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Specific net present value: An improved method for assessing modularisation costs in water services with growing demand

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ABSTRACT

A specific net present value (SNPV) approach is introduced as a criterion in economic engineering decisions. The SNPV expresses average costs, including the growth rate and plant utilisation over the planning horizon, factors that are excluded from a standard net present value approach. The use of SNPV favours alternatives that are cheaper per service unit and are therefore closer to the costs that a user has to cover. It also shows that demand growth has a similar influence on average costs as an economy of scale. In a high growth scenario, solutions providing less idle capacity can have higher present value costs and still be economically favourable.

The SNPV approach is applied in two examples to calculate acceptable additional costs for modularisation and comparable costs for on-site treatment (OST) as an extreme form of modularisation. The calculations show that: (i) the SNPV approach is suitable for quantifying the comparable costs of an OST system in a different scenario; (ii) small systems with projected high demand growth rates and high real interest rates are the most probable entry market for OST water treatment systems; (iii) operating expenses are currently the main economic weakness of membrane-based wastewater OST systems; and (iv) when high growth in demand is expected, up to 100% can be additionally invested in modularisation and staging the expansion of a treatment plant.

1. Introduction

Water and wastewater treatment plants show a distinct economy of scale (e.g. Smith, 1968; Adams et al., 1972; Tihansky, 1974; US-EPA, 1981, 1983, 2001; Maurer and Herlyn, 2006). Unit costs decrease as the capacity increases due to economies of scale and reducing marginal costs with higher performance. The simple consequence of this is that larger plants are usually given preference over several smaller ones in typical economic evaluations of projects.

In engineering economics, a new treatment plant is planned and evaluated in several steps. The terms and requirements the plant has to fulfil, such as the planning horizon, capacity, performance, footprint, and others, are firstly evaluated. Secondly, this profile is passed on to the design office or used in a call for tenders. Thirdly, the alternatives generated in this way are evaluated by various criteria in which an economic comparison is usually prominent. One of the two methods is typically used for an engineering economic analysis: net present value (NPV) or equivalent uniform annual cash flow (EUAC) (Newnan et al., 2004). Both methods, NPV and EUAC, calculate the total cash flow for the project either as a lump sum (NPV) or as a homogenous annual cost over the planning horizon (EUAC). Projects with a higher NPV or EUAC are economically more favourable and win the evaluation if all other criteria are equally satisfied.

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Abbreviations and notations

Abbreviations

capex capital expenditure
opex operating expenses
OST on-site treatment
SNPV specific net present value

Notations

a_{OST} capital recovery factor or annuity factor, see Eq. (3) [–]
$C_{op,t}$ present value operating costs at time t [$]
$C_{op}(P_t)$ present value of opex at time t as a function of P_t [$]
I investment cost, capex [$]
I_{OST} specific investment for OST plants [$ PE^{-1}]
NPV present value of total expenses [$]
NPV_{cap} present value of capex [$]
NPV_{op} present value of opex [$]
P_{Dim} installed capacity [PE]
$P_{Dim,A/B}$ capacity of plant A/B [PE]
P_t load/demand at time t [PE]
P_0 load/demand at time 0 [PE]
PU plant utilisation [–]
r interest rate [T^{-1}]
t time [T]
T_D linear depreciation time, average lifespan [T]
T_{OST} average lifespan for OST plant [T]
T_P planning horizon [T]
α_{cap} scaling coefficient for capex [–]
α_{op} scaling coefficient for opex [–]
β_{cap} scaling factor for capex [–]
β_{op} scaling factor for opex [-]
λ growth rate of load/demand [T^{-1}]

Subscripts

OST on-site treatment system
CEN centralised treatment system
N denotes the number of stages (see Fig. 8 for an example)

Units

PE load/demand in population equivalents
$ cost
T time

Characteristic for many water services is the fact that in these natural monopolies there is no competitive (waste-) water market. The price for the services is usually determined by the costs, so that the overall revenue is proportional to the expenses (for an in-depth discussion of marginal vs. average price setting see Vickrey, 1948, 1987 and Hotelling, 1938). Not having a cost independent price for water services cripples the information value of the NPV or EUAC substantially and renders other methods, such as the internal rate of return (IRR), pointless. As a consequence only the present value of the costs is used in the economic evaluation of water projects, excluding the revenues. In this manuscript, we still use the term 'NPV' as a reference to the specific method in economic engineering.

Planning horizons for centralised treatment plants are generally large, typically around 30 years. Forecasting the needs for such a long duration is very tricky and prone to large uncertainties. As a consequence, the planning approach described above commonly leads to overcapacities, except in the rare circumstance where the load remains constant over the planning horizon of 30 years. In any other case, involving growth or decay, there will be overcapacities at some point of the life-span of the plant. Depending on the growth rate, these can be quite substantial and raise the question as to the conditions in which it would be beneficial to apply modularisation.

In this paper, we argue that the commonly used NPV is not adequate to evaluate water treatment plants in a growth scenario. A new evaluation approach, known as the specific net present value (SNPV) method, is consequently introduced. SNPV is used in one example to estimate the cost of modularisation needed to offset the costs for overcapacity. The second example investigates the financial conditions for decentralised on-site treatment, the ultimate modularisation scheme. The results clearly show that in situations where demand grows over the planning horizon, the SNPV approach is more suitable for comparing different treatment approaches, whereas the conventional NPV method is restricted to similar technical configurations.

2. Background

2.1. Net present value (NPV)

The net present value is usually defined as the total sum of the capital expenditure (capex), operating expenses (opex) and income generated by the service. For monopolistic water businesses, it can be argued that the income is directly defined by the costs, i.e. the income is not independent and is commonly regulated to be proportional to the costs. For an engineering cost analysis, the NPV can typically be reduced to comparing costs (capex and opex) only:

$$NPV = NPV_{cap} + NPV_{op} \tag{1}$$

where NPV_{cap} = present value of capex, and NPV_{op} = present value of opex.

