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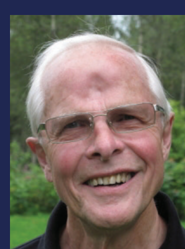

Edited by Wolfgang Rauch and Pernille Ingildsen

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Introduction to Professor Gustaf Olsson's *Festschrift*

Professor Gustaf Olsson has devoted countless hours over many years to *Water Science and Technology*, *Water Supply* and *Water Practice and Technology* as an author, reviewer, editor and editor in chief until finally stepping down from all functions in 2021. In order to honour Prof. Olsson's devotion and contribution to the journals, IWA Publishing has compiled a *Festschrift*: that is, a book made up of contributions from Prof. Olsson's former students, his colleagues (past and present), and of course his friends.

As the contributions testify, Gustaf's devotion and influence by far exceeds his work at *Water Science and Technology*. It has been a joy to read through the testimonies about Gustaf and how he has shaped and influenced lives and academic careers. They express an overwhelming gratitude for the way he has influenced and, in some cases, significantly formed both the professional and personal attitude of those he has touched. It also testifies to great scientific contributions, contributions that are strongly embedded in the water sector industry and with great impact at the time of publishing and clearly also well into the future. His leadership example is a source of inspiration to everybody in the water sector whether in academia or industry.

We urge you to read this *Festschrift* to celebrate Gustaf and get inspired about how to work in service for the greater good of water.

Wolfgang Rauch and Pernille Ingildsen
Editors

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Instrumentation, control and automation (ICA) of MBBR plants for nutrient removal in wastewater: ICA of MBBR plants

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ABSTRACT

Cold and dilute wastewater is a major challenge for N-removal at wastewater treatment plants. The moving-bed biofilm reactor process in combination with chemical coagulation/precipitation has proven suitable for nutrient removal under these conditions. Several full-scale plants based on combined pre- and post-denitrification for nitrogen removal and chemical coagulation/precipitation for phosphorous removal have been in operation for more than 20 years. These plants are still performing well, even at above design loads and at low temperatures (<10°C). The success of this process configuration can largely be attributed to its flexibility of operation and control. In this paper the key instrumentation, control and automation elements are discussed and recommendations regarding process choice, reactor configuration and design are given.

Keywords: MBBR, nutrient removal, instrumentation, control, automation

1.1 INTRODUCTION

The moving-bed biofilm reactor (MBBR) was invented in Norway in the late 1980s when the focus was on nitrogen removal caused by eutrophication of the North Sea (Ødegaard *et al.*, 1994). The concept was developed in close cooperation between the water treatment research group at Norwegian University of Science and Technology and SINTEF in Trondheim and Kaldnes Miljøteknologi AS in Tønsberg, Norway, a company founded and based on the MBBR technology. The development was enhanced by the establishment of a research programme (FAN) on nitrogen removal (1988–1992) that was financed by the Norwegian State Pollution Control Authority (SFT) (Ødegaard, 1992). The research led to design criteria that are still in use (Hem *et al.*, 1994; Norwegian Water, 2020; Rusten *et al.*, 1995a, 1995b). After a series of obstacles, the MBBR concept (reactor as well as carriers) was patent filed by Kaldnes Miljøteknologi in 1991 and the first plant was commissioned the same year as a small pre-denitrification plant (Lardal WWTP) – the first nitrogen removal plant in Norway. Over the years, the original patent was owned, and the process was marketed, by a series of companies; Kaldnes Miljøteknologi AS (1991–1995), Anglian Water Ltd (1995–2002), AnoxKaldnes AB (2002–2006) and Veolia Water Systems (2006–still). Several other companies around the world are now offering MBBR systems and MBBR-based processes are used in municipal plants (including on-site) as well as industrial plants, on all continents. There are now more than 1200 MBBR-based plants of some size around the world (>1000 on Veolia's reference list only) and several thousand on-site plants.

The MBBR is a flow-through, pure biofilm reactor, that is there is no recycling of biomass from the downstream separation reactor and back to the MBBR. The biofilm (or attached biomass) is growing on carriers that are suspended in the reactor and moving freely around with the currents set up by aeration (in aerobic reactors) and mixing (in anoxic and anaerobic reactors) – see Figure 1.1.

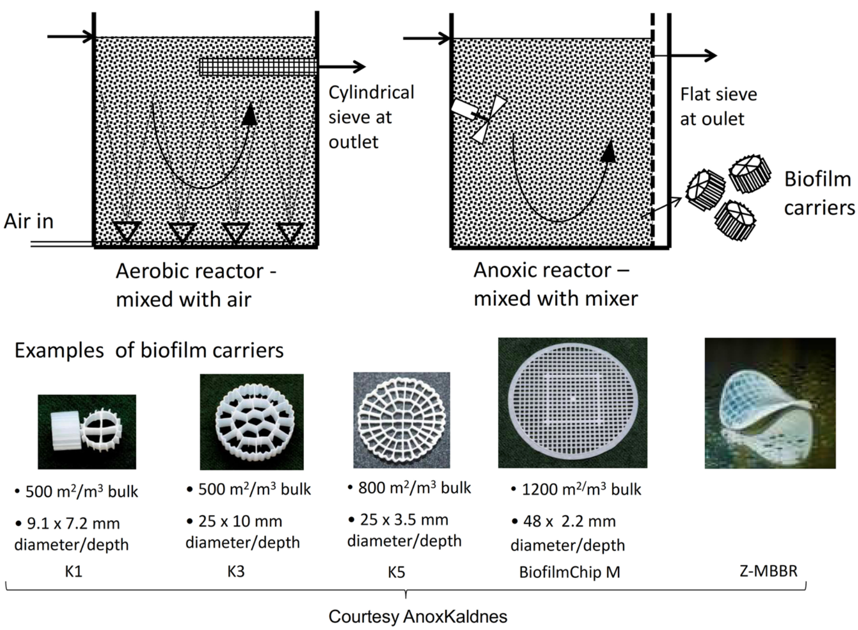

Figure 1.1 Principle of the MBBR and examples of carriers. (Source: Ødegaard, 2016)

