Project acronym:	AMEDEUS
Project full title:	Accelerate Membrane Development for Urban Sewage Purification
Proposal/Contract no.:	018328 AMEDEUS
Duration:	Oct. 2005 – Sept. 2008

WP6: IMPLEMENTATION OF SUBMERGED MODULE INSIDE OR OUTSIDE OF REACTOR

D38: FINAL REPORT – MONTH 30

Authors

Heleen De Wever	VITO
Matthew Brannock	UNSW

Report delivery date
May 15th 2008

Quality Management

	Name	Company	Date
Final edition	H. De Wever	VITO	May 15th 2008
1st control	M. Brannock	UNSW	June 5th 2008
2nd control	B. Lesjean	KWB	June 10th 2008

SIXTH FRAMEWORK PROGRAMME
Priority 1.1.6.3
"GLOBAL CHANGE AND ECOSYSTEMS"

SPECIFIC TARGETED RESEARCH PROJECT

Table of contents

1 Introduction

Work Package 6 of the AMEDEUS project aims to evaluate two implementations of submerged MBR modules:

- the inside configuration in which the membrane modules are set up directly in the aerated biological tank
- the outside configuration in which they are submerged in a separate tank which is dedicated to filtration only.

This deliverable report describes the main outcomes of this work package, which only looked at municipal wastewater applications and particularly considered investigations at pilot- and full-scale.

2 Alternative submerged MBR configurations

In the outside configuration (see Figure 1), membrane modules are placed outside the bioreactor. A pump circulates the mixed liquor from the bioreactor to the membrane module or back at a flow rate of 100 to 500% of the influent flow. In the inside configuration (Figure 1), membrane modules are immersed directly into the bioreactor.

In principle, the inside configuration approaches a continuous stirred tank reactor, whereas the outside configuration is marginally closer to a plug flow system due to the occurrence of a separate bioreactor and filtration compartment. This however can not be generalized since the flow regime depends to a large extent on the membrane configuration, the flow distribution, the aeration system, etc.

In an outside submerged configuration, the membrane filtration tank constitutes an extra biological compartment which contributes to the biological transformation processes.

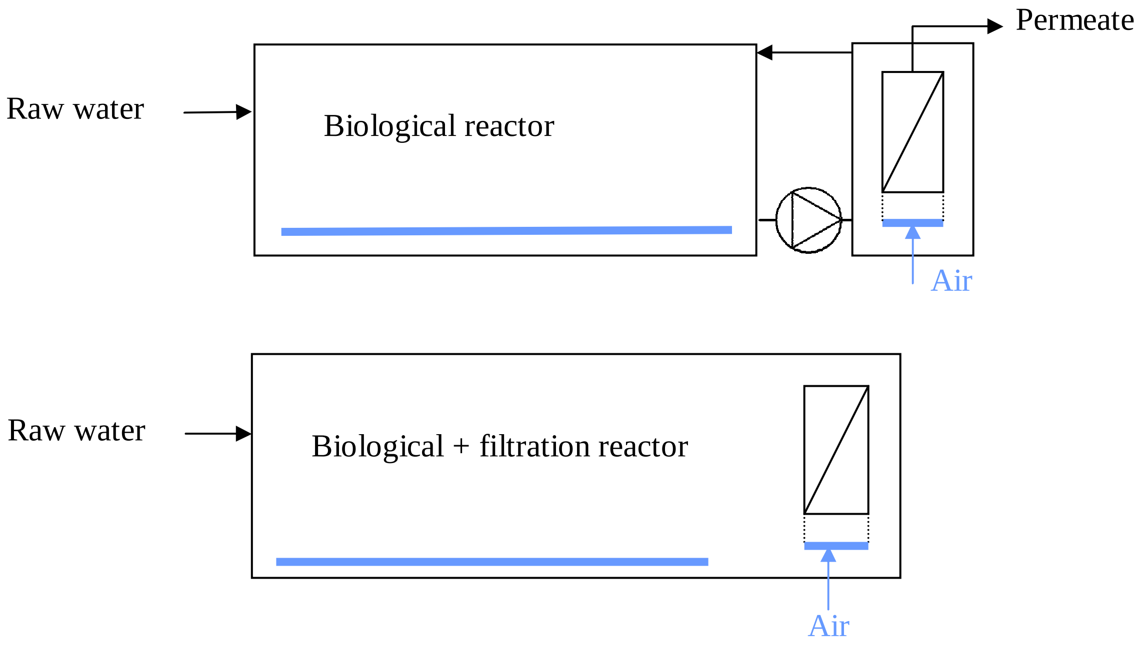

Figure 1: Conceptual representation of outside (top) and inside (bottom) configuration.

The main difference in design of an inside and outside submerged MBR is therefore the presence of an extra pump to recirculate the mixed liquor between the bioreactor and the membrane filtration tank and compartmentalization through a separate filtration tank.

3 Trends in selected configuration (Europe only)

To analyse trends in submerged MBR design, VITO compiled data on full-scale municipal submerged MBR installations which have been commissioned in Europe between 1996 and 2006. Starting from an overview available on www.waterforum.net, a list of 98 plants was obtained. For 54 of these, a clear indication on the presence or absence of a separate filtration tank could be found, with a majority of 63% inside MBRs. Membranes were from 8 different suppliers. Of the 54 plants, 25 had hollow fibre membranes and 29 flat sheet membranes, Twenty-nine MBR plants were the result of a retrofit and 28 had at least an anoxic zone to allow for nutrient removal.

Figure 2 shows how the submerged MBR configuration evolved over the past decade. Up until 2001, municipal MBRs (except one) did not have a separate membrane filtration tank, whereas this feature quickly became preferential from 2005 onwards.

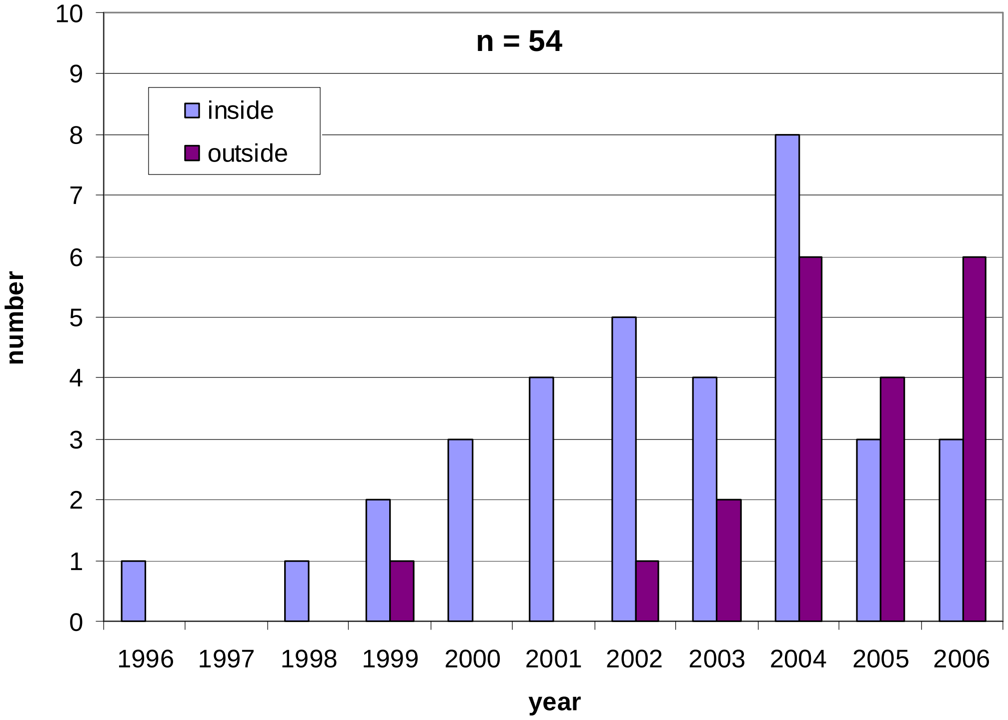

Figure 2: Evolution in inside and outside submerged MBRs in time. n = number of plants