Strictly speaking, Eq. (1) only represents the present value of the expenses and not a net value. To simplify the discussion, no lead times for the construction of a new plant are assumed and the annual capital costs are derived from the annuity (expressed as a uniform series capital recovery factor, a). The present value for the capital cost (NPV_{cap}) of an investment I can then be written as

$$NPV_{cap} = I \cdot a \cdot T_D \tag{2}$$

$$a = \frac{r(1+r)^{T_D}}{(1+r)^{T_D}-1} \tag{3}$$

where I = investment cost, r = interest rate and T_D = linear depreciation time or average lifespan.

All calculations are made with real costs and real interest rates.

2.2. Demand curve

In order to facilitate the calculations, we assume that the demand development of the plant can be described by an exponential growth curve:

$$P_t = P_0 \cdot e^{\lambda \cdot t} \tag{4}$$

where P_t = load in population equivalents at time t, P_0 = population equivalents at time 0, λ = growth rate of the population equivalents, and t = time.

Eq. (4) is not a required condition for the calculations in this paper, but it facilitates the formulation of algebraic solutions and hence improves the readability of this manuscript.

2.3. Economy of scale

The economy of scale for a treatment plant is commonly expressed with the following formula:

$$\frac{I_A}{I_B} = \left(\frac{P_{Dim,A}}{P_{Dim,B}}\right)^{\beta_{cap}} \tag{5}$$

where: $I_{A/B}$ = capex for treatment plants A and B, respectively, $P_{Dim,A/B}$ = capacity of plant A/B, and β_{cap} is the scaling factor.

The scaling factor β_{cap} is less than 1.0 and typically around 0.7 (see Table 1), indicating that the larger capacity can be built with smaller specific investments.

Eq. (5) is often expressed in another form (Adams et al., 1972; Tihansky, 1974; Tsagarakis et al., 2003):

$$I = \alpha_{cap} \cdot P_{Dim}^{\beta_{cap}} \tag{6}$$

$$\alpha_{cap} = \frac{I_{10,000\ PE}}{(P_{10,000\ PE})^{\beta_{cap}}} \tag{7}$$

where the parameter α_{cap} is expressed in terms of the investment for a specific size of treatment plant (in this example for 10,000 PE, see also Eq. (5)).

α_{cap} is typically a country or regional specific number that depends on construction price, legal and technical requirements and treatment efficiency (US-EPA, 1983, 2001).

Similarly, the costs for operation and maintenance (C_{op}, or opex) can be expressed as

$$C_{op,t} = \alpha_{op} \cdot P_t^{\beta_{op}} \tag{8}$$

$$\alpha_{op} = \frac{C_{op,10,000\ PE}}{(P_{10,000\ PE})^{\beta_{op}}} \tag{9}$$

where the parameter α_{op} is expressed in terms of the operating costs for a specific size of treatment plant (in this example 10,000 PE), $C_{op,t}$ = operating costs at time t, P_t = load of the plant, and β_{op} is the scaling factor. Typical values for β_{op} are listed in Table 2.

Eq. (8) defines the operating costs as a function of the actual load of the treatment plant. This simplification assumes that the load-specific running costs dominate opex. This is a good approximation for larger plants with high energy and disposal costs and low labour costs (Maurer et al., 2006; Bohn, 1997; US-EPA, 1981).

Eqs. (6) and (8) are commonly used approximations of capex and opex, based on input only. More sophisticated cost model are available that also include performance and treatment plant layout that if needed could be used instead (Lo and Chen, 1997; Vanrolleghem et al., 1996).

3. Plant utilisation

During the design and planning process, the treatment plant is typically designed for the maximal expected demand during the planning horizon, typically 25–30 years. According to Eq. (4), the installed capacity is then given as

Table 1 – Scaling factor β_{cap} (see Eq. (6)) for the capex of wastewater treatment plants. WWTP = wastewater treatment plant; DWTP = drinking water treatment plant.

Where	β_{cap}	Type of treatment plant	Source
Switzerland	0.72	WWTP, all types ($n = 128$)	Maurer et al. (2006)
Austria	0.7	WWTP, all types	Schönbäck (1995)
Germany	0.75	WWTP, all types	Bohn (1997)
Greece	0.68	WWTP, all types	Aivaliotis et al. (1991)
Greece	0.73 - 0.95	WWTP, incl. chlorination and sludge treatment; factor depends on applied technology	Tsagarakis et al. (2003)
USA	0.72	WWTP, secondary treatment	US-EPA (1983)
USA	0.74	WWTP, advanced treatment	
USA	0.68	DWTP, chlorination	US-EPA (2001)
USA	0.65	DWTP, several treatment steps	

Table 2 – Scaling factor β_{op} (see Eq. (9)) for the opex of wastewater treatment plants. WWTP = wastewater treatment plant.

Where	β_{op}	Type of treatment plant	Source
Switzerland	0.81	WWTP, all types ($n = 272$)	Maurer et al. (2006)
USA	0.78	WWTP, All types ($n = 671$)	US-EPA (1981)
USA	0.77	WWTP, secondary treatment	
USA	0.82	WWTP, advanced treatment	
USA	0.77	WWTP, activated sludge	Smith (1968)
USA	0.75	WWTP, activated sludge	Tihansky (1974)
Greece	0.67–0.80	WWTP, incl. chlorination and sludge treatment; factor depends on applied technology	Tsagarakis et al. (2003)

$$P_{Dim} = P_0 \cdot e^{\lambda \cdot T_P} \quad (10)$$

where P_{Dim} = installed capacity in population equivalents (PE), P_0 = population equivalents at time 0, λ = growth rate of the population equivalents, and T_P = planning horizon.

In a typical growth scenario, this means that the plant is not utilised at its peak capacity for a large part of its lifespan. Fig. 1 shows an example of a plant designed with the capacity to handle the demand expected at the end of the 30-year period with 2% annual growth. At this moderate growth rate, the plant has almost 25% idle capacity, or utilises 75% of its capacity over its entire lifespan.

