developed to be able to reduce chemical treatment, with the double purpose of reducing the costs and the harm to the environment from the use of chemicals (Svenskt Vatten, www, 2014). One of many possible configurations is presented in figure 5 below.

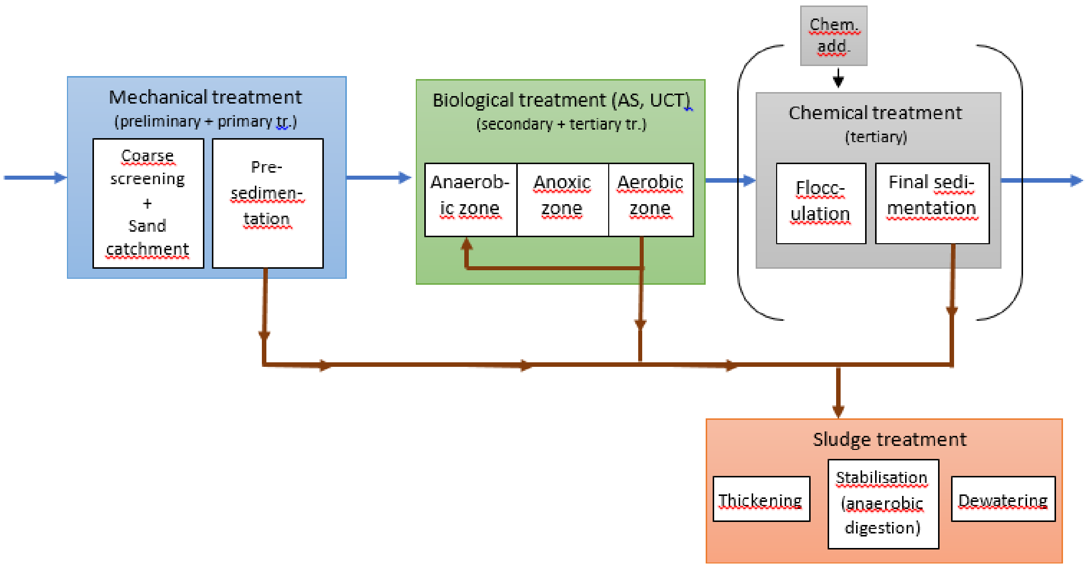


Figure 5: An EBPR treatment with the UCT set-up and additional chemical precipitation

The initial mechanical treatment is the same as used in a conventional WWTP. The biological treatment uses alternately aerobic and anaerobic conditions, while constantly recirculating some of the bacteria to sustain a stable culture. This allows the bacteria called PAO (phosphorus accumulating organisms) to use energy obtained from releasing cellular polyphosphates to digest organically bound carbon in the first anaerobic stage. In the next aerobic stage they use the energy from the organic coal to take up even more phosphorus than they released in the previous stage. These specific bacteria have the advantage that they can take up much more P than they need at the time.

In Sweden, EBPR usually needs to be supplemented by chemical treatment due to the strict requirements for maximum residual P in effluent water. Adding chemicals before the biological treatment is avoided, because it harms the AS-treatment. Thus, the addition must be made after the biological step. Jansen with colleagues (2009) describe that there are only a few plants worldwide with long term experience of EBPR and that it is only in Sweden that this process is used in a setting with such low limits for phosphorus in the effluent. However, they have found that EBPR can work with continuous addition of ferric chloride to meet the strict effluent limits, but it does affect the sludge's ability to absorb phosphorus. The chemical addition is thus best done separately after the biological treatment, to avoid recirculating chemicals.

Studies at Käppalaverket (Borglund, 2004) and at Källby WWTP (Jansen, *et al.*, 2009) have shown that biological phosphorus removal can be combined with chemical treatment resulting in a small economical profit. The process requires more control and thus more personnel, but that appears to be compensated by a reduction in cost of chemicals. Jansen with colleagues (2009, #2) have found that EBPR sludge is more easily dewatered than chemical sludge, but state clearly that the effects could not be quantified due to variation in dewatering qualities both for EBPR sludge and sludge from plants with chemical P removal. However, it is likely that the biological sludge has lower dewatering costs. Lower volumes also reduce the transportation costs compared to conventional sludge.

There appears to be no published studies going deeper into the economic aspects of the system. The exception is Borglund (2004) who calculated the operating costs of EBPR in a process line that had previously used conventional treatment. The cost was assumed to be the same as for the conventional treatment, minus a reduced cost of chemicals, plus the added cost of energy for an additional pump used to achieve an initial anaerobe zone.

The EBPR sludge contains less metals and more nutrients, compared to conventional sludge. The phosphorus in the EBPR sludge is also more bio-accessible as it is not bound strongly in metal compounds. A drawback is that EBPR sludge produces less gas in the anaerobic digestion. Another is that the process is disturbed by large variations in water flow or available VFA, which serves as energy source for the bacteria. Also some of the biologically bound P is released during the anaerobic digestion which is commonly used to stabilise the sludge (Borglund, 2004). The released P is returned with the reject water and thus adds to the P load and increases the demand for VFA.

6.1.3 REVAQ

Revaq is a quality-certification for WWTP:s. It has been developed by the Swedish Waste & Wastewater Association, the Federation of Swedish Farmers, the Swedish Food Federation and the Swedish Food Retailer's Federation in collaboration with the Swedish EPA. The aim of the certification is to avoid accumulation of heavy metals and other unwanted substances on farmland in the long term. Specific goals are no further accumulation of cadmium in soils after 2025 and to reduce accumulation of other non-essential substances to less than 0,2% per year from 2025. The first WWTP:s were certified in year 2008 and now more than half of the population is connected to a Revaq-certified WWTP (Persson, *et al.*, 2015).

Certified plants are required to perform stricter control and work towards influencing upstream sources in order to improve the quality of the incoming wastewater. This includes investigating and analysing the sources of unwanted substances, spreading information and campaigning to promote better practices (Persson, *et al.*, 2015). Revaq-plants are required to keep records of the sludge that has been applied at each farm. The sludge is also required to be stored a minimum of 6 months for before farm land application in order to disinfect against salmonella.

The requirements on a certified plant lead to additional costs, including a certification cost, costs for required personnel, more frequent and structured analysis and various projects for obtaining and spreading information. According to estimations from the Swedish Water and Wastewater Association the cost of upstream involvement varies from 5-50 SEK connected person and year (Finnson, personal communication, 2014).

To avoid accumulation, the goal is that the Cd/P-quote shall not exceed 17mg/kg P by the year 2025. In the yearly Revaq-report, Finnson (2015) writes that the average yearly reduction has been 4% over the last decade. Most certified plants will only need a yearly reduction of 2% to meet this goal. Regarding other substances, Mattsson with colleagues (2012) performed a case study of the WWTP Gryab, where they found a historic yearly reduction of 1-2% for mercury, zink and copper, and as much as 15% for silver, which is accredited to extensive campaigning. Naturally it is easier to find important point sources early on. Hence it is initially easier to achieve large reductions. After some years, the effect of the upstream involvement will likely lessen as the plant needs to find smaller and more diffuse targets to influence. When initiating upstream involvement, there is likely a delay before any effects can be seen on the wastewater. Changing people's and organisation's behaviour can be a slow process.

6.2 Sludge trends and challenges

Sludge may be utilised through direct field application, landfill coverage and soil fabrication. The use of sewage sludge in Europe faces a number of challenges such as decreasing numbers of open landfills and stricter regulations for farm application. Due to the nutrient-content, countries like Sweden have a tradition of applying sewage sludge to farmland for fertilisation. Though there is a strong opposition arguing against farmland application and in Europe farmland application has decreased over the last decade. In Belgium and Germany, over half of the sewage sludge is incinerated, and in Switzerland over 90%. The ashes can then be deposited in landfills, with or without preceding extraction of phosphorus.

In light of the increasing challenges, a number of studies on sustainable or effective practices have been made in the last decade, such as the 3-year EU-project ROUTES in which different processes for reducing sludge volumes were described through benchmarking using lifecycle analysis (LCA). The results of the project are summarised in Swedish by Bertholds and Olofsson (2014). To be able to make the LCA, many assumptions had to be made about water quality and the costs of upgrading already existing WWTP:s. The results of studies on different processes are said to only be comparable to a reference-alternative with no possibility for accurate comparison between the different processes. And this lack of comparability seems to be a fairly consistent trait of studies on WWT and related recycling processes.

To make handling and deposition of the sludge sustainable, the volumes need to be reduced, for example via anaerobic digestion. Within the ROUTES project, case studies were made on different processes. One of the findings is that for many of the researched processes, reduced sludge volumes would lead to increased residue in the effluent and higher nitrous oxide emissions. Bertholds and Olofsson (2014) also comment on the lack of research on the effects of working with upstream involvement, trying to reduce the use of unwanted substances at their source. According to this report, sludge treatment accounts for 15-20% of the costs in connection to wastewater treatment.

As a result of the controversy of direct application of sewage sludge to farmland, different processes for nutrient recovery are being developed. Further processing and extraction of nutrients lead to a loss of the organic matter in the sludge which can replenish humus. On the other hand, there are processes that have the potential of producing fertilisers of greater purity than commercial fertilisers from virgin materials. A common drawback with all processes for P-extraction, according to Tideström (Formas, 2011) is that they reduce the incentive to work towards preventing pollution at the source, upstream from the WWTP.