The choice for an inside or outside MBR configuration also depends on the membrane supplier. Kubota strongly favors an inside lay-out, whereas GE (Zenon) has a slight preference for the outside lay-out. For the other membrane suppliers, the number of municipal installations is too limited to be able to draw conclusions. When all flat sheet membrane suppliers are considered, 23 out of 29 full-scale installations are configured without a separate filtration tank. For the hollow fibre membrane suppliers, only 11 out of 25 MBRs were designed as such. This dependence on membrane configuration is most probably related to the membrane and module compactness. Flat sheet membranes are characterized by much lower packing densities. An additional filtration tank would strongly decrease the MBR compactness and is therefore less desirable.

When the compiled MBR installations were divided in three capacity ranges at cut-off values of 25 and 200 m³/h, plants below 200 m³/h (4.8 Ml/d) usually had an inside configuration whereas the largest ones preferentially had an outside one.

An additional distinction between plants can be made based on whether or not they were retrofits or newly constructed. In either case, the majority of plants did not have a separate filtration tank. This is conflicting with the observations of Lesjean et al. (2008) who described a preference for the outside configuration in retrofitted (large) MBRs. The larger number of inside configurations in the retrofitted

MBRs found in our analysis, is probably due to the fact that the Kubota MBRs, which usually have an inside configuration, outnumbered the other ones.
The requirement of nutrient removal may also affect the MBR configuration. Figure 3 clearly indicates that systems which only have to achieve C removal, do not have a separate filtration tank. It needs to be emphasized though that most of these installations were equipped with Kubota membranes which strongly affects the selected configuration.

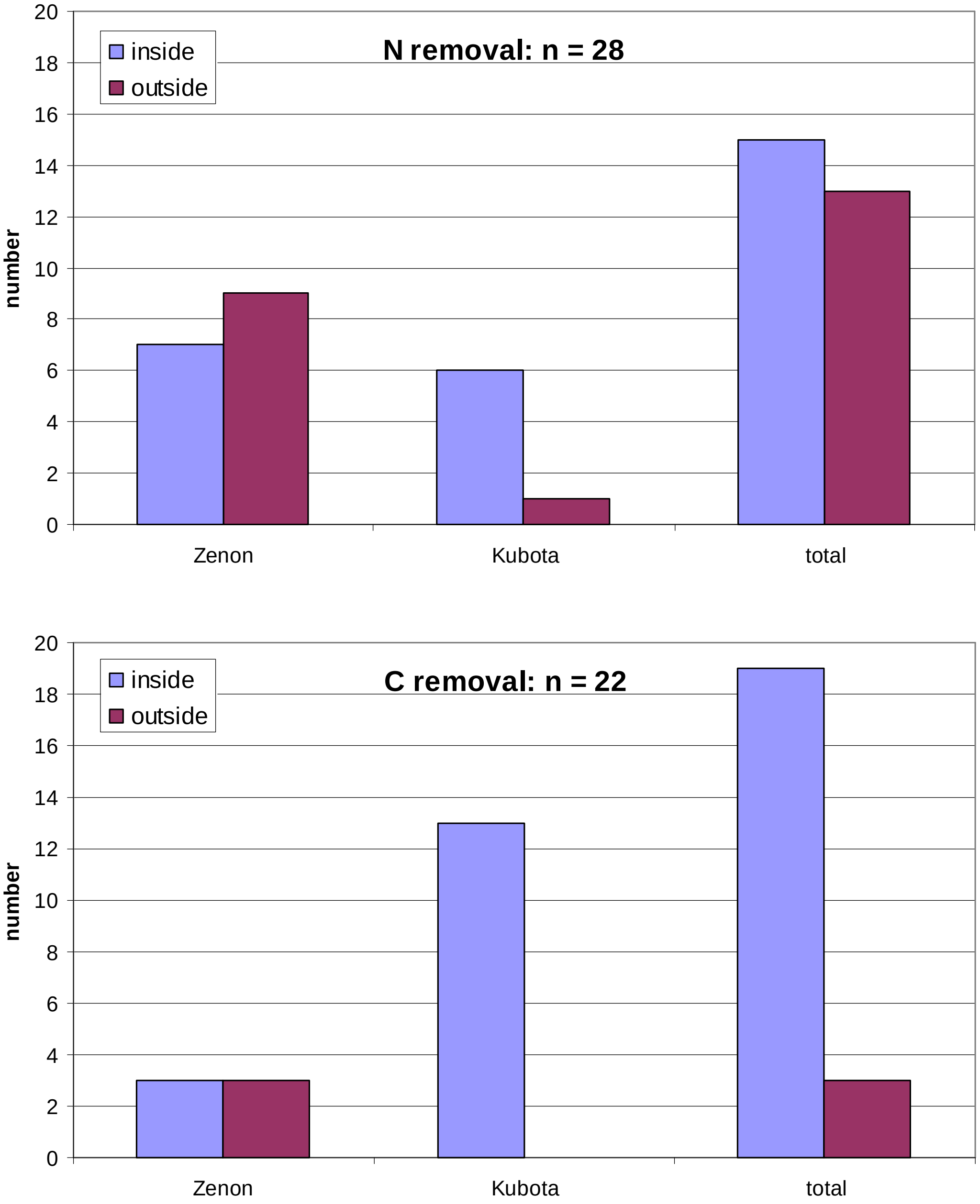

Figure 3: Submerged MBR configuration in relation to requirement for N removal. n = number of plants

It can be concluded from our data that outside submerged MBRs appeared later in time but quickly became the favored MBR design for municipal plants in Europe. The inside configuration is however strongly preferred for smaller plants, for flat sheet membrane applications or for systems where only C removal needs to be achieved.

4 Claimed advantages/disadvantages of both configurations

In literature several advantages and disadvantages are claimed for the inside and outside submerged MBR configurations.

With separate membrane tanks, the membrane module can easily be separated from the biomass and is easily accessible for inspection, maintenance or cleaning interventions. A report on www.waterforum.net cites Philip Schyns who indicates that membrane cleaning is easier, because the smaller separate tanks can be emptied much faster than the larger aeration tanks. Particularly at high cleaning frequencies, this leads to reductions in energy, time and resources. In addition, the outside layout allows improved chemical cleaning (Wedi and Joss, 2007).