The total plant utilisation, PU, can be calculated with

$$PU = \frac{\int_0^{T_P} P_0 \cdot e^{\lambda t} dt}{T_P \cdot P_{Dim}} \quad (11)$$

$$PU = \frac{1 - e^{-\lambda T_P}}{\lambda T_P} \quad (12)$$

where P_0 = demand (PE) at time 0, T_P = planning horizon, λ = demand growth rate, and t = time.

The plant utilisation PU characterises the utilised capacity of the plant over its entire lifespan. Correspondingly, the idle capacity can be calculated as (1 − PU) (see example in Fig. 1). Eq. (12) indicates that the plant utilisation rate is determined only by the demand growth rate and the planning horizon. It is worth mentioning that the PU is completely independent of the plant size and affects all scales equally. From Fig. 2 it can be seen that in slow growing situations with annual growth rates of 1–2%, about 10–25% of the total plant capacity is not utilised. But the overall plant utilisation could even be 50% or less in the case of fast-growing demand of 5% or more annually.

4. The specific net present value (SNPV) approach

Having substantial idle capacity means that the cost per utilised capacity is higher than indicated by the net present value

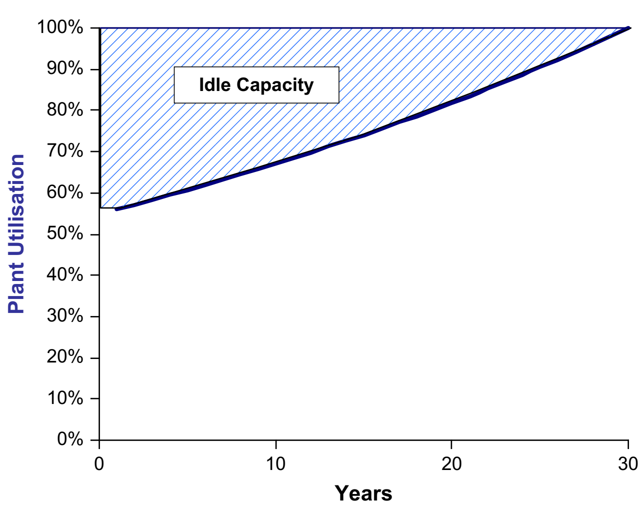

Fig. 1 – Plant utilisation over 30 years, assuming a demand growth rate $\lambda = 0.02\ a^{-1}$. The shaded area defines the idle capacity (overcapacity) of the plant due to a typical design process.

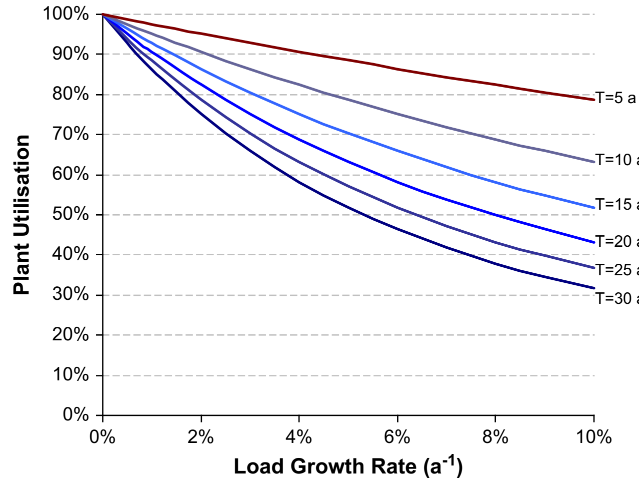

Fig. 2 – The calculated plant utilisation PU from Eq. (12) shows a strong dependency on the planning horizon T_P and the growth rate of the load. Typically, the lifespan of a WWTP is 25–30 years, which also determines the planning horizon.

of the installed performance. As a consequence, two plant designs with the same NPV may still have different average costs if their utilisations differ. Idle capacity increases the average cost of a serviced unit.

One way of influencing plant utilisation is to choose appropriate technical approaches that keep less capacity idle: this can be done by staging the construction of the plant, i.e. introducing modularisation. The additional costs for these measures cut into the financial benefit of constructing larger treatment plants. We will show in this paper that demand growth and economy of scale have similar importance for average costs.

The sensitivity analysis presented in Fig. 2 clearly shows that projects with an equal NPV evaluation but different growth scenarios will have different costs per service unit (average costs). In scenarios with high growth rates, the plant utilisation (PU) will be low and the average costs will therefore be higher than in a case with high PU. In order to compensate for this effect, we suggest replacing the commonly used present value of expenses with a specific NPV that expresses the NPV per service unit or per PE:

$$SNPV = \frac{NPV}{\frac{1}{T_P} \cdot \int_0^{T_P} P_t \cdot dt} \quad (13)$$

where P_t = demand (PE) at time t, T_P = planning horizon, and NPV = present value of total expenses.

The SNPV can comprise the specific present value of capex and the present value of opex:

$$SNPV = SNPV_{cap} + SNPV_{op} \quad (14)$$

The opex typically depends on the load of the treatment plant. The $SNPV_{op}$ can then be expressed as

$$SNPV_{op} = \int_0^{T_P} \frac{C_{op}(P_t)}{P_t} dt \quad (15)$$

where: $C_{op}(P_t)$ = present value of opex at time t as a function of P_t, P_t = demand (PE) at time t, and T_P = planing horizon.

By substituting Eq. (12) into Eq. (13), the $SNPV_{cap}$ can be calculated with

$$SNPV_{cap} = \frac{NPV_{cap}}{PU \cdot P_{Dim}} \tag{16}$$

Eq. (16) shows clearly that the specific present value of the capital costs ($SNPV_{cap}$) depends on the plant utilisation, which itself is a function of the growth rate. Fig. 3 shows the increase of $SNPV_{cap}$ for the same treatment plant but different growth rates. At a 5% growth rate, the specific capital costs for the same plant are 1.9 times as high as with no growth. At 2%, this factor is still 1.3, highlighting the importance of growth rates as a factor in the economic evaluation of projects.