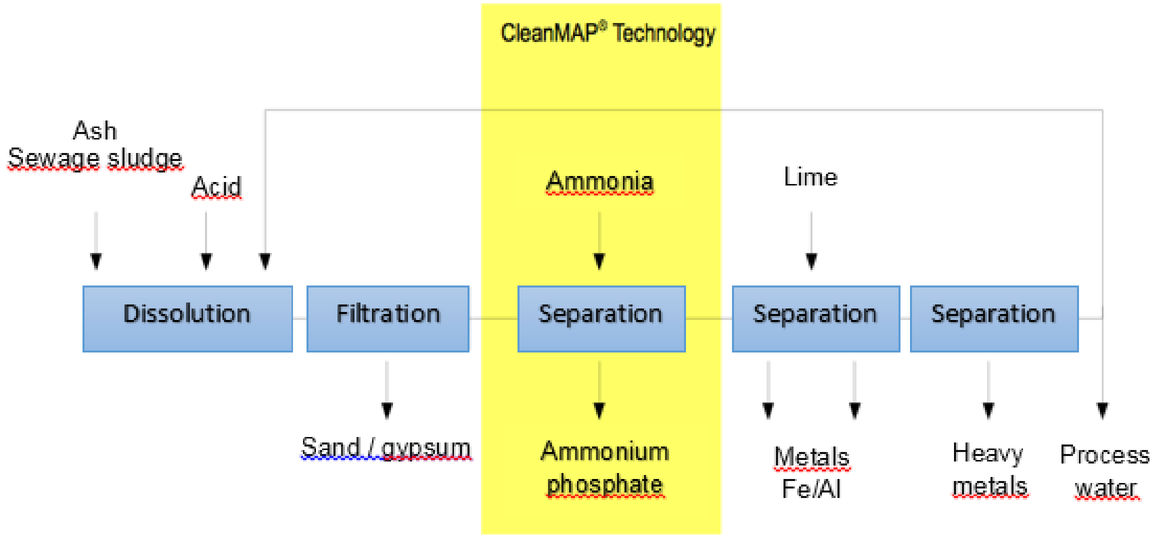
6.3 Processes for P recovery

Worldwide, processes have been developed to recycle P from wastewater, sludge and sludge ashes. Egle et alia (2013), tried to develop a model for integrated, comparative assessment of these processes, but found that due to the complexity of the problem with potential process combinations and possible effects on the total system, it was not possible to find one overall indicator. Nor could a predominant technology be derived without ambiguity. As the P-source vary, the processes vary greatly in design, complexity and efficiency. Data on costs, efficiency and environmental impact on different processes is often either not available or not comparable (ibid.).

6.3.1 CleanMAP

CleanMAP is a patented technology owned by the company Easy Mining Sweden. This technology can be used for phosphorus recovery from ashes or other fractions. In other European countries it is not uncommon with destruction of sewage sludge through incineration. In Sweden there is however only one incineration plant built to handle mono-incineration and it is no longer in use. There are however plans to start up an operation for incinerating sludge and extracting phosphorus from the ashes.

The Clean-MAP process consists of dissolution of the ashes in acid. Firstly bigger particles like sand and gypsum are filtered out, then phosphate is precipitated as mono ammonium phosphate (MAP) using ammonia. It is actually this stage in the process that is called CleanMAP. The following steps include precipitation of iron and aluminium lime and possible precipitation of heavy metals (Enfält, P., personal communication, 2014). Apart from the phosphorus, which can be sold for fertiliser production, iron and aluminium may be sold back to the WWTP for reuse as precipitation chemicals in the wastewater treatment.



Figur 6: Process schedule of the CleanMAP process (own translation; original image from Enfält, 2013).

This is still a new technology and is not yet running full scale. Costs have thus been estimated based on the assumption that sludge on average contains just above 20% DM, from which half is ash which contains a high enough P-concentration to be extracted. To cover the costs pretreating and incinerating the sludge as well as the extraction process, this is expected to cost the WWTP about 1000 SEK per ton sludge (Kihl, A., personal communication, 2015). This is however an estimation behind which there are a number of uncertainties.

6.3.2 Other possible treatments (AshDec and Ostara)

When the Swedish EPA updated their proposal for new directives on phosphorus recycling, Sweco were assigned to investigate different processes. They looked further into Ostara and Ash Dec, as they were considered relatively suitable for Sweden. However implementation within a near future was deemed unlikely for either process (as well as for other similar processes). They both produce phosphorus as clean as or cleaner than the purest commercial mineral fertilisers and have been developed far enough to work on a commercial scale (Tideström; through Formas, 2011). Ostara produces struvite (magnesium ammonium phosphate) from the reject water from dewatering the sludge. The process only works in combination with EBPR. Another drawback with the Ostara process is the low recycling potential of 20-25% of the total P content in the sewage. This can be compared to the national goal of 40% recycling.

AshDec on the other hand has a much greater potential of recycling 95% of the phosphorus from wastewater. In this process, sludge ashes are roasted at a high temperature together with magnesium and calcium chlorides. The process achieves a high degree of purification for most metals, the exceptions being nickel, chromium and arsenic. A drawback with this process as with most other recovery from ashes is that it requires ashes with a high percentage of phosphorus and thus it needs to come from an incineration plant designed for mono-incineration of sewage sludge. There is currently no such plant in operation in Sweden. Still, Tideström (ibid.) states that AshDec has greater potential of successful large scale implementation in Sweden than the Ostara process. Though previously other processes for recycling from ashes such as Krepro and BioCon have been tested in Sweden but ruled out due to bad adaption to the market and problems with operating techniques.

Norström and Kärrman (2009) have assessed AshDec and Ostara from an economic perspective, including all costs for the sewage system and wastewater treatment as well as the sludge treatment to calculate the cost per PE. They use the annuity method to calculate yearly costs of investments, assuming a cost of capital of 5 %. In their basic cost assumptions they assume an existing WWTP with chemical-biological (i.e. conventional) wastewater treatment. They refer back to Reich (2002) for business ratios and key figures and arrived at a cost for operating a WWTP of 94,1 SEK $pe^{-1}year^{-1}$, excluding investment/construction costs and costs for pathogen reduction. They assume 30km as an average distance to farmland, 1,2 SEK $ton^{-1}km^{-1}$ and 40 SEK ton^{-1} for spreading sludge. They arrived at a slightly higher cost per pe for AshDec compared to Ostara, including the cost of additional mineral fertiliser necessary to obtain the desired nutrient addition per hectare. However the difference between the reference scenario with direct sludge application and the two extraction processes was small. AshDec and direct application however have much greater recirculation percentage.

7 Results

In the table of calculated costs for different processes presented below, it is clear that the fixed costs for a WWTP are much larger than the variable costs. This indicates that it is the construction of the WWTP that is the sole variable with largest impact on total costs. It was found that estimates from other countries are not easily applicable to a Swedish context as foreign WWTP:s operate under different conditions. It was also concluded that there are not enough plants around in Sweden, in a similar size as the case plant or otherwise, that has been constructed recently enough that the same costs and set-up are relevant for estimations of today's costs. No available cost data has been found which differentiate between EBPR and conventional treatment. In conclusion, the results should be interpreted with the understanding that many estimations made in this study are based on a data originates from another context.

The result of the optimisations in the different scenarios is presented in table 5 below. The results of the calculations can be reviewed in appendixes 2-4. Again, in scenario 0, the limit values for heavy metal residue in sewage sludge are the same as today. Scenario 1 is based on suggested new limit values, and scenario 2 is a scenario with yet stricter limit values.

Table 5 Optimum process combination and subsequent minimum cost

Scenario	Optimum process combination	Including technologies /processes	Total cost (min)
0	P2	T2	133 009 716
1	P4	T2+T3	135 240 613
2	P6	T2+T4	141 287 288

Figure 7 below provides an overview of the costs for each possible process combination, showing total costs as the sum of fixed costs and variable costs resulting from each process that is used within that set-up (process combination).

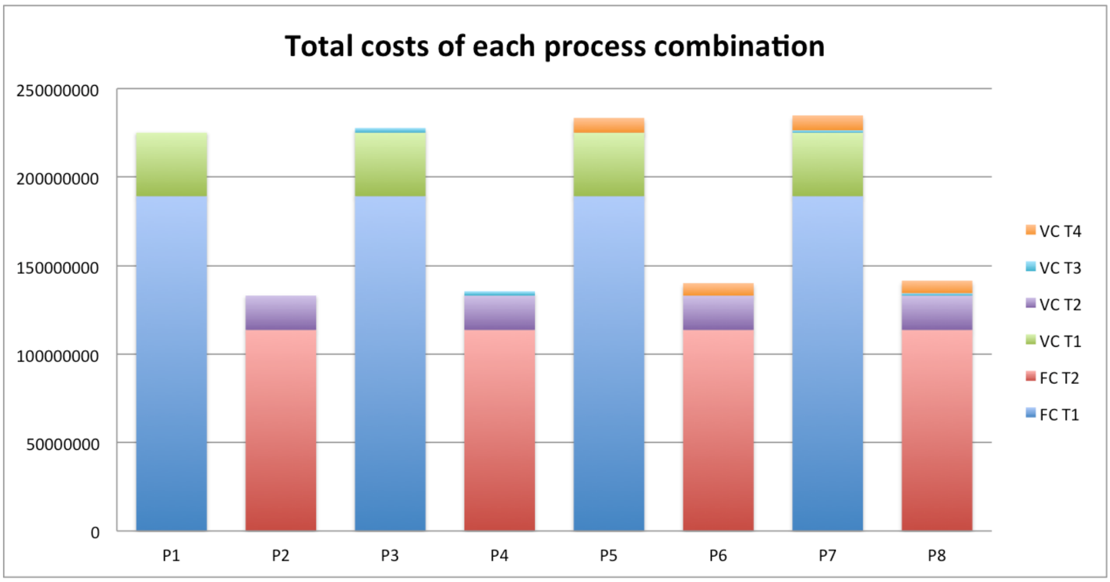


Figure 7 Total costs in SEK (FC+VC) of each process combination, including all costs from the wastewater treatment and sludge storage, transport and field application.