Furthermore, membrane fouling in outside submerged MBRs is lower. On the one hand, this is related to the fact that hydraulics and fluid dynamics can be independently optimized in the separate filtration tank. Sludge distribution in the vicinity of the modules can for instance be better controlled (Lesjean et al., 2008). On the other hand, the biological system can be separately optimized. Sludge quality can be influenced through adjustments in process conditions and this may lead to a reduced fouling potential. Apparently, the recirculation pump is not expected to adversely affect sludge quality. Finally, direct contact between the influent and the membranes is avoided, which is beneficial in terms of fouling.

Separate membrane filtration tanks also allow for extra control on clogging. Frechen et al. (2007) described how braids can be formed in highly turbulent zones in the bioreactor, even after proper pretreatment. In an outside MBR, the formed braids can be removed before they reach the membranes through additional sieving of the sludge mixture between the bioreactor and the filtration tank.

A separate filtration tank leads to cascading, and as such may affect the sludge distribution in the system. Since the sludge concentration in the vicinity of the membranes should not exceed 18 g/l or on the long term 12-15 g/l (Brepols et al., 2005), the concentration in the bioreactor will typically be lower. The solids mass balances will depend on the applied recirculation rate and tank volumes.

The outside submerged MBR configuration is said to yield better effluent qualities. First, this is related to the hydraulic retention times (HRT) which determine the achievable effluent concentrations. Since outside submerged MBRs usually have lower MLSS concentrations, their specific volume is larger (Brepols et al., 2005) and this increases their hydraulic buffer capacity. Second, this is attributed to the fact that the separate filtration tank leads to cascading of the total reactor volume, which makes this type of configuration less susceptible to strong fluctuations in feed flow or loading conditions (Brepols et al., 2005; Lesjean et al., 2008). However, a small membrane chamber will only allow limited peak load equalization. In this case, sufficient nitrification will have to be achieved before the influent enters the membrane chamber (Wedi and Joss, 2007).

Particularly when stringent nutrient discharge norms have to be reached, MBRs with a separate filtration tank are recommended (Brepols et al., 2005; Lesjean et al., 2008). This is not only due to their larger buffering capacity, but also due to the possibility to more easily optimize denitrification. Recycle of the sludge from the filtration to the aerobic tank can indeed be separated from the recirculation from the aerobic to the anoxic tank and this avoids the introduction of near saturated oxygen levels in the anoxic tank. Mulder also indicates that an effluent quality of < 2.2 mg/l N (MTR or maximal allowable risk level in the Netherlands) can only be achieved with separate tanks because denitrification can be better controlled (www.waterforum.net).

For retrofitted installations, an outside configuration may be advantageous for 2 reasons. Existing tanks from a conventional activated sludge system may not have the proper dimensions for the filtration systems which necessitates the construction of separate tanks. Additionally, the construction of an extra filtration tank may not interfere with the operation of the existing treatment plant.

The use of a separate tank evidently results in a larger footprint than for the integrated concept.

Outside submerged MBRs show a higher operational flexibility when operating in several parallel lanes. As stated by Brow (2007), one aeration tank can be isolated and flow may continue from the remaining aeration lanes to all filtration tanks. In an inside layout, both the biological capacity of the tank and the hydraulic capacity of the membranes in that lane would not be available.

Investment costs for an outside configuration are evidently larger than for an inside one due to the costs for construction of extra tanks and for recirculation pumps.
Operational costs mainly relate to aeration for membrane scouring and pumping to recirculate the mixed liquor to the filtration tank. However, even for inside MBRs, sludge recirculation to the head tank is applied to avoid sludge accumulation near the membranes. The increase in pumping energy for the outside configuration may however be offset by the decrease in fouling and cleaning actions. While the coarse bubble aeration directly contributes to oxygen supply in inside submerged MBRs, this is much less the case for the outside set up. One may therefore expect that the costs for oxygen supply will be higher in the outside configuration. Tao et al. (2005) indeed noticed the lowest air to permeate ratio for the MBR pilot which combined aeration and membrane tank in one (Table 1).

Table 1: Comparison of air/permeate ratio for three MBR pilots operated in parallel (after Tao et al., 2005)

	baseline	Phase 1	Phase 2
MBR A (outside)	50	34	28
MBR B (inside)	24	21	16
MBR C (outside)	30	25	20

For three 75 m³ pilots, Tao et al. (2005) also observed that energy consumption was at least 8% lower in the inside plant (Table 2). A comparison of energy consumption for full-scale plants shows that the ranges are fairly similar (see also 8). Where Erftverband claims energy consumptions of 0.8 kWh/m³ for the inside MBR in Nordkanal (Germany), the outside Varsseveld MBR (The Netherlands) has a yearly average of 0.88 kWh/m³ which can probably be further reduced to 0.75 kWh/m³ through further optimization (van Bentem et al., 2007).

Table 2: Comparison of energy consumption (kWh/m³) for three MBR pilots operated in parallel under 3 different conditions (after Tao et al., 2005)

	baseline	higher flux	lower air consumption
MBR A (outside)	1.4	1.2	1.0
MBR B (inside)	1.3	1.0	0.8
MBR C (outside)	1.7	1.3	1.1

5 Comparative trials

Several comparative pilot trials have been or are being performed. The ones which compared inside and outside submerged MBR configurations at the same location are

- Escondido and San Diego in California: in most test phases, an inside and outside pilot of different suppliers were operated in parallel. Parallel systems typically showed rather similar biological treatment efficiencies. With respect to membrane performance, Adham et al. (2004) concluded that each MBR system showed the ability to run for 75 d between membrane cleanings with a minimum to moderate increase in transmembrane pressure (TMP). It is noteworthy that only the two inside submerged MBR configurations showed foaming after chemical cleaning. Because cleaning was performed in-line for both systems, the chemicals came in direct contact with the activated sludge and this resulted in foaming. Judd (2006) also remarked that the total specific aeration demands (m³ total air/m³ permeate) were similar for all technologies operating without anoxic zone. Therefore, the aeration requirements do not seem to depend on MBR configuration.

- Bedok in Singapore: 1 inside and 2 outside MBR pilots were tested in parallel. All units produced comparable effluent qualities. Sludge production was found to be similar as well. Tao et al. (2005) noted that the air/permeate ratio (see also Table 1) and the energy consumption were always lowest in MBR B which had the inside configuration. With the available information, no conclusions can be drawn on differences in membrane fouling related to configuration (Judd, 2006).
- Hawaii: 5 MBRs with or without separate membrane tanks are being tested in parallel (Babcock et al., 2005; http://www.watereuse.org/ca/2005conf/papers/A2_rbabcock.pdf). The authors state that water quality differences among the units are negligible. The discussion mainly addresses supplier specific differences and does not mention any impact of inside or outside configuration.

6 Expert opinions

Literature information was complemented with the experience of MBR operators and suppliers, through interviews with selected experts. To this end, a questionnaire was developed which asked for expert opinion on the following issues:

- differences in design of inside and outside submerged configurations
- reasons to choose for one or the other configuration
- parameters which determine the choice for either configuration
- expected differences in biological or membrane performance, sludge characteristics and costs.

Feedback was received from 9 end-users and operators, as well as from 2 hollow fibre membrane suppliers.