Using SNPV for the economic evaluation allows overcoming the deficit of the classic NPV approach, in case where the water revenues are by definition proportional to the expenses. In these cases the SNPV allows alternatives that are cheaper per service unit and therefore come closer to the cost that a user must ultimately cover. Fig. 3 underlines the fact that the net present value of a more modular project (e.g. with decentral treatment plants) can be substantially higher while still being economically more favourable for the user. It also indicates that fast developing settlements, e.g. in developing countries, face additional financing challenges for treatment facilities compared with their counterparts in more developed OECD countries.

The next section discusses the value of the SNPV for two possible examples of adaptation to high growth rates: (1) on-site (decentralised) treatment as an extreme form of modularisation, and (2) modularisation of treatment capacity.

5. Application of the SNPV approach

5.1. *Example 1: on-site treatment (OST)*

The following example assumes that the treatment capacity is provided either by a single large plant or alternatively by

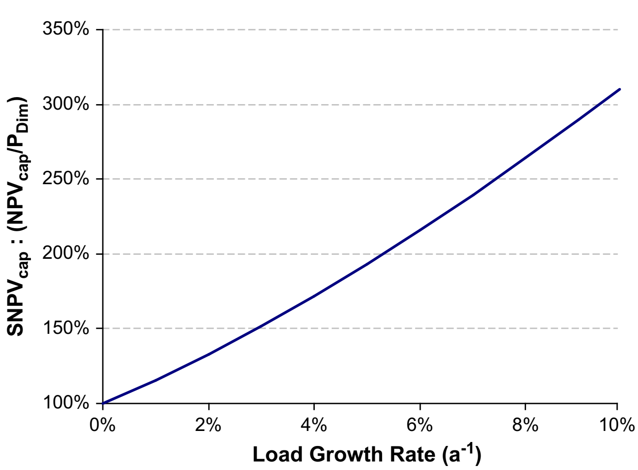

Fig. 3 – The increase of specific capital costs (per unit load or PE), $SNPV_{cap}$, at higher load growth rates for the same size treatment plant. Planning horizon T = 30 a. Higher growth rates mean lower plant utilisation and therefore higher capital costs per treated unit over the life cycle of the plant.

several local small-scale treatment plants (on-site treatment OST). A very comprehensive comparison of decentralised and centralised systems can be found in Pinkham et al. (2004); reasons for the advantages of such OST systems are given in Green and Ho (2005).

To simplify the calculations, it is assumed that these are standardised modules with standard capital expenditure (capex or I_{OST}), lifespan (T_{OST}) and operating costs (opex or C_{OST}). Moreover, it is assumed that the installed capacity corresponds exactly to the demand that there are no changes in the setup of the transport system and that the overall performance of OST systems is comparable to that of central systems. It also needs to be emphasised that the economic comparison is performed for identical forms of organisational and financial set-up.

The following examples aim to demonstrate the benefits of using the SNPV approach for economic evaluations. Some economic characteristics of OST systems are also outlined.

5.1.1. *Case 1A: similar operating expenditure (opex) for OST and central systems*

The first case assumes that the specific present value of opex is equal in both systems ($SNPV_{op,OST} = SNPV_{op,CEN}$). This enables us to directly compare the investment costs of both systems and to derive an estimate of upper capex levels for OST units. Using Eqs. (14), (16), (2), and (3), the following equations can be derived for the central system (CEN):

$$SNPV_{CEN} = SNPV_{op,CEN} + SNPV_{cap,CEN} \tag{17}$$

$$SNPV_{cap,CEN} = \frac{NPV_{cap,CEN}}{PU \cdot P_{Dim}} = \frac{I_{CEN} \cdot a_{CEN} \cdot T_P}{PU \cdot P_{Dim}} \tag{18}$$

Similarly, for the OST system:

$$SNPV_{OST} = SNPV_{op,OST} + SNPV_{cap,OST} \tag{19}$$

$$SNPV_{cap,OST} = I_{OST} \cdot a_{OST} \cdot T_P \tag{20}$$

where T_P = planning horizon, I_{OST} = specific investment cost for one PE independent of the unit size, a_{OST} is the annuity factor from Eq. (3) with a lifespan T_{OST} for the OST unit and an interest rate r.

The OST system is economically favourable if the following condition applies:

$$SNPV_{OST} \le SNPV_{CEN} \tag{21}$$

Under the assumption that the specific opex values are equal in both systems, this transforms into:

$$SNPV_{cap,OST} \le SNPV_{cap,CEN} \tag{22}$$

or

$$\frac{I_{OST}}{I_{CEN}} \cdot P_{Dim} \le \frac{a_{CEN}}{a_{OST}} \cdot \frac{1}{PU} \tag{23}$$

Fig. 4 shows the graphic representation of Eq. (23) for different growth rates and interest rates. Ratios below 1.0 indicate that the specific investment costs for OST systems must be lower than for comparable centralised systems in order to be economically competitive. Under conditions with low real interest rates (typically <5%) and growth rates (typically <0.02 a^{-1}), decentralised systems can only be viable if the capex values of OST plants are substantially lower than for a central plant. This semi-quantitative conclusion also holds true if a less favourable lifespan ($T_{OST} < 15$ a) and higher operating costs are assumed for the OST systems. For both these cases, the lines in Fig. 4 shift downwards, in favour of the centralised systems. On the other hand, Fig. 4 also indicates that OST systems might be economical under circumstances with high growth rates (>5%) even if their specific capex values are higher, especially if the interest rates are high.

It is important to keep in mind that these conclusions are based on similar conveyance systems for both cases. This is for example the situation in wet areas where the combined sewers in the centralised case are similar to the stormwater system in the OST case.

Fig. 4 compares relative costs only. Absolute costs for central treatment plants depend greatly on their size (economy of scale). The next exemplary case shows the investment level at which OST systems are viable.