The EBPR-based process combinations appear to be much less costly. The estimated cost of conventional treatment is 69 percent higher than that of EBPR (compare columns P1 and P2). The fixed costs are about 67 percent higher and the variable costs 85 percent higher. Working with Revaq gives an additional cost of 2.7 MSEK for a conventional plant and 2.5 MSEK for an EBPR-plant. CleanMAP adds 8.4 MSEK to a conventional plant and 7.1 MSEK for an EBPR-plant, if applied to all sludge.

It is clear from figure 7 that it is the actual waste water treatments which constitute most of the costs in the process combinations including T3 and T4. This is seen by comparing the total costs of processes based on T_1 with each other (the columns with odd numbers) or the process combinations based on T_2 (even numbered columns). Though the cost for additional treatments may be high (2.5-8.4 MSEK), they are a minor part of the total cost as T_1 in itself has a yearly cost of 225 MSEK and T_2 of 133 MSEK.

The more explicit estimation of costs for different process combinations for the case plant are presented in table 6. Again, FC is fixed costs. VC_w is the variable costs resulting from the wastewater treatment (SEK/m^3) and VCs are the variable costs (SEK/tonne) resulting from the sludge, including all costs after the sludge has been dewatered and needs to be removed from the WWTP. KSEK stands for kilo (thousand) SEK and SEK is Swedish krona.

Table 6: Costs and production volumes of each process combination in case of implementation

Process combo	P1	P2	P3	P4	P5	P6	P7	P8
Treatments in each Pi	T_1	T_2	$T_1 + T_3$	$T_2 + T_3$	$T_1 + T_4$	$T_2 + T_4$	$T_1 + T_3 + T_4$	$T_2 + T_3 + T_4$
FC	189 206 553	113 618 535	189 206 553	113 618 535	189 206 553	113 618 535	189 206 553	113 618 535
VC_w	1,61	0,80	1,68	0,87	1,61	0,80	1,68	0,87
VC_s	362	362	466	466	1033	1033	1033	1033
w	19 500 000	19 500 000	19 500 000	19 500 000	19 500 000	19 500 000	19 500 000	19 500 000
s	12 459	10 511	12 459	10 511	12 459	10 511	12 459	10 511
w * VCw	31 375 000	15 589 700	32 765 000	16 979 700	31 375 000	15 589 700	32 765 000	16 979 700
s * VC_s	4 505 816	3 801 481	5 801 522	4 894 646	12 874 954	10 862 381	12 874 954	10 862 381
sum VC	35 880 816	19 391 181	38 566 522	21 874 346	44 249 954	26 452 081	45 639 954	27 842 081
Total Cost, SEK	225 087 369	133 009 716	227 773 075	135 492 881	233 456 506	140 070 616	234 846 506	141 460 616
KSEK	225 087	133 010	227 773	135 493	233 457	140 071	234 847	141 461
Ranking (1-8; 1=least costly)	5	1	6	2	7	3	8	4

Table 7 (below) describes the estimated residue in the sludge from each process combination in relation to limit values for the different scenarios. Residue levels exceeding the limit values are marked red. It becomes clear that P1 and P2 exceeds the limit values in scenario 1 with the suggested new regulations. This is why P4, which is the second least costly option becomes the optimal solution, despite P2 being less costly. In scenario 2, P1-P4 exceeds the limit values, which makes P6 the optimal process combination. The source or calculation behind these residue levels can be found in appendix 5.

Table 7: Residue of unwanted substances in relation to limit values in the different scenarios.

Process combo	P1	P2	P3	P4	P5	P6	P7	P8	Limit Value	
Unwanted substances (mg/kg dm) in sewage sludge or P-product from different process combinations										
Scenario 0, unchanged limit values										
Pb	12	12	9	9	0	0	0	0	<=	100
Cd	0,58	0,58	0,43	0,43	0	0	0	0	<=	2
Cu	378	378	279	279	0	0	0	0	<=	600
Cr	17	15	13	11	0	0	0	0	<=	100
Hg	0,61	0,61	0,45	0,45	0	0	0	0	<=	2,5
Ni	14	11	10	8	0	0	0	0	<=	50
Ag	1,9	1,9	1,4	1,4	0	0	0	0		
Zn	443	441	327	327	0	0	0	0	<=	800
Scenario 1, suggested limit values										
Pb	12	12	9	9	0	0	0	0	<=	25
Cd	0,58	0,58	0,43	0,43	0	0	0	0	<=	0,8
Cu	378	378	279	278,95	0	0	0	0	<=	475
Cr	17	15	13	11	0	0	0	0	<=	35
Hg	0,61	0,61	0,45	0,45	0	0	0	0	<=	0,6
Ni	14	11	10	8	0	0	0	0	<=	30
Ag	1,9	1,9	1,4	1,4	0	0	0	0	<=	3
Zn	443	441	327	327	0	0	0	0	<=	700
Scenario 2, stricter limitvalues										
Pb	12	12	9	9	0	0	0	0	<=	20
Cd	0,58	0,58	0,43	0,43	0	0	0	0	<=	0,4
Cu	378	378	279	278,95	0	0	0	0	<=	350
Cr	17	15	13	11	0	0	0	0	<=	20
Hg	0,61	0,61	0,45	0,45	0	0	0	0	<=	0,5
Ni	14	11	10	8	0	0	0	0	<=	15
Ag	1,9	1,9	1,4	1,4	0	0	0	0	<=	2
Zn	443	441	327	327	0	0	0	0	<=	550

8 Sensitivity Analysis

It is important to recognise that the input data is based on estimations and assumptions. Thus the results are not definitive. The uncertain results make the sensitivity analysis all the more important. To give this chapter some structure, the text is divided into sections, where the first one describes the effects of varying the assumptions regarding the fixed costs. The second part describes what happens when the different input values of the fixed costs are varied.

8.1 Fixed costs: construction costs, lifetime & interest rate

The construction cost is perhaps the most unsure cost parameter used in this calculation and at the same time it is the basis of calculating the annuity of fixed costs which makes up a much larger sum than the variable costs for the wastewater treatments. The estimated construction costs for the two wastewater treatments differ from the common opinion that EBPR ought to be more costly. Holmström (personal communications, 2015) argues that EBPR demands a larger biological treatment and Borgström (2004) states that it demands additional pumps. The costs are based on estimates from Uppsala Vatten and Borås E&M for conventional and EBPR facilities respectively. None of these estimates are validated by a fully constructed plant. There are no known reasons why EBPR should have a lower construction cost than conventional treatment. The difference is thus likely due to site specific conditions and/or over- or under estimates from one or both sides.

There are three questions asked in relation to the fixed costs in the analysis. These are:

- What happens to total costs if we vary the interest rate?
- What happens to total costs if we assume a longer economic lifetime?
- How much higher could the construction cost for EBPR (T_2) be before the total annual cost equals or exceeds that of conventional treatment (T_1)?

Varying the interest rate will have no effect on the ranking of alternatives. The effect on the fixed annual costs are seen in figure 8 on the next page. Varying the interest rate, or any other variable affecting the fixed costs will result in the same increase or reduction in costs for all process combinations based on conventional treatment (T_1), that is P1, P3, P5 and P7. The same is true for all process combinations based on EBPR (T_2), that is P2, P4, P6 and P8. This is because it only changes the fixed costs and only the capital costs of T_1 and T_2 are treated as such. The variable costs for the optimum process combination, P4, is included in figure 8 only to illustrate the relative magnitude of fixed costs for T_1 compared to the total costs of T_2.

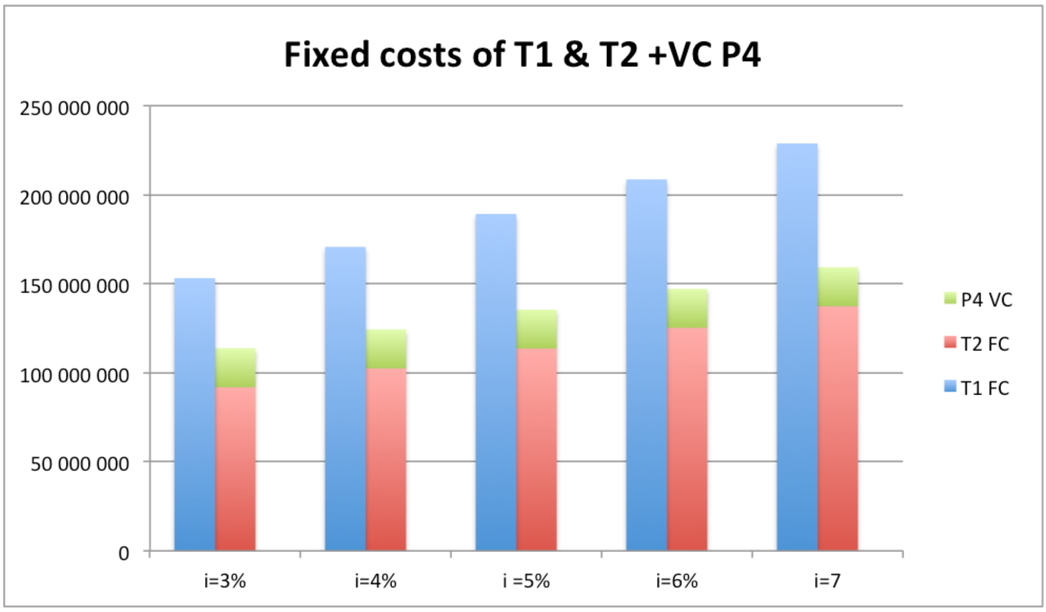


Figure 8: Fixed costs of T1 & T2 at different interest rates. The stacked columns (T2 FC + P4 VC) shows the total cost of P4.