Design of submerged MBRs

The experts indicated that inside and outside submerged MBRs differ in more aspects than just the compartmentalization and the presence of an extra pump between the bioreactor and the filtration tank. The systems are characterized by different MLSS mass balances, sludge hydrodynamics, hydraulics, handling of membranes, possible cleaning strategies, size of membrane compartments, external forces on membrane modules and cassettes, as well as by more flexible operation of the biological process and the need for extra aeration capacity in the membrane tanks for air scouring. The extra filtration tank may require additional instrumentation to monitor processes in both tanks.

It was further indicated that an extra filtration chamber is an unavoidable choice when the biological process is alternating between aerobic and anoxic conditions. Additionally, since membrane modules with high packing densities always require pumping to remove the accumulating sludge, there is no advantage in not providing a separate filtration tank. Finally, some module designs such as the US Filter one, require an outside set up.

Whether or not the filtration tank of an outside MBR should be included in the design of the bioreactor, is not so clear. Four out of 11 respondents said it is not included in the design. It may therefore provide an extra safety but may also lead to too safe oversizing of the biological process volume. Other respondents indicated that the membrane tank should be considered as it represents a large biological volume. For enhanced biological nutrient removal however, all biological mechanisms should occur before the filtration tank. One expert stated that the more stringent the discharge norms are, the less the membrane volume should be taken into account.

In an outside submerged MBR, it is preferable to pump the mixed liquor to the filtration compartment with an overflow back to the biology and to have a weir overflow in the tank to avoid trapping of foam or floating debris. This also prevents accidental draining of the tank. However, an accumulation of grit on the bottom of the filtration chamber is possible which can clog the aeration system.

Performance of biological system

The experts were asked to indicate which treatment, fouling or cost related parameters determined the choice for either submerged MBR configuration. Figure 4 shows the results for the performance or treatment related parameters. End-users and suppliers agreed that influent quality and COD effluent quality are of minor importance when it comes to selecting an inside or outside system. Parameters which are considered when choosing the final layout, were size, the need for nutrient removal, nutrient effluent quality and treatment efficiency.

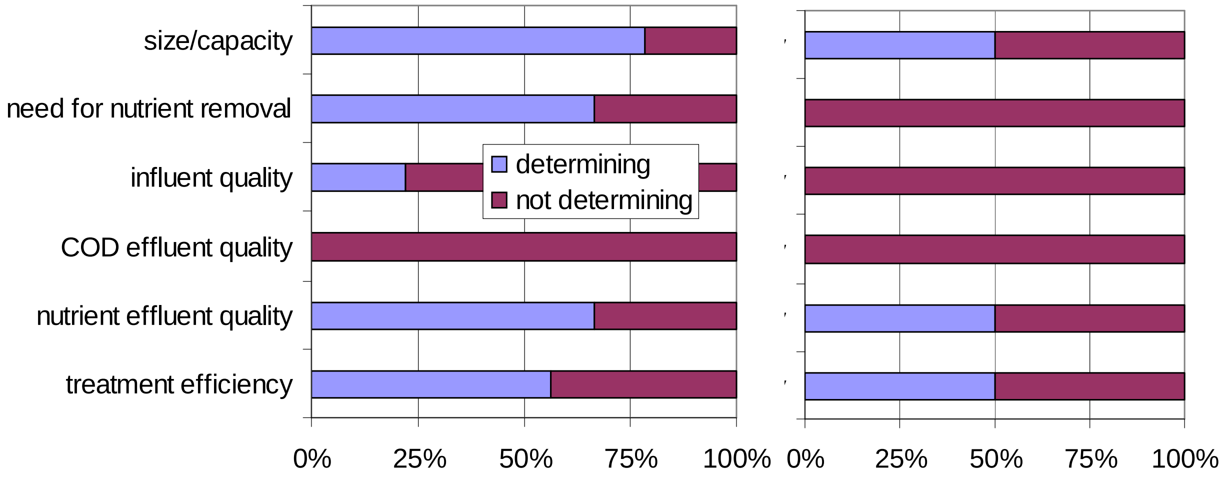

Figure 4: Importance of treatment related parameters towards choice of submerged MBR configuration according to 9 MBR operators/end-users (left) and 2 suppliers (right).

On the other hand, the interviewees were also asked whether they noticed a difference in treatment efficiency or effluent quality between the two configurations (Figure 5). One out of two suppliers thought there could be an effect on treatment efficiency. This was conform the experience of the end-users, who also expected a difference in effluent quality for nutrients.

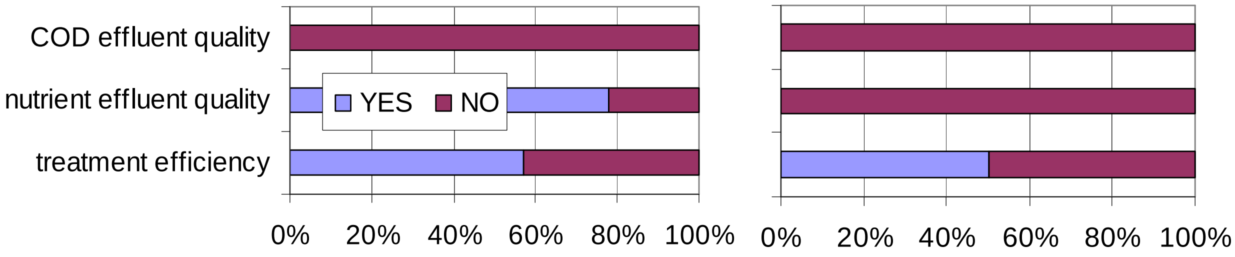

Figure 5: Treatment related parameters which may differ between submerged MBR configuration according to 9 MBR operators/end-users (left) and 2 suppliers (right).

Performance of membrane filtration system

Fouling related parameters were clearly very important in the choice for a submerged MBR configuration (Figure 6). End-users and suppliers agreed that the level of flexibility to operate biology and membranes, ease of access to the membranes, flexibility in cleaning and the risk of contact between chemicals and sludge are all favoring an outside configuration. Whereas the hollow fiber MBR suppliers did not think aspects such as short circuiting, fouling susceptibility, expected cleaning frequency, foaming and dead zones played a role, the end-users and operators considered this differently. The inside MBR layout is more appropriate when low to medium flexibility in biological and membrane operation and a low to medium frequency and flexibility in chemical cleaning suffices. Otherwise, an outside layout is preferential.