5.1.2. *Case 1B: quantitative SNPV evaluation of OST and central systems*

In the first case, the capex values of OST systems were expressed relatively to those of central treatment plants. This means that, due to the economy of scale in centralised systems, the SNPV of viable OST systems also change as a function of catchment size. The following calculations give a quantitative approach to estimate the size dependency of viable OST systems as another example of the usefulness of the SNPV method.

For a single centralised treatment plant, the $SNPV_{cap,CEN}$ can be expressed by substituting Eq. (6) into Eq. (18):

$$SNPV_{cap,CEN} = \frac{a_{CEN} \cdot T_P}{PU \cdot P_{Dim}} \cdot \alpha_{cap} \cdot P_{Dim}^{\beta_{cap}} \quad (24)$$

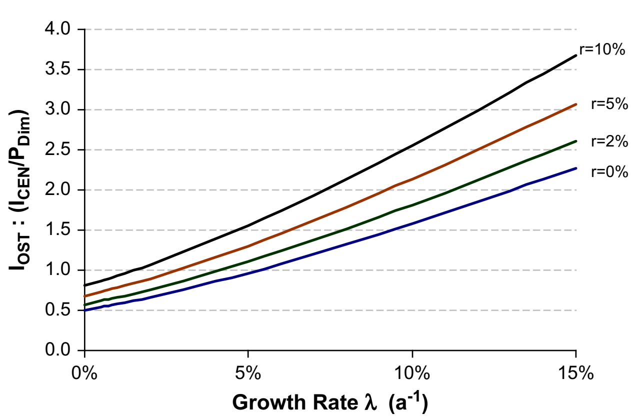

Fig. 4 – The investment for OST systems (I_{OST}) relative to the specific investment for central systems (I_{CEN}/P_{Dim}) according to Eq. (23) for different growth rates λ and real interest rates r. The lifespan for centralised plants is assumed to be 30 years and for decentralised units 15 years. Areas below the lines are economically favourable for OST systems. See text for the specific assumptions underlying the calculations.

And substituting Eq. (8) into Eq. (15) the SNPV for the opex can be estimated with

$$SNPV_{op,CEN} = \int_0^{T_P} \frac{C_{op}(P_t)}{P_t} dt = \int_0^{T_P} \alpha_{op} \cdot P_t^{(\beta_{op}-1)} dt \quad (25)$$

If the demand follows an exponential growth scenario (Eq. (4)), then the $SNPV_{op,CEN}$ can be expressed as

$$SNPV_{op,CEN} = \frac{\alpha_{op}}{\lambda \cdot (\beta_{op} - 1)} \left(P_{Dim}^{(\beta_{op}-1)} - P_0^{(\beta_{op}-1)} \right) \quad (26)$$

The decentralised OST system is economically favourable if the following condition applies

$$SNPV_{OST} \le SNPV_{CEN}$$
$$SNPV_{OST} \le SNPV_{cap,CEN} + SNPV_{op,CEN}$$
$$SNPV_{OST} \le \frac{a_{CEN} \cdot T_P}{PU} \cdot \alpha_{cap} \cdot P_{Dim}^{(\beta_{cap}-1)} + \frac{\alpha_{op}}{\lambda \cdot (\beta_{op} - 1)} \left(P_{Dim}^{(\beta_{op}-1)} - P_0^{(\beta_{op}-1)} \right) \quad (27)$$

Fig. 5 shows the specific net present value for centralised plants ($SNPV_{CEN}$) as a function of plant size. The numbers are based on the Swiss data presented in Tables 1 and 2 that show a very typical economy of size and assume no interest rates. In order to compensate for the fact that absolute numbers may vary for different countries (Maurer et al., 2006), the diagram is normalised with the $SNPV_{CEN}$ for a Swiss plant with $P_{Dim} = 10{,}000$ (1385 US\$ PE^{-1}). This enables us to draw some general conclusions going beyond Switzerland, mainly because the shape of the curves depends on the scaling factor β and the interest rate, both generic factors. The lines in Fig. 5 are a typical representation of the absolute SNPV variations due to the growth and size of the plant.

The area below a specific line in Fig. 5 indicates the economic conditions favourable for an on-site treatment system ($SNPV_{OST} < SNPF_{CEN}$). Two immediate conclusions are

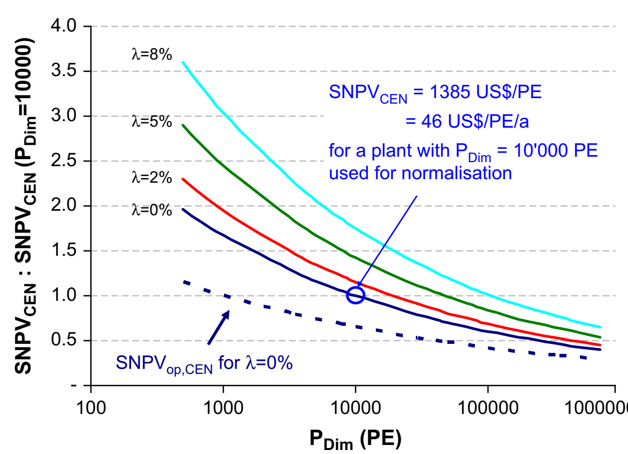

Fig. 5 – The dependency of SNPV on plant size and growth rates λ (life-span $T_D = 30$ a). The numbers are relative to the cost of a plant with $P_{Dim} = 10{,}000$ PE and no growth (λ = 0.0). The value for Switzerland is: $SNPV_{CEN} = 1385$ US\$ PE^{-1} = 46 US\$ PE^{-1} a^{-1}; see Tables 1 and 2 for the economy of scale parameters applied; no interest rates (r = 0.0). Purchasing power parity conversion factor US\$:CHF = 0.60, German€:CHF = 0.52 (OECD, 2008). Additionally, the specific operating cost for the zero-growth case is shown by the dotted line.

apparent: smaller systems have substantial higher SNPV, and high growth rates have an over-proportional effect on smaller systems and emphasise the first effect described. This shows very clearly that the rate of demand growth has a similar effect on costs as the economy of scale. Fig. 5 also shows that the entry markets for OST systems are most probably small systems with high growth rates. Detailed economic evaluations may be performed with the help of Eq. (27). A more detailed discussion can be found below (Sections 6 and 7).