One thing that becomes obvious is that even if T_2 would be associated with greater risk, which would warrant a higher interest rate of two percentage points, it would not change the ranking. It is perhaps not as obvious at first glance, but a change in 1% up or down corresponds to a change in total costs of less than 20 MSEK for T_1, with the same effect on each corresponding process combination (the higher columns). For T_2-based process combinations (the lower columns) the effect is a little more than half of that, with an increase in 1% interest rate corresponding to a raise in fixed costs with 11.6 MSEK. A decrease of 1% to i = 4% results in a slightly lower cost reduction of 11,1 MSEK.

One could argue in favour of assuming another economic life times than the 25 years assumed here. Machinery for example has a lifetime closer to 15 years, while basins and other buildings are usually said to have an economic lifetime of 25-30 years, but a technical lifetime closer to 50. Re-estimating the economic life time does not affect the ranking of different alternatives and P4 remains optimal. There are no grounds for assuming different economic lifetimes for T_1 and T_2 that have been discovered in study. Even if there was, the effect of +/- 5 or 10 years for one process or the other makes little difference to how these compare to each other. The effect on total costs is illustrated in the next chart, figure 9.

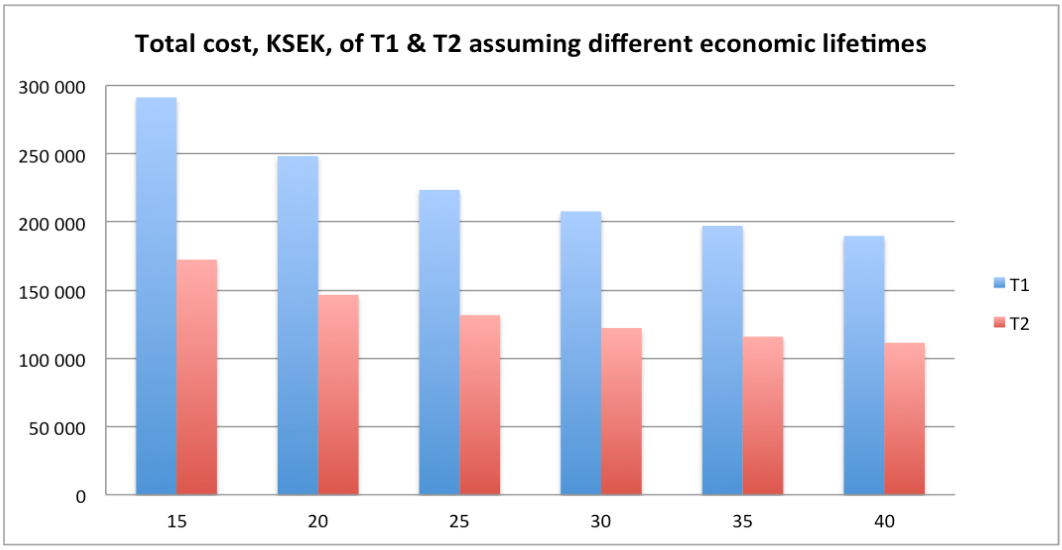


Figure 9: Total costs of P1 (T1) and P2 (T2) depending on assumed economic lifetime

This confirms that the fixed costs become lower as the investment (construction costs) are distributed across a longer period of time. However, the effect of assuming a life time which is 5 years shorter or longer is smaller when the economic lifetime is higher.

So if changing the interest rate or assumed lifetime of either one of these treatments does not affect the ranking of different options, it is only the size of the investment, in this case the construction cost, that determines whether a process set-up with conventional WWT or EBPR has the lowest cost. Assuming for now that O&M costs are fixed. The interesting question here is how high the construction cost for T_2 can be before it becomes the more expensive treatment. This is calculated by setting the total costs of T_1 to equal the total cost of T_2 ($TC_{T1} = TC_{T2}$) and then breaking out the construction cost for T_2 such that

$Cc_2^* = (TC_1 – VC_2) / 0{,}0710$

Cc_2^* is the highest construction cost that T_2 would be allowed to have before it becomes more expensive than T_1. In this formula 0,0710 is the annuity factor (see methodology-chapter). The result is illustrated alongside the previously estimated Cc_2 and Cc_1 in the next figure (10).

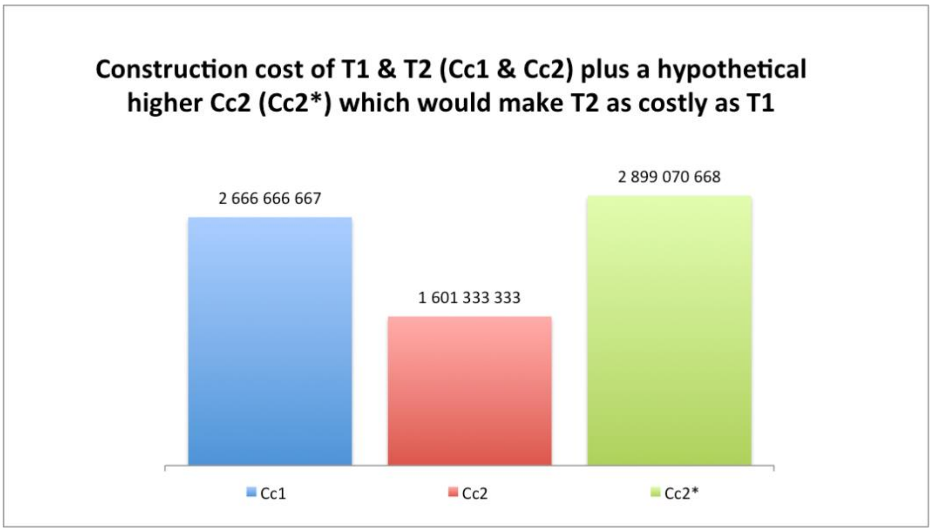


Figure 10: Construction costs of T1 and T2 plus highest Cc for T2 while being cheaper than T1

This shows that the construction cost for EBPR can be 1.3 billion SEK (or circa eighty percent) higher than has been assumed here and still be the least costly wastewater treatment of the two. It can however not exceed Cc1 with more than 232 MSEK. That is

$$TC_2 < TC_1$$

$$\text{if} \quad Cc_2 < Cc_1 + 232 \text{ MSEK}$$

this is however only true as long no other costs are changed.

8.2 Variable costs (O&M)

The variable costs make up only 14 to 20 percent of total costs for the different process combinations. So what happens to the result if the cost or need for one of the inputs changes? The variable costs for T_1 has been quoted in seven categories by Swedling (personal communication, 2015). These categories have been kept for the sake of analysis. However what was quoted as contracting by Swedling has been incorporated with other costs. The costs quoted by Lindqvist (personal communication, 2015) for EBPR have been divided into the same categories as best possible. It is however likely that some of the costs that have been categorised as “other costs” for T_2 are categorised differently for T_1. The costs have been grouped as:

- personnel & wage costs
- chemicals & other consumables
- energy
- repairs & maintenance
- other costs

A low level of preciseness of the input data limits what can be analysed in terms of variable costs. For example, the cost of chemicals has not been separated from other consumables, which makes it impossible to know how a change in chemical consumption affects the costs. The costs for T3 can be divided into personnel and other costs, while the costs for T4 cannot be dissected and categorised. Thus these two additional treatments are analysed separately at the end of this subchapter.

First is tested what happens when the cost of personnel changes for T1 or T2. The total variable costs at different levels of personnel costs are shown in figure 11 below:

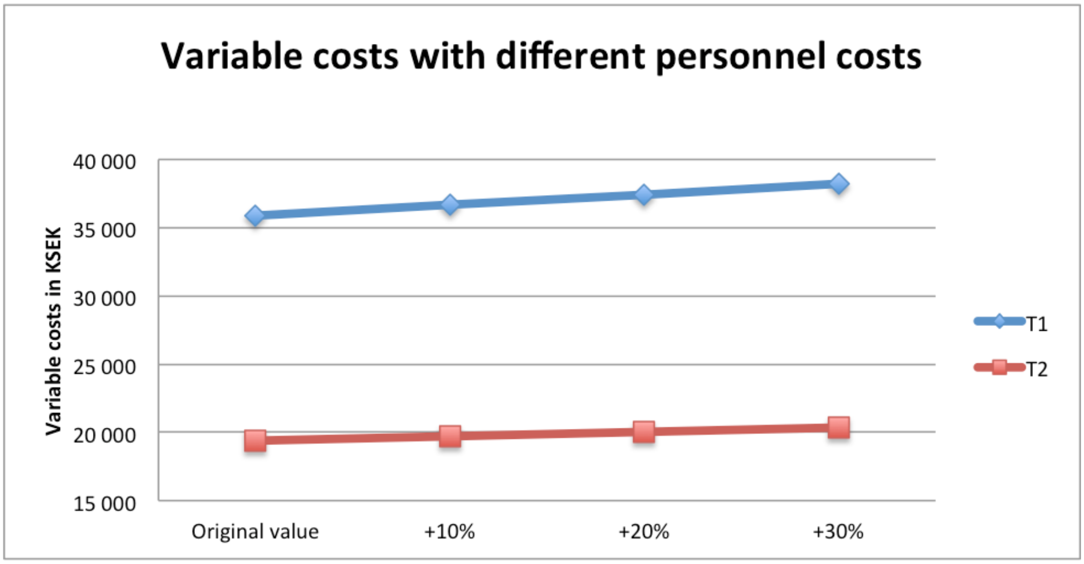


Figure 11: How the variable costs vary when assuming different cost of personnel

Note that the chart (figure 11) shows the costs in thousand, KSEK and that the y-axis start at 15 000SEK. A 10% increase in personnel costs corresponds to a rise in costs for T1 with 774 KSEK. For T2 the costs increase with 314 KSEK. The variable costs for T3 are not shown in this chart as the costs are coupled with T1 or T2. The change effected by varying personnel costs is however the same, 60 KSEK. The data from the studied plants suggest that the conventional plant has more personnel. The literature however suggests that EBPR demands more personnel (Gustavsson, 2005).