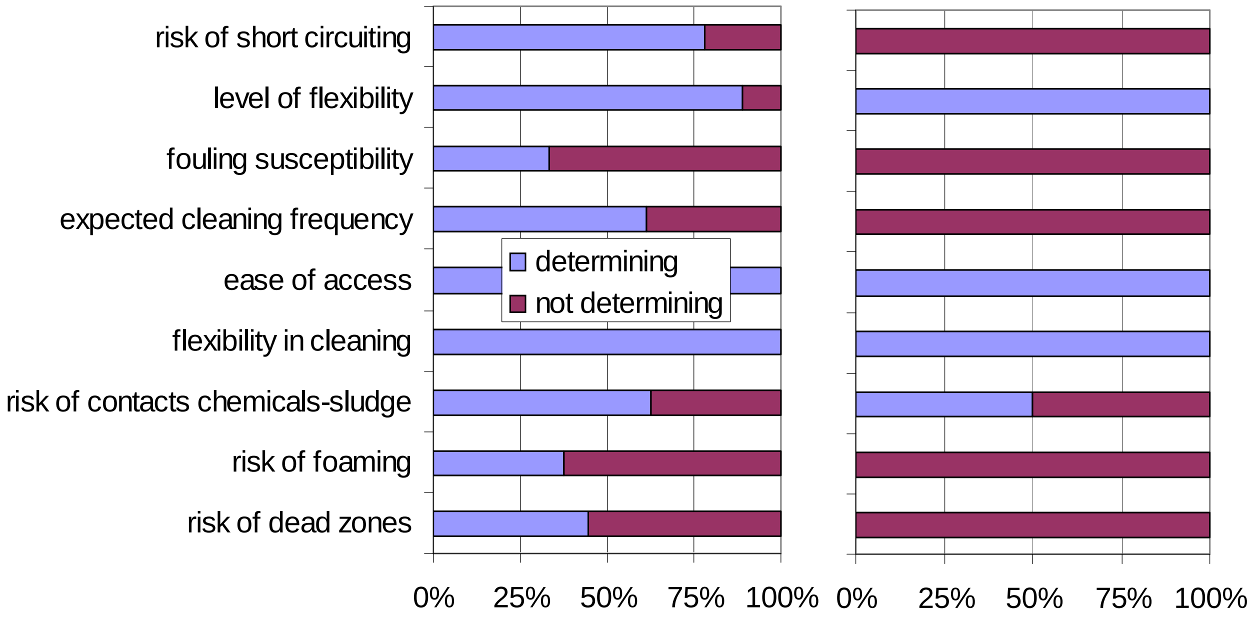

Figure 6: Importance of fouling related parameters towards choice of submerged MBR configuration according to 9 MBR operators/end-users (left) and 2 suppliers (right).

The hollow fiber MBR suppliers did not expect or had never noticed a difference in fouling related parameters between both MBR configurations. The end-users however, did observe differences mainly in dead zones, clogging, fouling behaviour and frequency of intensive clean (Figure 7).

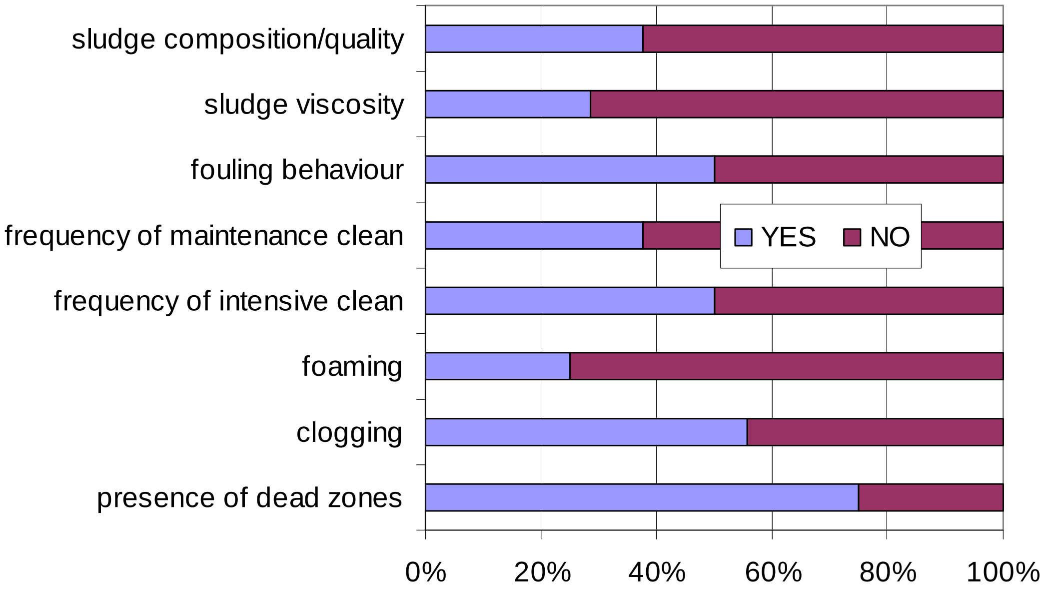

Figure 7: Fouling related parameters which may differ between submerged MBR configuration according to 9 MBR operators/end-users.

Costs of inside and outside submerged MBRs

As opposed to the MBR suppliers, the operators concluded that cost related aspects are important when choosing the plant layout (Figure 8). Outside configurations are perceived to have higher investment and operational costs. End-users and suppliers agreed that aeration requirements, energy consumption and maintenance differ between inside and outside layouts.

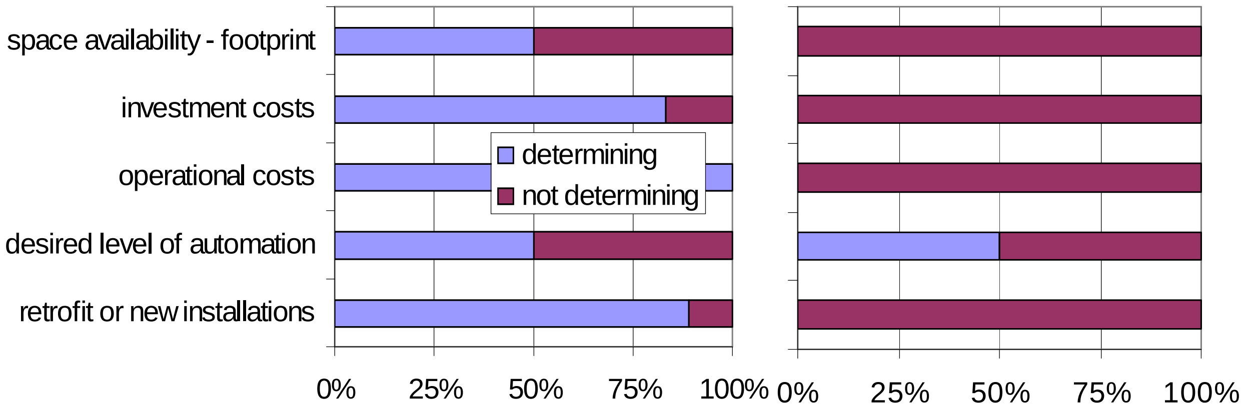

Figure 8: Cost related parameters which may determine the choice for a submerged MBR configuration according to 9 MBR operators/end-users (left) and 2 suppliers (right).

7 CFD simulations

MBRs are designed mainly based on biokinetic and membrane fouling considerations even though the hydrodynamics within an MBR system is of critical importance to the performance of the system. Consequently, the effect of the flow regime in the MBR process unit has been an insufficiently understood aspect of MBR design. Current methods of design for a desired flow regime within the MBR are largely based on empirical techniques. It is difficult to predict how vessel design in large scale installations (e.g. size and position of inlets, baffles or membrane orientation) affects hydrodynamics, hence overall performance. Computational Fluid Dynamics (CFD) provides a method for prediction of how vessel features affect the hydrodynamics and thus optimise MBR design and performance. Within the framework of AMEDEUS, a CFD model was developed which accounts for aeration and membrane configuration and couples liquid and gas hydrodynamics. Details of the modelling methodology, validation and results are available in Work Package 6 Deliverable 39. For more case-specific comparison of designs see Brannock *et al.* (2007a) and Brannock *et al.* (2007b).