Fig. 5 assumes no interests on the investment costs. Inclusion of an interest rate in the calculations has a stronger effect on high growth rates. The effect of an interest rate on the lines in Fig. 5 is consequently to increase the spread between the curves with different growth rates (data not shown), stressing the effect of high growth rates even more. This intensifying effect of the interest rate on the growth rate also can be seen in Fig. 4.

5.1.3. *Case 1C: example of a membrane-based OST wastewater system*

A comparison of the current cost estimate for OST plants can give some valuable insights and show the usefulness of the results developed in case 1B. Fletcher et al. (2007) evaluated the capital and operating costs associated with a small package membrane bioreactor (MBR). This type of treatment promises a range of advantages over conventional wastewater treatment (Stephenson et al., 2000; Abegglen et al., 2008). The capex of such on-site high-end MBRs are expected to be between US$742 and US$1009 per population equivalent (€645–€877; US$: German€ = 1.15; year 2006, OECD, 2008) for small units (5 PE) and US$296–US$614 (€257–€534) for larger plants (200 PE). The average lifespan was estimated to be 13.8 years.

Figs. 6 and 7 show the same results as Fig. 5 but divided into capex (Fig. 6) and opex (Fig. 7). The capex and opex of the small-scale MBRs (5 PE) were additionally integrated as $SNPV_{cap,OST}$ and $SNPV_{op,OST}$, using the lower-end figures found

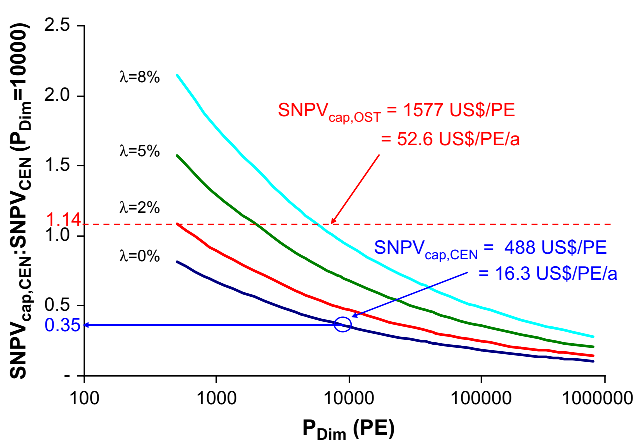

Fig. 6 – Comparison of capex for small-scale MBRs (€645 PE^{-1}) with centralised systems. The numbers are relative to the cost of a plant with P_{Dim} = 10,000 PE and no growth (λ = 0.0). The value for Switzerland is: $SNPV_{CEN}$ = 1577 US$, PE^{-1} = 52.6 US$ PE^{-1} a^{-1}; see Tables 1 and 2 for the economy of scale parameters applied; no interest rates (r = 0.0). Purchasing power parity conversion factor US$:CHF = 0.60, German€:CHF = 0.52 (OECD, 2008).

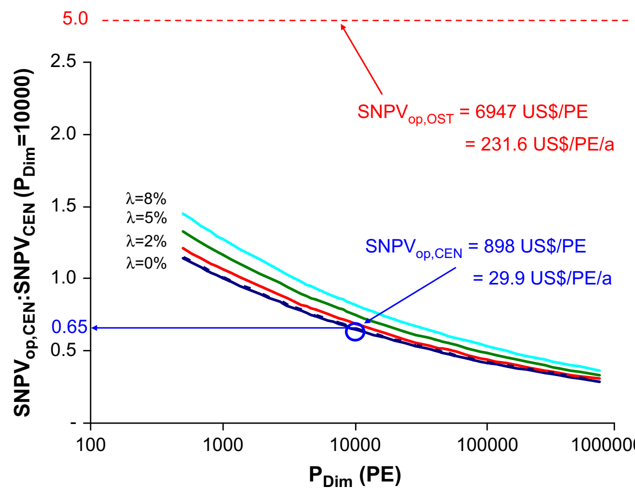

Fig. 7 – Comparison of opex for small-scale MBRs (€206 PE^{-1} a^{-1}) with centralised systems. See caption of Fig. 6 for more details and conversion rate used.

in the paper (Fletcher et al., 2007). Fig. 7 indicates on the basis of the capex that OST systems may be competitive in smaller systems with high growth rates. However, Fig. 7 shows very clearly on the basis of current opex estimates that MBR based OST systems are economically only viable in places where they can replace extremely costly sewerage. This analysis shows clearly what technological developments MBR-OST systems need to focus on in order to be competitive.

5.2. *Example 2: staged expansion*

Fig. 2 shows explicitly that the utilisation for a single-stage treatment plant in communities with high growth rates is really low and the average costs are consequently high. Another way of avoiding this (apart from using OST) is to stage the construction of the treatment plant and upgrade it over time in line with the required capacity (modularisation). Staged service provision generally has a higher capex because the plant will be unable to profit as much from the economy of scale as a single-staged plant. Thus construction work has to be commissioned for each stage, or additional provisions are needed to upgrade the plant, with corresponding extra costs. Modularisation reduces the idle capacity of the plant and must therefore be worth something. The following calculations will explore the maximum permissible capex of this modularisation in quantitative terms.

For the calculations, it is assumed that the operating costs are strictly proportional to the load (see Eq. (8)), so that they can be neglected in a direct comparison. The modularisation is implemented in equal performance steps over the planning horizon. Fig. 8 shows an example of a performance increase in four stages; all the increases on the ordinate are equally spaced whereas the times on the abscissa decrease for every successive stage due to the exponential growth function.