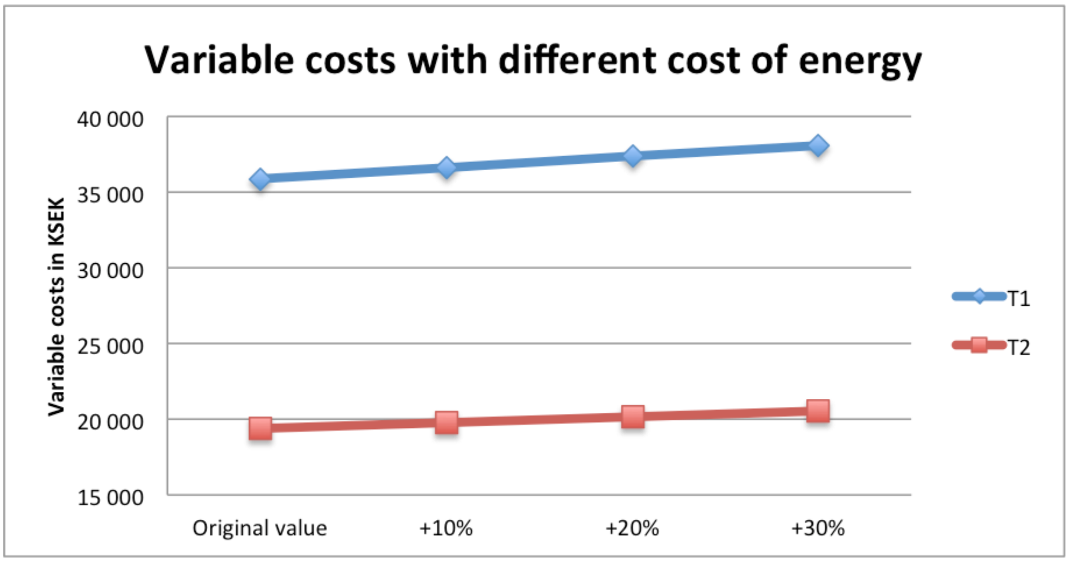


Figure 12: Total variable costs with different costs of energy

The effects of changing the energy cost is very similar, see figure 12 on the next page. The difference of an additional 10% is 734 KSEK for conventional treatment and 394 KSEK for EBPR. This is also inconsistent with the notion that EBPR uses more energy to achieve the right conditions in the biological stage (Borglund, 2004). There is however also a reduced amount of sludge to digest, which may correspond to a reduced energy consumption. The likelihood of this accounting for the lower cost for EBPR has not been investigated further in this study. The cause may also be different efficiency of equipment or that these costs are reported differently at the plants upon which these estimates are based.

The costs for chemicals and consumables for EBPR is little more than half of those for conventional treatment. This is somewhat more consistent with what is to be expected, as conventional treatment uses chemical precipitation. Figure 13, below, shows that an increase in cost of chemicals and consumables raises the sum of variable costs with 571 KSEK for conventional treatment and with 330 KSEK for EBPR.

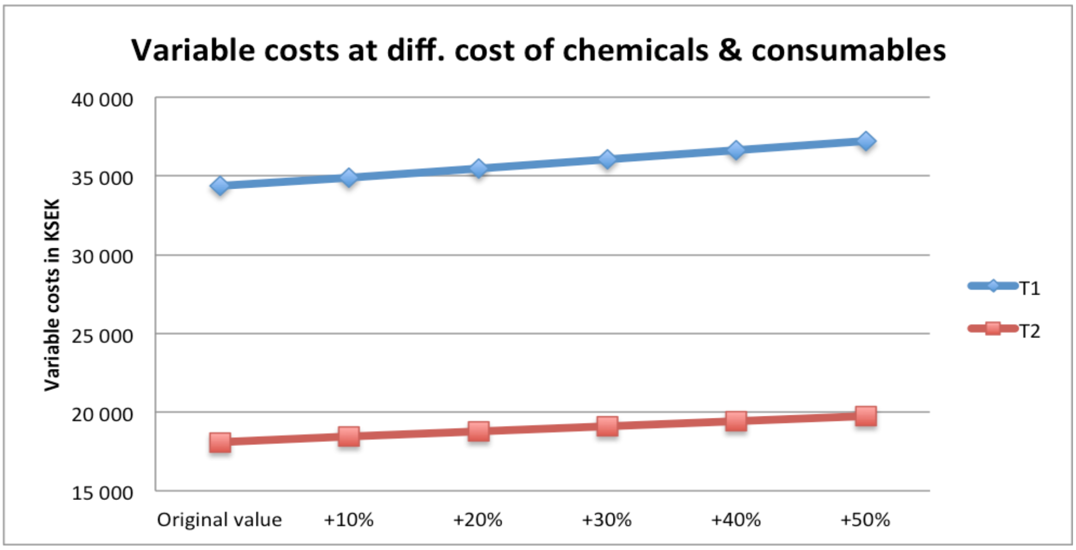


Figure 13: How total variable costs vary when assuming different costs of chemicals & consumables

Varying the costs of repairs and maintenance, shows that an increase in this category of 10% give rise to an additional 373 KSEK and 124 KSEK for conventional treatment and EBPR respectively. See figure 14.

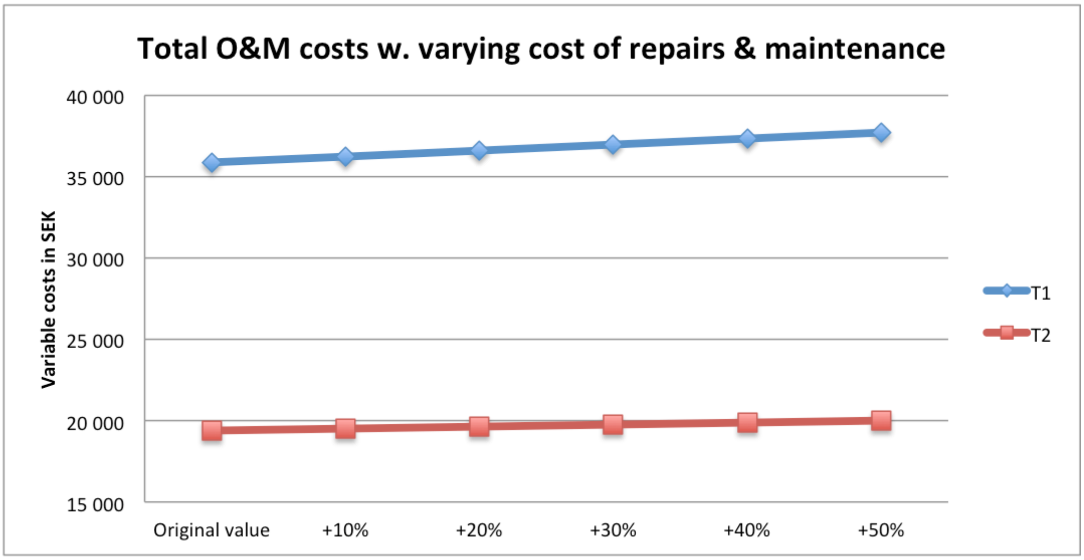


Figure 14: The effect on total variable costs of increased costs of repairs & maintenance

To conclude the analysis of the two wastewater treatments, let us look at total variable costs (O&M) for EBPR in relation to conventional treatment. Figure 15, shows that for the operation of EBPR to be more expensive than conventional treatment in this case, the costs of EBPR would have to be 90% higher. This means that the actual cost has to be almost double of what could be estimated based on the costs for Öresundsverket.