It was found that there is a complex relationship between membrane location (i.e. outside or inside submerged), aeration rate, vessel configuration (i.e. inlet position and baffle) and the closeness to ideal mixing regimes (i.e. complete mixing and plug flow). However, from the modelling exercises it can be concluded that the main mixing influence is the aeration rate. This, beyond all other factors, affects the type of mixing regime occurring within an MBR.

In terms of the membrane location (i.e. outside or inside submerged) the outside configuration consistently created a mixing regime closer to plug-flow. However, the differences between the inside and outside configurations, in terms of closeness to plug-flow, were very small. Therefore, similar treatment efficiencies and effluent qualities would be expected.

In terms of other design features, the inlet position was a large factor in affecting closeness-to-plug-flow, 'short circuiting' and 'dead zones' but not internal recirculation. The presence of a baffle in the outside configuration on the other hand encouraged greater liquid recirculation, prevented short circuiting and affected the Residence Number (i.e. closeness to plug-flow) in a complex manner.

For vessel design, at least at the scale modelled (i.e. pilot-scale), the level of aeration should be determined via the biological requirements (i.e. in terms of DO) and fouling control, as any level of aeration will provide significant mixing. Introducing a decoupled sludge transport sub-model, along with a bioreactions sub-model, into the MBR CFD model would allow prediction of these oxygen requirements. The inclusion of MBR vessel features such as inlet position or the use of a baffle, will help prevent 'dead zones' and 'short circuiting' if positioned correctly.

The results are to an extent case-specific. One should evaluate each design, be it pilot-scale or full-scale, on its own merit as the influence of design features are complex, especially with respect to mixing. CFD, as demonstrated by the cited study, can be used to predict the subtle effects of these design features. Ultimately the CFD model developed here may be used to optimise an MBR's performance in terms of energy usage and reactor design. The position of the membrane (i.e. inside or outside submerged) will play a role in the optimisation.

8 Comparison of full-scale systems

Among the operational full-scale municipal MBRs, two installations were selected because they are equipped with the same membranes, have different submerged MBR configurations and sufficient operational and cost data are available, either through literature or through contacts with the operator. These were

- Kaarst, Germany (Nordkanal, Erftverband): inside submerged MBR
- Varsseveld, the Netherlands (Water Authority of Hollandse Delta): outside submerged MBR.

The plants are equipped with Zenon membranes and have comparable designs. The Nordkanal plant has a pretreatment consisting of a 5 mm step screen, an aerated grit/fat chamber and a 0.5 mm drum sieve. The actual biotreatment is a contact stabilization with predenitrification. In Varsseveld, there is a pretreatment consisting of a 6 mm fine screen, an aerated grit/grease removal and 0.8 mm microsieves. The aeration tank is a circuit system with a predenitrification volume.

The design parameters summarized in

Table 3, show that the Varsseveld and Kaarst plants differ in capacity by a factor 3-4. Target MLSS values were similar in both cases, but the design flux was 50% higher in the Varsseveld case. Discharge consents were comparable for both systems, except for total N. The Varsseveld plant with the more stringent discharge requirements, has an outside submerged MBR design. This is not surprising in view of the expert opinions (see Section 6).

Both plants are operated under similar conditions of organic loading, hydraulic retention time and sludge age. Average operational fluxes are similar in Kaarst and Varsseveld and amount to 7-9 $l/m^2.h$. As these are important factors determining sludge quality and hence fouling behaviour, no large differences in fouling are expected.

As the plants are currently both using intermittent aeration, the specific aeration rates are fairly similar when expressed per m^2 or per m^3 of permeate produced. Physical and chemical cleaning is analogous as well and is probably more related to the selected membrane type than to the MBR configuration. Information on the frequency of intensive cleans could not be found, but there are no indications that these would differ significantly between the considered plants.

The relative footprints conform to the general assumption that outside MBRs occupy a larger surface area than inside ones. For Varsseveld, the total footprint of the bioreactor and membrane filtration tanks was calculated to be 792 m^2. In Kaarst it covers a surface area of 2 430 m^2. When these values were backcalculated per PE, the inside MBR of Kaarst is the most compact one.

Table 3: Comparison of the Kaarst and Varsseveld MBR plants (Judd, 2006; Pinnekamp and Friedrich, 2006; van Bentem et al., 2007; www.mbrvarsseveld.nl, Brepols: 2008). DN: denitrification, N: nitrification.

Design parameter	**Kaarst**	**Varsseveld**
Lay-out	inside	outside
Capacity (PE)	80 000	23 000
Bioreactor volume (m^3)	9 200	3 000
Biotreatment	DN/N with integrated membranes	DN/N/filtration tanks
Membrane supplier and type	GE (Zenon ZW500c)	GE (Zenon ZW500d)
Membrane area (m^2)	84 480	20 160
Sludge concentration (g/l)	12	10
Discharge consents		
COD (mg/l)	90	100
BOD (mg/l)	20	10
NH_4-N (mg/l)	10	/
N_{tot} (mg/l)	18	10
P_{tot} (mg/l)	1	1
AOX (mg/l)	0.1	/
Operation		
Treated flow per year (m^3)	5 236 000 (598 m^3/h)	1 825 000 (208 m^3/h)
Sludge loading (kg BOD/kg MLSS.d)	< 0.05	0.04
HRT (h)	4.6	4-14
Sludge retention time (d)	25	24-35
Aeration	intermittent (15 s off/15 s on)	intermittent (15 s off/15 s on)
Aeration rate (m^3/h)	34 000 (membranes)	2 080 (bioreactor) + 9 000 (membranes)
Specific aeration demand (Nm^3 air/h.m^2)	0.43	0.55
Physical cleaning	every 800 s backflush for 60 s	every 360 s backflush for 20 s
Chemical cleaning	maintenance clean every 1 or 2 weeks	maintenance clean every 1 or 2 weeks

Table 4 gives an overview of various cost items. Energy consumption turns out to be similar for the Kaarst and Varsseveld plants. For Varsseveld however, further optimizations are planned and targets of 0.75 kWh/m^3 are being claimed (STOWA, 2006).

The total capital costs evidently depend on the plant size. Expressed per PE (design value), the inside MBR in Kaarst is by far the cheapest. Also when the actual treated flow is considered, the capital costs are significant lower than those of the Varsseveld plant. Figure 9 shows the capital costs in more detail. At first sight, it appears that the civil works constitute a larger fraction for the inside MBR than for the two outside ones. The opposite is true for costs related to electrical work and automation. The former is probably related to the differences in size. The latter seems logical when the simpler layout of inside MBRs is concerned. However, the large contribution of initial costs related to consulting, building inspection, etc. for the Varsseveld plant, makes comparison difficult.

When the operational costs are calculated per PE, the Kaarst plant again appears as the most cost effective one. Even when the actual treated volume is considered, the operational costs are only 70% of those in the outside Varsseveld MBR. These data confirm the expert opinions that outside MBRs have higher investment and operational costs than inside ones.