Fig. 8 also shows that the staged approach has a much higher plant utilisation than a single stage. This can be used to calculate the increase in capex for the staged version of the plant. Analogously to Eq. (18), the SNPV can be calculated with

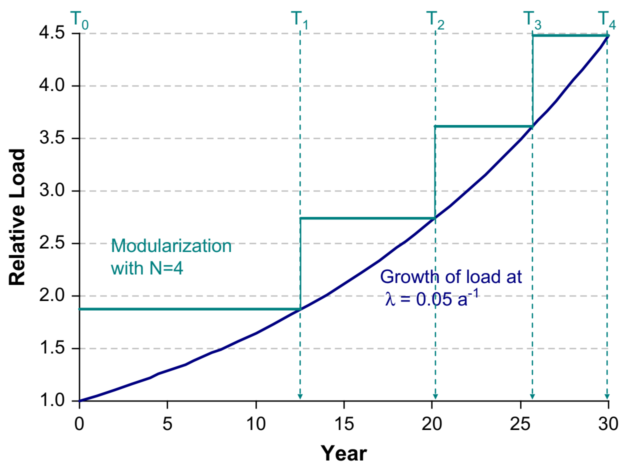

Fig. 8 – Example of the underlying modularisation approach.

$$SNPV_{cap,N} = \frac{I_N}{PU_N} \cdot \frac{a \cdot T_P}{P_{Dim}} \tag{28}$$

where I = capex, PU = plant utilisation, a = annuity (see Eq. (3)), T_P = planning horizon, P_{Dim} = installed capacity in population equivalents (PE), and the subscript N denotes the number of stages (see also Fig. 8 for an example).

On the basis of these assumptions, the staged version of the plant should have lower or equal costs:

$$SNPV_{cap,N} \le SNPV_{cap,1} \tag{29}$$

$$\frac{I_N}{PU_N} \cdot \frac{a \cdot T_P}{P_{Dim}} \le \frac{I_1}{PU_1} \cdot \frac{a \cdot T_P}{P_{Dim}} \tag{30}$$

$$\frac{I_N}{I_1} \le \frac{PU_N}{PU_1} \tag{31}$$

The plant utilisation PU_N can be derived from Eq. (12):

$$PU_N = \sum_{n=1}^{N} \frac{1 - e^{-\lambda(T_n - T_{n-1})}}{\lambda(T_n - T_{n-1})} \tag{32}$$

The implementation times T_n for the individual stages can be calculated with

$$T_n = \frac{1}{\lambda} \ln\left[1 + n\frac{P_{Dim} - P_0}{N \cdot P_0}\right] \tag{33}$$

where PU = plant utilisation, P_{Dim} = installed capacity in population equivalents (PE), P_0 = load at time 0 in PE, λ = growth rate of the load (a^{-1}), and the subscript N denotes the number of stages (see also Fig. 8 for an example).

A graphic example of T_n is given in Fig. 8. Fig. 9 is a graphic representation of Eq. (31) showing how much higher the investments for the modularised alternative can be for different growth rates. More stages mean that the overall plant utilisation is better and greater investments can be made in delivering treatment performance.

Fig. 9 again makes it very clear that the expected growth rate has a substantial impact on the economically viable cost for modularisation and therefore has a similar effect on the average cost as the economy of scale.

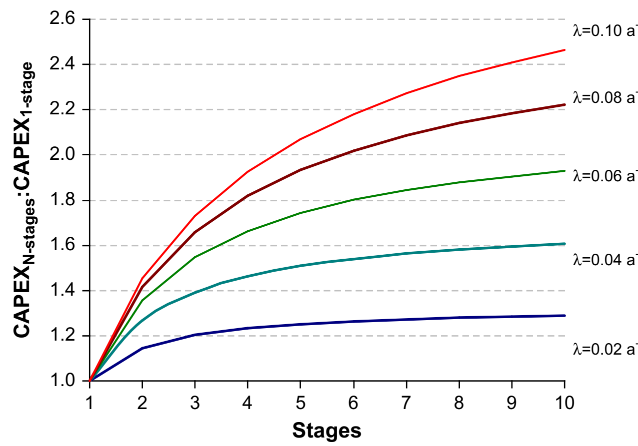

Fig. 9 – Graphic representation of Eq. (31) showing how much higher the investments for the modularised alternative can be for different stages and different growth rates (λ). The area below each curve indicates which capex would be economically favourable for modularisation.

It is important to keep in mind that the results in Fig. 9 (and correspondingly Eqs. (31)–(33)) do not contain two important factors: (i) the interest gained by delaying part of the investment until the future (the approach assumes that all funds are reserved at time = 0), and (ii) the useful life of the stages implemented later, which may not end at the planning horizon, depending on the technology chosen for modularisation. Both factors favour modularisation and would therefore shift the lines in Fig. 9 up. This means that the conclusions drawn from the simplified approach will be still valid and can be viewed as a conservative assessment. If more comprehensive calculations with more specific numbers are needed, it would be easy to adapt the SNPV approach presented here.

6. Discussion

6.1. *Specific net present value (SNPV) evaluation*

The definition of the specific net present value (SNPV) corresponds to the present value of the sum of all average costs over the planning horizon. This paper argues for the use of the SNPV in an economic engineering analysis of water and wastewater plants. Two examples highlight the strength of this approach.

In many water companies, the price charged to the customers is commonly based on the fully distributed costs, usually calculated from the total capital, operating and maintenance costs. Not having a cost independent price for water services cripples the information value of the NPV substantially. The SNPV is aimed to resolve this deficiency. To minimise the overall cost to the consumer, it is better to minimise the SNPV than the NPV. This paper shows clearly that the SNPV approach is more appropriate in situations with rapid demand growth. SNPV allows average costs to be minimised, thus balancing the benefits of economy of scale with the additional costs of demand growth. The cases presented here show that, in a demand growth situation, the SNPV may well favour a modular system with higher NPV costs.