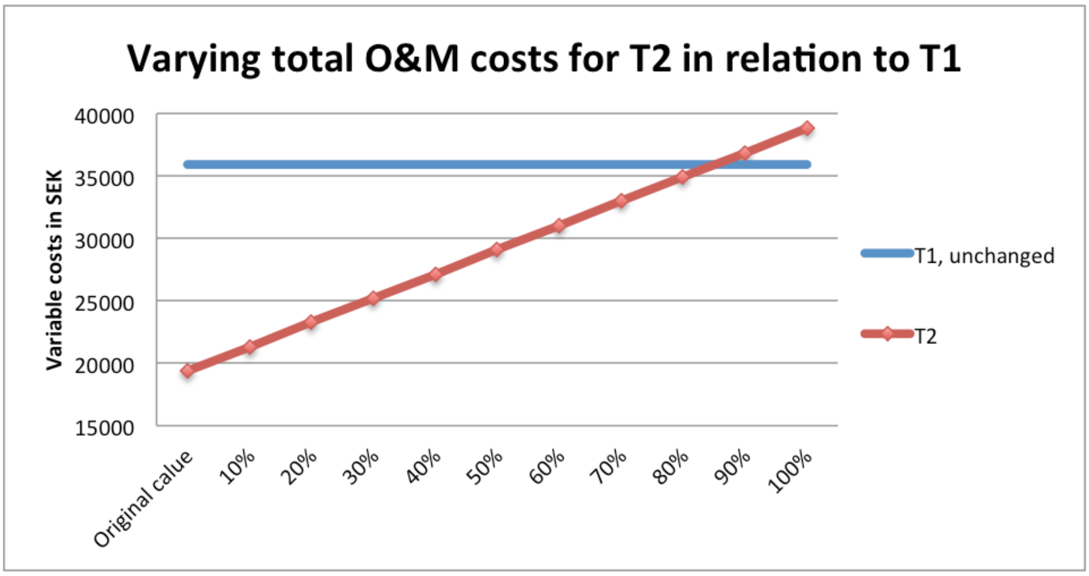


Figure 15: Varying total cost of T2 in relation to unchanged costs for T1

Analysing the total costs of the additional treatments, Revaq (upstream management) or CleanMAP (incineration and extraction from ashes), cannot be conducted without assuming the sludge production of one of the previously discussed wastewater treatments. As stated before, this is because the data is coupled. Let us first examine the cost per tonne sewage sludge, figure 16 and 17. Note that these are relative costs. This means that savings of costs for field application have been deducted from T4 and the cost for storing T3-sludge long term for pathogen reduction has been reduced by a standard cost for non-T3 sludge. Thus the following charts show only the additional cost of these treatments relative to the base-treatment level wastewater treatment.

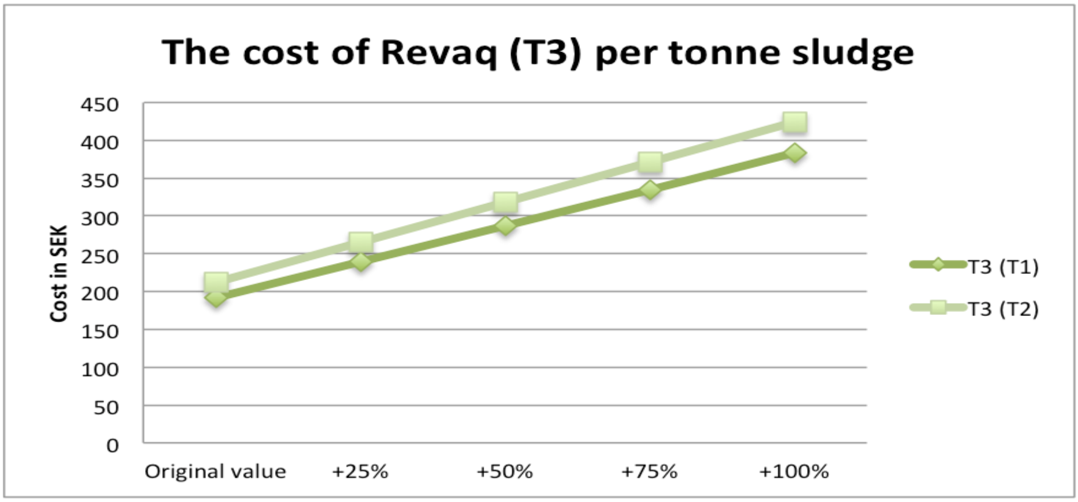


Figure 16: Additional cost of T3 in SEK per tonne sludge depending on assumed WWT (T1 or T2)

The reason why the cost per tonne sludge differs for Revaq is because the total cost is constant, while the volume sludge differs for the two wastewater treatments. An increase in 25 percent in the total cost of Revaq corresponds to an increase of 53 or 60 SEK per tonne for T1 and T2 respectively.

Figure 17 below shows the additional cost per tonne sludge for CleanMAP compared to direct application of the sludge to farmland. This shows that a 25% increase in the assumed price for T4, raises the additional cost of T4 with 200 SEK. Note that the trend line starts at a potentially lower cost and not as previous charts with the original value. This is because the process is not fully commercialised and a price for the WWTP:s is not set. It is thus interesting to include more variance in the analysis.

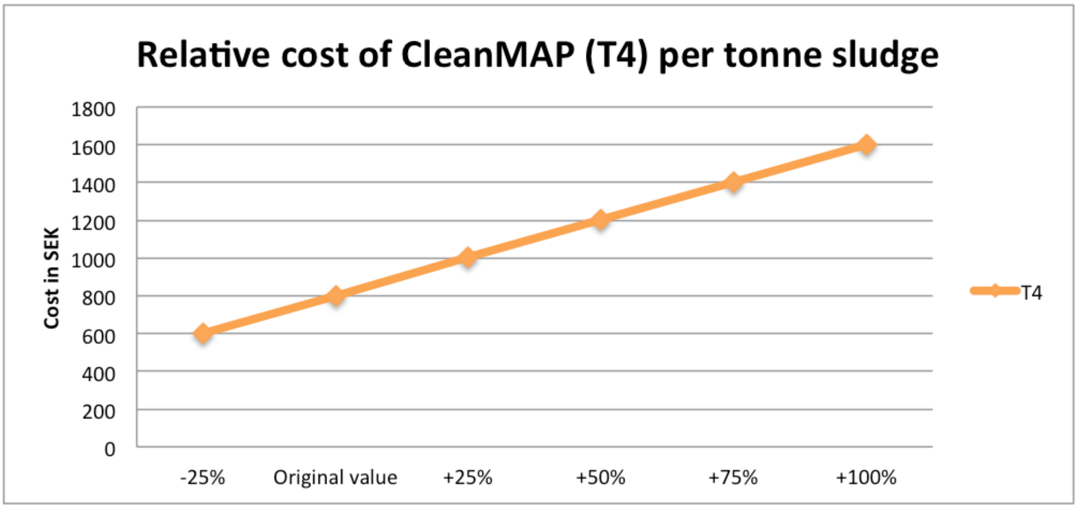


Figure 17: Additional cost (SEK/t) from CleanMAP, assuming diff. costs of the treatment

The effect of variations in assumed costs for T3 and T4 (shown up to a 50% change) are illustrated in figure 18 on the next page.

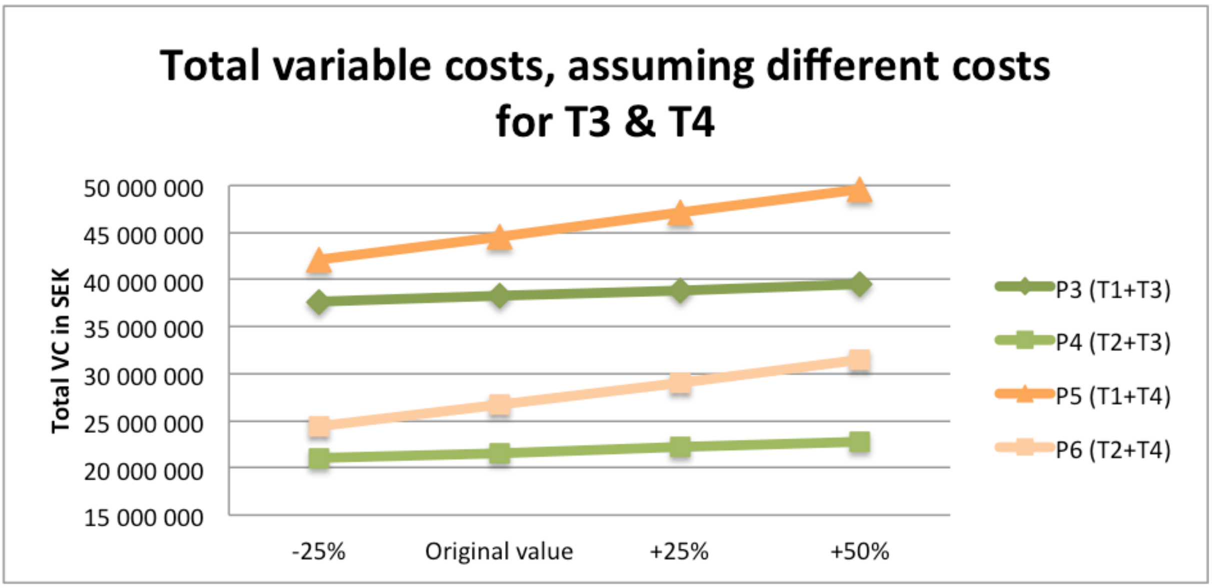


Figure 18: Effects on total variable costs of varying the costs of Revaq and CleanMAP

In conclusion, the ranking of alternatives is insensitive even to very large variations in price (or similarly consumption) of any of the input variables. The variable costs (operation & maintenance of the WWT and additional upstream management or phosphorus recovery) make up only a small part of the total costs. The fixed costs constitute 85% of the total cost for conventional treatment. The fixed cost amounts to 84% of total costs if the plant is Revaq certified and 81% of total costs if all sludge is to be treated with CleanMAP. For EBPR the fixed costs, although much lower than those for conventional treatment, constitute 86% of total costs. Adding Revaq reduces the part of fixed costs to 84% and CleanMAP to 81%.