Figure 10 shows that the relative contribution of energy costs is highest in the Kaarst plant. However, chemicals consumption makes up around 20% of the total operational costs, where this is around 30% in Varsseveld. Sludge disposal is equally important in both systems. Membrane cleaning is a minor cost factor. Personnel costs seem quite different between the Erftverband plants and the Varsseveld one, but these should probably be combined with the item 'maintenance'. When the number of personnel is considered, the Kaarst plant seems to be the most labor intensive one as 1 FTE is needed per 13 333 PE or 873 000 m³ yearly flow treated or 14 080 m² membranes. These numbers are about twice as high as those in Varsseveld. Whether this is due to the difference in MBR lay-out or rather to a different evaluation of various cost items is not clear.

Table 4: Comparison of cost related parameters for the Kaarst and Varsseveld MBR plants (Brepols, 2008; Judd, 2006; STOWA, 2006; van Bentem et al., 2007; www.mbrvarsseveld.nl).

Parameter	**Kaarst**	**Varsseveld**
Energy consumption (kWh/m³)		
Total specific power demand	*0.9*	*0.9*
Membrane aeration	0.23	0.34
Membrane supply pumps	0.03	0.11
Permeate pumps	0.04	0.12
Bioreactor aeration	0.30	0.24
Bioreactor impellers	0.05	0.04
Others	0.25 (incl. sludge dewatering)	0.05
Costs		
Capital costs (MEUR)		
total	21.5 (excl. transport pipe)	11.2
capital cost (EUR/PE)	269	487
capital cost (EUR/m³/d)	1 499	2 240
Operational costs (kEUR/yr)		
total	1 343	658
operational cost (EUR/PE)	17	29
operational cost (EUR/m³ treated)	0.26	0.36

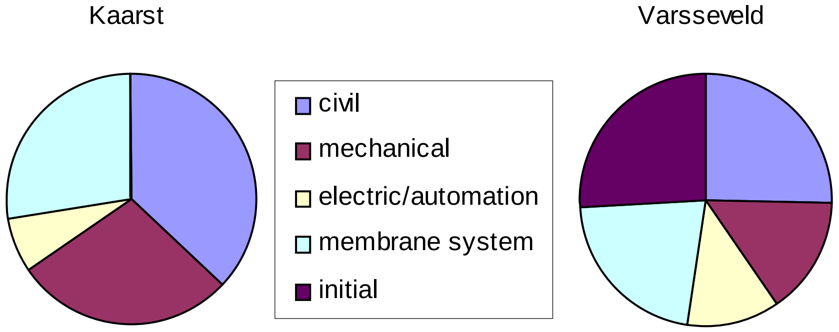

Figure 9: Relative contribution of various items to capital costs of two full-scale MBRs.

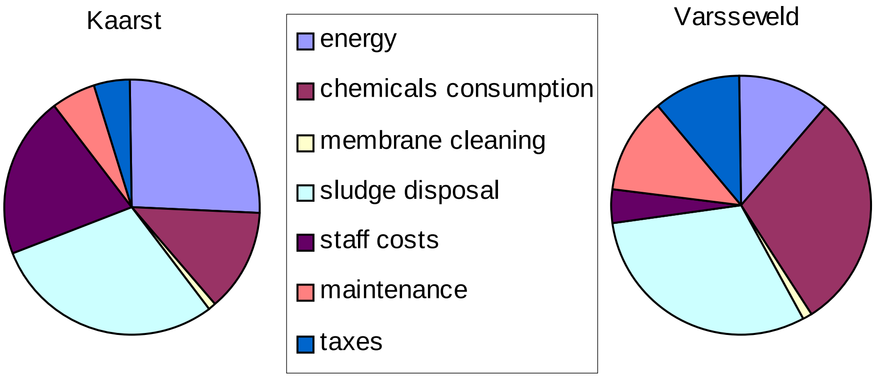

Figure 10: Relative contribution of various items to operational costs of two full-scale MBRs.

Table 4 already indicated identical energy consumptions at the inside Nordkanal and outside Varsseveld plant. Figure 11 gives a more detailed analysis of energy consuming factors. The relative contribution of membrane aeration is clearly lower in the inside MBR of Kaarst than in the outside MBRs. For bioreactor aeration, the trend is opposite. For the total aeration requirement, the procentual contribution is slightly higher in Varsseveld (64%) than in Kaarst (59%). The presence of coarse bubble aeration in inside submerged MBRs therefore seems to reduce the overall aeration requirements. These results are in line with the observations of Tao et al. (2005) (see Table 1) that an inside MBR pilot had a significantly lower aeration requirement than two outside ones.
As expected, the contribution of membrane supply pumps is much lower in the Kaarst plant than in Varsseveld and the contribution of the bioreactor impellers is slightly higher.

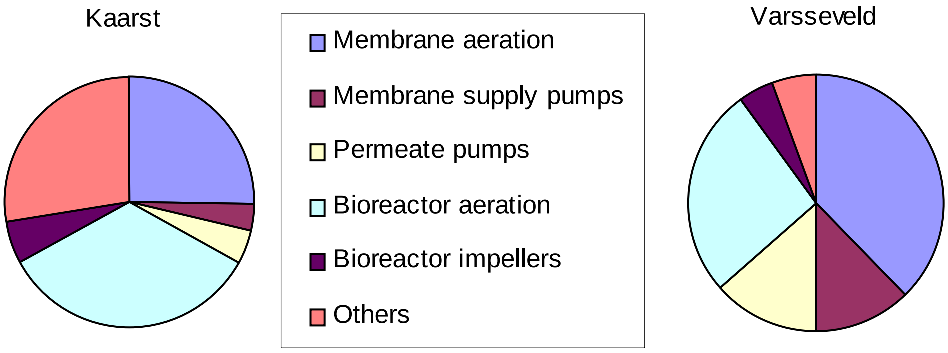

Figure 11: Relative contribution of various items to energy consumption for two full-scale MBRs.

9 Overall conclusions

An analysis of trends in submerged MBR design indicated that outside submerged MBRs are a more recent development, which is preferred for retrofitted plants, for plants with medium to large capacity or flow and for sites with high peaking factors or with stringent nutrient discharge consents. Smaller plants, MBRs equipped with flat sheet membranes with lower packing densities and systems where only C removal needs to be achieved, typically take the inside lay-out. When alternating anoxic/aerobic cycles are applied in the bioreactor, the outside configuration is the only option.

A summary of advantages and disadvantages of the inside and outside configuration as gathered from literature and experts, is given in Table 5. The outside configuration evidently provides the highest flexibility in operation and allows independent optimization of biological and membrane processes, but this goes with a higher investment and operational cost. This was corroborated from comparison of full-scale plants. In spite of higher manpower requirements to operate an inside MBR, its operational costs were 30% lower than for the outside MBR. Capital costs were also around 70% of those for an outside MBR but this may have been related to a difference in size and hence economy of scale.