It is worth mentioning that the SNPV as defined in Eq. (13) does not depend on the exponential growth introduced in Eq. (4). This growth approach was used to create algebraic solutions for this manuscript. Any growth scenario can be introduced and applied to real-life calculations. Similarly, the approach can easily be expanded to use more differentiated depreciation models. The general term for calculating the SNPV (Eq. (13)) does not depend on a specific depreciation model or on a specific lifespan approach. The simplified approach used in Eqs. (2) and (3) is used for illustrative purposes only.

The use of SNPV is not limited to water and wastewater treatment plants, but also applies to all investment decisions for public services where the price is set on the basis of fully distributed or average costs.[1] Alternatively, the price could be set on the basis of the marginal cost, which is by definition lower than the average costs for natural monopolies. Economists argue that short-run marginal cost pricing produces ''an optimum allocation of resources [...] (even though this may involve a subsidy in the case of decreasing-cost industries)'' (Vickrey, 1948, 1987; Hotelling, 1938). The SNPV approach developed in this paper is no longer useful in this case because the investments are decoupled from the growth of demand.

6.2. *Cost comparison for on-site and centralised treatment plants*

Pure on-site treatment (OST) systems do not currently represent competitive alternatives to centralised water treatment plants. However, recent developments in material and communication technology indicate that this situation may well change in the near future (Green and Ho, 2005; Adler, 2007; Tadkaew et al., 2007; Abegglen et al., 2008). The results of this paper help to identify criteria for the conditions under which on-site treatment plants could be a financially viable alternative.

It is important to highlight that these examples are by no means provide a comprehensive comparison of on-site with centralised systems. In all calculations it is assumed that the conveyance systems are identical and that the overall performance of the entire system remains constant without going into details what this entails for the single plants. Therefore, the presented results are a kind of an economic 'worst case', where novel treatment concepts are integrated into an existing system without additional benefits from other system adaptation.

Fig. 4 shows clearly that in established towns with an efficient transportation network, the investment cost of an OST system must be substantially lower than for a comparable centralised plant. Even under favourable conditions with real interest rates at 3%, a long lifespan (15 a) and similar operation and maintenance costs for OST plants, their construction costs must be at least 40% lower than for comparable centralised plants. The level of these costs can be estimated from Fig. 5, which shows the strong influence of system size. Two immediate conclusions are apparent: (i) smaller systems have substantially higher SNPV costs, and (ii) high growth rates have an over-proportional effect on smaller systems and emphasise the effect described in (i). This indicates that small systems with high demand growth rates – thus combining the effects of growth and economy of scale – may well be a good entry market for OST systems.

By combining the information in Figs. 4 and 5, the following conclusions may be drawn:

- The most probable entry markets for OST water treatment systems are small systems with projected high rates of demand growth.
- Changes in the conveyance system that lead to lower costs due to the implementation of OST plants lower the economic barrier for their implementation. Examples are local water reuse, infiltration, and open-channel transportation. Fast-growing systems without an existing transport infrastructure as well as those with high rehabilitation demand represent other favourable entry markets.
- High (real) interest rates favour OST systems, especially in high-growth situations.
- From Figs. 6 and 7 it can also be concluded that operating expenses clearly represent the current economic weakness of membrane-based wastewater OST systems.

The examples with OST systems show the strength of the SNPV approach in the economic comparison of alternatives with different abilities to adapt to growing demands. This key strength of OST systems is not reflected in the traditional NPV approach, due to the missing consideration of revenues. The SNPV therefore is a strong parameter to characterise transition options in sustainable water system research.

6.3. *Modularisation*

The SNPV introduced here can be used to estimate the additional capex for the staged expansion of a treatment plant. Fig. 9 nicely summarises the main results of these calculations. At low projected rates of demand growth ($<0.02\ a^{-1}$), a modularised project should involve less than 20% additional capex compared to the single-stage alternative. For fast-growing situations, this additional cost can be substantially higher and even reach 100%. It is worth mentioning that these results are independent of the size of the project and the estimates made are relatively conservative.

Fig. 9 can also help to identify the optimal number of stages in a real case by adding the real relative costs of a staged alternative to the graph. The greatest difference between this projected line and the actual curve indicates the optimal number of stages.

6.4. *Growth rate*

One of the interesting results of this study is that demand growth has a similar effect on average costs to economy of scale. High growth rates lead to low plant utilisation (PU). The higher the growth, the smaller PU becomes – with direct consequences for the number of customers sharing the capex of a plant. So far, this factor has not been explicitly included in typical economic engineering decisions made for treatment plants in the water sector. This paper argues that because the SNPV approach considers plant utilisation, it therefore

[1] Not to be confused with the rates and the structure of how they are charged to the customers. This paper is about the overall cost of the service and not about how these costs are collected from the customers.

represents the appropriate criterion to be used in engineering economic decisions for water services.

7. Conclusions

- The SNPV approach is more appropriate in situations with rapid demand growth. SNPV allows average costs to be minimised, thus balancing the benefits of economy of scale with the additional costs of demand growth.
- In a demand growth situation, the SNPV approach may well favour a modular system with higher NPV costs but better abilities to adapt to growing demand.
- The most probable entry markets for OST water treatment systems are small systems with projected high rates of demand growth.
- Ways of implementing alternative transport systems that could benefit from OST plants could lower the barrier for their implementation. Fast-growing systems without an existing transport infrastructure as well as those with high rehabilitation demand represent therefore potential favourable entry markets.
- High (real) interest rates favour OST systems, especially in high-growth situations.
- The example shows that operating expenses clearly represent the current economic weakness of membrane-based wastewater OST systems.
- The SNPV introduced here can be used to estimate the additional capex for the staged expansion of a treatment plant. Depending on the projected rates of demand growth, a modularised project could involve between 20% and 100% additional capex compared to the single-stage alternative. These results are independent of the size of the project and the estimates made are relatively conservative.
- Demand growth has a similar effect on average costs as economy of scale.
- This paper argues that because the SNPV approach considers plant utilisation, it therefore represents the appropriate criterion to be used in engineering economic decisions for water services.

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