In the sensitivity analysis it was also tested whether an assumed lower possible reduction of substances as a result from upstream management affects the ability to achieve acceptable sludge quality with Revaq. The outcome was tested assuming a 1% yearly reduction instead of the original assumption of 2%. The margin between the level of metals in the sludge and the corresponding limit values shrink, but it does not affect the ability of the optimal process combination (P4) to produce a sludge that can be applied to farmland in compliance with regulations.

9 Discussion

The result of this research is discussed in the second section, but first a short discussion on the quality of the data and how it affects the outcome of this study.

9.1 How the quality and choice of data affects the result

There appears to be a general uncertainty of specific costs for different processes, likely due to many possible variations in process set-up and site specific conditions. There are few examples of any given set-up built in the last decade that are relevant for this case. There is also a reluctance to quote investment cost data without a warning that costs vary greatly from case to case. Holmström (presonal communication, 2015) did for example not want to get into a deeper discussion on how the estimated costs of a new facility was divided between different stages of the wastewater or sludge treatment, to avoid the risk that their estimations might further down the line be treated as some sort of true costs for different technologies. There is also a tendency to warn against assuming any previously estimated investments and applying to new cases.

The investment cost of facilities are based on the only two relevant examples available. Taking data from single facilities (as in this case) and using out of its original context can only give a rough indication of what the same process might look like in the new context where the data is applied. The expectation was that an EBPR plant would prove to be more expensive, due to a more advanced biological treatment. The data is however contradicting this expectation. No matter if the data is adjusted to the size of the case plant using the exponential function of plant size in cubic meters suggested by Huang (1980) or linearly as a function of personal equivalents as in this case, the result suggests that an EBPR plant is less costly. Considering the process setup, this is unlikely to be the case. Whether this (assumably) mis-representative result is due to site specific conditions of the input data or under- or overestimating has not been possible to determine within the scope of this study. Holmström (personal communication, 2015) suggests that this could be because the WWTP at Sobacken, which the EBPR costs are based on, is part of an environmental complex, where some buildings might be shared. Fransson (personal communication, 2015) however argues that all costs are included.

The basic data for the variable costs have also been collected from a single plant representing each treatment and then adjusted to this case primarily by adjusting the costs for assumed case specific need for chemicals. The cost data received was provided differently from the two plants. Some of the differences between the same cost categories for the two treatments could possibly be caused from the costs having been grouped differently. That would to some extent explain why some of the costs contradict expectations. The fact that the costs for chemicals and other consumables have been grouped, makes it impossible to analyse the chemical costs on their own. The costs of T4, CleanMAP is also an uncertain variable, as this technology is not yet commercialised.

9.2 The answer to the research question & its implications

This study suggests that using EBPR (Bio-P) in combination with Revaq is likely to produce a sludge that can be applied as a fertiliser under the expected new regulations. Using chemical precipitation makes it less likely to produce a sludge with low enough content of chemicals. Conventional treatment also appears to be more costly, and even if the sludge would be approved for field application, the EBPR process is preferable from a cost perspective. As stated in the sensitivity analysis, this holds true if the variable costs (O&M) are correctly estimated and the construction of an EBPR plant does not exceed the cost of a conventional plant with more than 200 MSEK. Adding the process of CleanMAP for process recovery avoids any application of restricted substances to farmland, but at an increased cost of

6MSEK compared to using Revaq (assuming that the WWTP uses EBPR).

9.3 Other findings

As suggested by Wei (2013), data needs much preparation in order to be transferred from its original context and applied to another case. Regarding operational cost, the effects of different quality of wastewater or requirements on effluent can be handled by assuming a greater or lesser need for chemicals. A complicating and unforeseen factor that affects the transferability of costs from one case to another is that a WWTP does not necessarily use the same practices on the entire flow. Not just the case plant, but other plants considered as sources for data collection, had more than one type of treatment. This is important to be aware of when using the data.

9.4 Aspects of processes that are not covered by the optimisation

This model does not include constraints corresponding to the suggested new limit values for organic compounds, simply because it is a new phenomenon. The search for literature on expected reductions of unwanted substances in sludge as a result of upstream management rendered the one study by Mattson with colleagues (2012) of the estimated reductions at Gryab WWTP. This study estimated reductions of metals but did not include any organic substances due to lack of knowledge of how organic compounds may be targeted or respond to source reduction strategies, these compounds were left out. The result here thus only investigates the ability of the sludge to comply with limit values for metals.

There are a number of other aspects relevant to the decision on preferred processes at a wastewater treatment plant that are not included in the model and thus not in the analysis. One of these is the effect of different treatments on the effluent water. For example, Gustavsson (2005) writes that EBPR does not give rise the the same salinity in the recipient as conventional treatment, due to the lower use of chemicals. Also upstream management (Revaq) does not just improve the quality of the sludge, but also the water. Phasing out different substances and materials in society has positive effects on health and environment. However, continuous reduction and replacement of source materials can be costly. Take copper for example. The sources of copper in wastewater includes piping, roofs and brake pads in vehicles. Replacing these involve stakeholders with different agendas and may be costly and time consuming (Mattson, *et al.*, 2012). On the other hand, the Swedish Water and Wastewater Association state that effective upstream management can reduce the need for additional energy intensive treatment and thus reduce the costs at the WWTP. The association also describes upstream management and point source reduction as the only sustainable solution and the most important action to achieve the national objective of a toxic-free environment (Svenskt Vatten, www, 2015).

Another important aspect, which is not considered in this model is the different fertiliser value of different sludges or an extracted phosphorus product. Comparing direct application of sewage sludge to recovered mono-ammonium phosphate, MAP, the most obvious differences is that by direct application one also recycles the unwanted substances that are in the sludge. However the sludge also contains organic matter and nitrogen which is valuable to plants. This is all lost with incineration (Linderholm, *et al.*, 2012). Sewage sludge can serve as a conditioner for improving the soils physical properties due through it's high organic content. Application of sludge increases aeration, water infiltration and retention. It also lowers the soils bulk density and decreases surface crusting (Zorpas & Inglezakis, 2012). In sandy soils, sludge application also reduces the need for irrigation. Phosphorus in sewage sludge is however usually bound to iron from the precipitation agent. Iron and aluminium phosphates tend to have low solubility and plant availability (Cohen, *et al.*, 2011).

10 Conclusion

The result of the optimisation implies that EBPR is preferable to conventional treatment both in terms of costs and sludge quality. However, with the same water quality as Kungsängsverket, the addition of strategic upstream management is needed to produce a sludge that can be applied to farmland in compliance with the new limit values, if suggested new regulations are implemented.

10.1 Further research

This study only included one process for phosphorus recovery, to have an alternative operation in case the other processes were not enough to produce a recyclable product. It would have been interesting to make comparisons of different technologies. Some have been made, but none including CleanMAP. In hindsight this research may not be as applicable as expected. However a similar analysis would give a more reliable result down the road when the construction of the EBPR plant at Sobacken is finished, as the estimation of construction costs for T_2 can be validated. There will also be another plant which uses EBPR to 100% which can be considered when estimating costs of operation and maintenance.

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Appendix 1: Search words and combinations

The following search words or phrases have been used in various combinations.

“wastewater treatment”	“economics”
“wastewater treatment plant”	“efficiency”
“sewage sludge”	“cost”
“phosphorus”	“cost of capital”
“phosphorus recycling”	“construction cost”
“phosphorus recovery”	“processes”
“nutrient recovery”	“technologies”
“recirculation”	“profitability”
“wastewater treatment plant design”	“conventional treatment”
“bio-P”	“tertiary treatment”
“EBPR”	

The engines used have been mostly Google, Web of Science, Science Direct. Epsilon and Google-scholar have also been used.

Appendix 2: Optimisation in excel – scenario 0 (reference sc. w. today's limit values)

Optimering med process-kombinationer P1-P8

	Min	**131 712 003**
Result:		
Optimum preocess setup		
P-?	**P2**	**<-- Filled in manually**
COST		
Tot cost	**131 712 003**	
Treated volumes:		
ww	**19500000**	**m3**
sludge	**10511**	**tonnes**
Residue levels in sludge		
Pb	**12**	**mg/kg dm**
Cd	**0,58**	**mg/kg dm**
Cu	**378**	**mg/kg dm**
Cr	**15**	**mg/kg dm**
Hg	**0,61**	**mg/kg dm**
Ni	**11**	**mg/kg dm**
Ag	**1,9**	**mg/kg dm**
Zn	**441**	**mg/kg dm**

Process comb	P1	P2	P3	P4	P5	P6	P7	P8	
Treatments c	T1	T2	T1 + T3	T2 + T3	T1 + T4	T2 + T4	T1 + T3 +T4	T2 + T3 +T4	
Pi	0	1	0	0	0	0	0	0	<-- Binary variables
FC	189206553	113618535	189206553	113618535	189206553	113618535	189206553	113618535	
VC(w+s)/m3	1,76	0,93	1,88	1,04	2,26	1,35	2,34	1,42	
w	19500000	19500000	19500000	19500000	19500000	19500000	19500000	19500000	<-- Treated as constant
VCtot	34342664	18093468	36729361	20324365	44153897	26371040	45543897	27761040	
Tot cost	0	131712003	0	**0**	0	0	0	0	