Table 5: Advantages and limitations of two submerged MBR configurations

Parameter	Inside	Outside
independent optimization of hydraulics & fluid dynamics	lower	higher
control sludge distribution near membranes	lower	higher
separate optimization biological system	lower	higher
hydraulic buffer capacity	lower	higher
effluent quality	lower	higher
susceptibility to flow or loading fluctuations	higher	lower
biological and filtration redundancy	lower	higher
dead zones and short circuiting	higher	lower
fouling potential	higher	lower
accessibility for inspection, maintenance, cleaning	lower	higher
ease of cleaning	lower	higher
flexibility in cleaning	lower	higher
frequency of cleaning actions	higher*	lower*
energy, time, resources needed for cleaning	higher	lower
foaming risk after cleaning	higher	lower
control on clogging	lower	higher
footprint	lower	higher
investment costs	lower	higher
pumping energy	lower	higher
air:permeate ratio	lower*	higher*
overall energy consumption	lower	higher
maintenance	higher	lower

*or no difference depending on pilot trials considered

Finally, a decision tree was tentatively compiled which indicates the major factors affecting the choice for an inside or outside MBR configuration. This is shown in Figure 12.

The CFD simulations specific to the design of inside and outside MBR pilot plants did not show major differences in terms of closeness to plug flow. Therefore, no difference in effluent quality or in treatment efficiency are expected. However, the inside configuration appeared to have slightly more dead zones and short circuiting. This may result in higher foulant production. Aeration was found to be the major mixing mechanism. Reducing aeration may favor plug flow and therefore improve effluent quality. However, aeration is required for fouling control so this may be the main determinant of the optimal aeration level. It needs to be further emphasized that the results are to an extent case-specific. One should evaluate each design, be it pilot-scale or full-scale, on its own merit as the influence of design features are complex. Ultimately the CFD model developed here may be used to optimise an MBR's performance in terms of energy usage and reactor design. The position of the membrane (i.e. inside or outside submerged) will play a role in this optimisation.

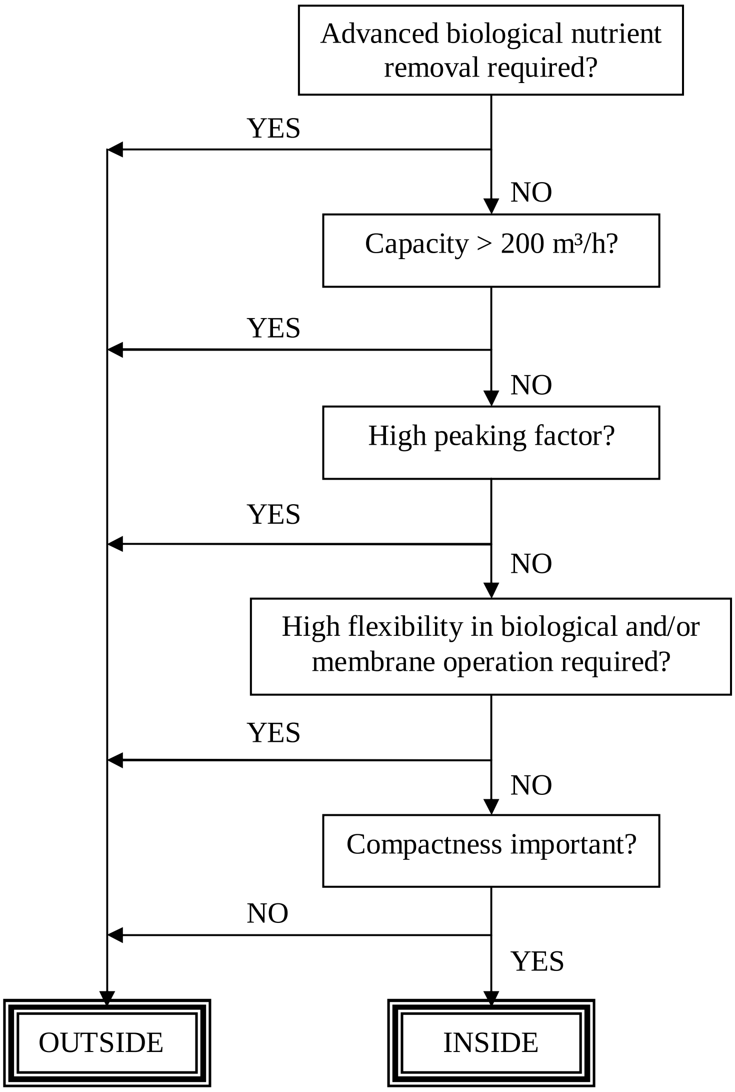

Figure 12: Decision support system for submerged MBR design.

References

Adham, S., Decarolis, J.F. and Pearce, W. (2004) Optimization of various MBR systems for water reclamation – Phase III. Desalination and Water Purification Research and Development report No. 103. US Department of Interior

Babcock, R., Huang, T. and Debroux, J.-F. (2005) Pilot test comparison of five different membrane bioreactors, CD-ROM 20th annual WateReuse symposium, 18-20 September 2005, Denver, Colorado

Brannock, M.W.D., De Wever, H., Wang, Y. and Leslie, G. (2007a) Evaluation of membrane bioreactor performance via computational fluid dynamics modelling: effect of membrane configuration and mixing, International Conference on Membranes for Water and Wastewater Treatment, 15-17 May 2007, Harrogate, UK

Brannock, M.W.D., De Wever, H., Wang, Y. and Leslie, G. (2007b) Computational fluid dynamics simulations of MBRs: inside submerged versus outside submerged membranes, 6th International Membrane Science and Technology Conference IMSTEC07, Sydney, Australia

Brepols, C. (2008). Personal communication.

Brepols, C., Schäfer, H. and Engelhardt, N. (2005) Hinweise zur verfahrenstechnischen Integration getauchter Membranfilter in kommunalen Membranbelebungsanlagen, KA – Abwasser, Abfall 52 (1): 45-50

Brow, P. (2007) Ballyclare MBR WwTW: the cost and challenges of compliance with stringent standards, International Conference on Membranes for Water and Wastewater Treatment, 15-17 May 2007, Harrogate, UK

Frechen, F.-B., Schier, W. and Linden, C. (2007) Pretreatment of municipal MBR applications, International Conference on Membranes for Water and Wastewater Treatment, 15-17 May 2007, Harrogate, UK

Judd, S. (2006) The MBR book: Principles and applications of membrane bioreactors in water and wastewater treatment, Elsevier, Oxford, UK

Lesjean, B., Ferre, V., Vonghia, E. and Möslang, H. (2008) Market and design considerations of the 37 larger MBR plants in Europe, Presentation at EDS MDIW08 Conference, 20-22 October, Toulouse, France

Pinnekamp, J. and Friedrich, H. (2006) Membrane technology for wastewater treatment, FIW Verlag, Aachen, Germany

STOWA (2006) Onderzoek MBR Varsseveld, report 2006-6, STOWA, Zwijndrecht, The Netherlands

Tao, G., Kekre, K., Wei, Z., Lee, T.C., Viswanath, B. and Seah, H. (2005) Membrane bioreactors for water reclamation, Wat Sci Technol 51 (6-7): 431-440

van Bentem, A.G.N., Petri, C.P., Schyns, P.F.T. and van der Roest, H.F. (2007) Membrane bioreactors. Operation and results of an MBR wastewater treatment plant. STOWA report, IWA Publishing, London, UK

Wedi, D. and Joss, A. (2007) Dimensioning of membrane bioreactors for municipal wastewater treatment, International Conference on Membranes for Water and Wastewater Treatment, 15-17 May 2007, Harrogate, UK