	Process comb	P1	P2	P3	P4	P5	P6	P7	P8	**Bivillkor** Sum Pi*aij		
	Unwanted substances (mg/kg dm) in sewage sludge or P-product from different process combinations											
	Scenario 0, unchanged limit values											sc0
a_1	Pb	12	12	9	9	0	0	0	0	12	<=	100
a_2	Cd	0,58	0,58	0,43	0,43	0	0	0	0	0,58	<=	2
a_3	Cu	378	378	279	279	0	0	0	0	378	<=	600
a_4	Cr	17	15	13	11	0	0	0	0	15	<=	100
a_5	Hg	0,61	0,61	0,45	0,45	0	0	0	0	0,61	<=	2,5
a_6	Ni	14	11	10	8	0	0	0	0	11	<=	50
a_7	Ag	1,9	1,9	1,4	1,4	0	0	0	0	1,9		
a_8	Zn	443	441	327	327	0	0	0	0	441	<=	800
ej villkorad	s	0	10511	0	0	0	0	0	0	10511		
a_{10}	Pi	0	1	0	0	0	0	0	0	1	=	1
a_{11}	ww	0	19500000	0	0	0	0	0	0	19500000	=	19500000

Appendix 3: Optimisation in excel – **scenario 1** (suggested new limit values)

Optimering med process-kombinationer P1-P8

	Min	**133 942 899**
Result:		
Optimum preocess setup		
P-?	**P4**	**<-- Filled in manually**
COST		
Tot cost	**133 942 899**	
Treated volumes:		
ww	**19500000**	**m3**
sludge	**10511**	**tonnes**

Process com	P1	P2	P3	P4	P5	P6	P7	P8	
Treatments c	T1	T2	T1 + T3	T2 + T3	T1 + T4	T2 + T4	T1 + T3 +T4	T2 + T3 +T4	
Pi	0	0	0	1	0	0	0	0	<-- Binary variables
FC	189206553	113618535	189206553	113618535	189206553	113618535	189206553	113618535	
VC(w+s)/m3	1,76	0,93	1,88	1,04	2,26	1,35	2,34	1,42	
w	19500000	19500000	19500000	19500000	19500000	19500000	19500000	19500000	<-- Treated as constant
VCtot	34342664	18093468	36729361	20324365	44153897	26371040	45543897	27761040	
Tot cost	0	0	0	**133942899**	0	0	0	0	

Residue levels in sludge		
Pb	**9**	**mg/kg dm**
Cd	**0,43**	**mg/kg dm**
Cu	**279**	**mg/kg dm**
Cr	**11**	**mg/kg dm**
Hg	**0,45**	**mg/kg dm**
Ni	**8**	**mg/kg dm**
Ag	**1,4**	**mg/kg dm**
Zn	**327**	**mg/kg dm**

	Process com	P1	P2	P3	P4	P5	P6	P7	P8	**Bivillkor** Sum Pi*aij		
	Unwanted substances (mg/kg dm) in sewage sludge or P-product from different process combinations											
	Scenario 0, unchanged limit values											sc1
a_1	Pb	12	12	9	9	0	0	0	0	9	<=	25
a_2	Cd	0,58	0,58	0,43	0,43	0	0	0	0	0,43	<=	0,8
a_3	Cu	378	378	279	279	0	0	0	0	279	<=	475
a_4	Cr	17	15	13	11	0	0	0	0	11	<=	35
a_5	Hg	0,61	0,61	0,45	0,45	0	0	0	0	0,45	<=	0,6
a_6	Ni	14	11	10	8	0	0	0	0	8	<=	30
a_7	Ag	1,9	1,9	1,4	1,4	0	0	0	0	1,4	<=	3
a_8	Zn	443	441	327	327	0	0	0	0	327	<=	700
ej villkorad	s	0	0	0	10511	0	0	0	0	10511		
a_{10}	Pi	0	0	0	1	0	0	0	0	1	=	1
a_{11}	ww	0	0	0	19500000	0	0	0	0	19500000	=	19500000

Appendix 4: Optimisation in excel – scenario 2 (reference sc. w. stricter limit values)

Optimisation with process combinations P1-P8

	Min	139 989 575
Result:		
Optimum preocess setup		
P-?	**P6**	**<-- Filled in manually**
COST		
Tot cost	**139 989 575**	
Treated volumes:		
ww	**19500000**	**m3**
sludge	**10511**	**tonnes**
Residue levels in sludge		
Pb	**0**	**mg/kg dm**
Cd	**0,00**	**mg/kg dm**
Cu	**0**	**mg/kg dm**
Cr	**0**	**mg/kg dm**
Hg	**0,00**	**mg/kg dm**
Ni	**0**	**mg/kg dm**
Ag	**0,0**	**mg/kg dm**
Zn	**0**	**mg/kg dm**

Process com	P1	P2	P3	P4	P5	P6	P7	P8	
Treatments c	T1	T2	T1 + T3	T2 + T3	T1 + T4	T2 + T4	T1 + T3 +T4	T2 + T3 +T4	
Pi	0	0	0	0	0	1	0	0	<-- Binary variables
FC	189206553	113618535	189206553	113618535	189206553	113618535	189206553	113618535	
VC(w+s)/m3	1,76	0,93	1,88	1,04	2,26	1,35	2,34	1,42	
w	19500000	19500000	19500000	19500000	19500000	19500000	19500000	19500000	<-- Treated as constant
VCtot	34342664	18093468	36729361	20324365	44153897	26371040	45543897	27761040	
Tot cost	0	0	0	0	0	139989575	0	0	

										Bivillkor		
	Process com	P1	P2	P3	P4	P5	P6	P7	P8	Sum Pi*aij		
	Unwanted substances (mg/kg dm) in sewage sludge or P-product from different process combinations											
	Scenario 0, unchanged limit values											sc2
a_1	Pb	12	12	9	9	0	0	0	0	0	<=	20
a_2	Cd	0,58	0,58	0,43	0,43	0	0	0	0	0,00	<=	0,4
a_3	Cu	378	378	279	279	0	0	0	0	0	<=	350
a_4	Cr	17	15	13	11	0	0	0	0	0	<=	20
a_5	Hg	0,61	0,61	0,45	0,45	0	0	0	0	0,00	<=	0,5
a_6	Ni	14	11	10	8	0	0	0	0	0	<=	15
a_7	Ag	1,9	1,9	1,4	1,4	0	0	0	0	0,0	<=	2
a_8	Zn	443	441	327	327	0	0	0	0	0	<=	550
ej villkorad	s	0	0	0	0	0	10511	0	0	10511		
a_{10}	Pi	0	0	0	0	0	1	0	0	1	=	1
a_{11}	ww	0	0	0	0	0	19500000	0	0	19500000	=	19500000

Appendix 5: Calculated residue in sludge/P-product from each process combination

Process combo	P1	P2	P3	P4	P5	P6	P7	P8	Limit Value	
Included treatments	T1	T2	T1 + T3	T2 + T3	T1 + T4	T2 + T4	T1+T3+T4	T2+T3+T4		
Value background: Calculation or source										
R1= residues in T1-sludge, **R2**= residue in T2-sludge and so on	R1 = Current levels of residue in Kungsängsverkets sludge (Uppsala Vatten, 2015, #1)	R2 = R1 - addition of metals from the precipitation chemicals (calculated based on data fom Environment report (Uppsala Vatten, 2015, #1)	R3(T1) = R1*(1-2%)^15	R3(T2) = R2*(1-2%)^15	R4 = 0	R4 = 0	R4 = 0	R4 = 0		
			2% is the assumed yearly reduction for T3 and 15 is the number of years [at the time of calculation] to 2030 when the new limit values are suggested to be fully implemented.		Based on statements in previous research (Cohen et al., 2011; Jonsson, 2015)					
Unwanted substances (mg/kg dm) in sewage sludge or P-product from different process combinations										
Scenario 0, unchanged limit values										
Pb	12	12	9	9	0	0	0	0	<=	100
Cd	0,58	0,58	0,43	0,43	0	0	0	0	<=	2
Cu	378	378	279	279	0	0	0	0	<=	600
Cr	17	15	13	11	0	0	0	0	<=	100
Hg	0,61	0,61	0,45	0,45	0	0	0	0	<=	2,5
Ni	14	11	10	8	0	0	0	0	<=	50
Ag	1,9	1,9	1,4	1,4	0	0	0	0		
Zn	443	441	327	327	0	0	0	0	<=	800
Scenario 1, suggested limit values										
Pb	12	12	9	9	0	0	0	0	<=	25
Cd	0,58	0,58	0,43	0,43	0	0	0	0	<=	0,8
Cu	378	378	279	278,95	0	0	0	0	<=	475
Cr	17	15	13	11	0	0	0	0	<=	35
Hg	0,61	0,61	0,45	0,45	0	0	0	0	<=	0,6
Ni	14	11	10	8	0	0	0	0	<=	30
Ag	1,9	1,9	1,4	1,4	0	0	0	0	<=	3
Zn	443	441	327	327	0	0	0	0	<=	700
Scenario 2, stricter limitvalues										
Pb	12	12	9	9	0	0	0	0	<=	20
Cd	0,58	0,58	0,43	0,43	0	0	0	0	<=	0,4
Cu	378	378	279	278,95	0	0	0	0	<=	350
Cr	17	15	13	11	0	0	0	0	<=	20
Hg	0,61	0,61	0,45	0,45	0	0	0	0	<=	0,5
Ni	14	11	10	8	0	0	0	0	<=	15
Ag	1,9	1,9	1,4	1,4	0	0	0	0	<=	2
Zn	443	441	327	327	0	0	0	0	<=	550