At steady state the net biomass growth is sloughed off the carriers due to erosion caused by the movement and mixing, and the produced biomass is separated from the water in a down-stream clarification reactor. The suspended solids (SS) that have to be separated are composed of the biomass produced as well as the incoming SS that are not degraded in the reactor. Since there is no recycle, the concentration of this mixed liquor SS is low (typically 150–250 g SS/m^3) which allows for the use of any separation reactor alternative. Frequently compact separation alternatives are used, such as dissolved air flotation (DAF), lamella settling, micro-sand-enhanced floc blanket lamella settling as well as various kinds of filters (micro-screens, cloth filters, sand filters and membrane filters). Used in this way, MBBR plants may become extremely compact with a foot-print for nitrogen removal of only 15–25% of that of a conventional activated sludge process based on settling.

Thoughts on smart process control in wastewater treatment plants (WWTP) was published by Gustaf Olsson already in 1976 where the role of process control and sensors were discussed (Olsson, 1976). Olsson and Newell (1999) presented predictions on how the treatment plants of year 2025 would be controlled and automated. Today we can see that those predictions were accurate. Processes in the water sector of today are using ICA tools to make them smarter and more efficient. MBBR plants are no exception, although still there is a room for improvement.

1.2 THE RECOMMENDED PROCESS OF MBBR PLANTS FOR NUTRIENT REMOVAL

Based on Norwegian experiences, Figure 1.2 shows the recommended process scheme for a nutrient removal MBBR plant. The key unit processes are:

(1) **A primary step** (normally based on settling) with pre-coagulation/precipitation as an option.
(2) **A secondary step** based on combined pre- and post-denitrification in a MBBR.
(3) **A tertiary step** based on post-precipitation/flocculation and floc separation – the latter being settling or preferably DAF, optionally proceeded by a filtration step.

1.2.1 The primary step

The primary step that follows pre-treatment (screening and grit-removal) is normally based on settling. The option to carry out enhanced particle removal by pre-coagulation/precipitation is included in some plants – adding to the flexibility of operation. By coagulation the biochemical oxygen demand (BOD) removal in the primary step may be increased from typically 30% to typically 70% if enhanced flocculation and dosing control is implemented. Most plants have the option of adding a coagulant to the grit chamber and polymeric flocculants ahead of settling to enhance flocculation, but optimally designed plants have physical flocculation tanks included.

Normally, the primary step will be operated without chemical pre-treatment. However, chemically enhanced pre-treatment may have its benefits. It is

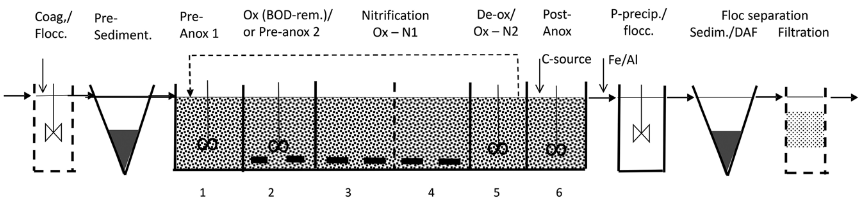

Figure 1.2 Recommended flow diagram for wastewater nutrient removal plants based on MBBR.

primarily the soluble, easily biodegradable organic matter that is useful for denitrification. Particulate organic matter needs to be hydrolysed before it can act as carbon source in the pre-denitrification step, and since the residence time in the pre-denitrification MBBR is quite low, only very limited denitrification will be caused by the particulate organic matter entering the plant. It will, however, require capacity and energy in the BOD-removal step (steps 2 and 3 in Figure 1.2) and hence be beneficially removed ahead of the MBBR. If biogas is produced at the plant, the increased organic matter amount in the coagulated sludge will also enhance biogas production, thus producing energy instead of consuming energy in the BOD-removal step.

Since phosphorous is needed for the biological processes in the MBBR, it is primarily coagulation (colloid separation) one is aiming at by chemically enhancing the primary step – and not phosphate precipitation. If a metal salt (Al, Fe) is used as coagulant, a smart control system may be implemented in order to optimize or balance the removal of particulate organic matter versus the removal of phosphorous. Normally, coagulants are added proportional to the flow, while such dosing could easily be either over- or under dosage, since the optimal dosage is a function of flow, pH, particles and phosphates. A low metal dose combined with a cationic polymeric flocculant, or metal coagulants with high basicities, may be used to maximize particulate organic matter removal while at the same time not remove more PO_4-P than acceptable for the proceeding biological processes.

Increased addition of inorganic coagulants has been reported to reduce the fertilizer value of sludge. However, the use of smart dosing systems, which also optimize the balance between inorganic coagulants and organic flocculants, has been reported to improve the fertilizer value by increasing phosphate availability to plants (Ratnaweera, 2020).

1.2.2 The secondary (MBBR) step

A typical build-up of the MBBR step is shown in Figure 1.3.

The first reactor stage (R1 in Figure 1.3) is normally a mixed, anoxic pre-denitrification stage that receives nitrate-containing water from the end of the nitrification zone (R5 in Figure 1.3). The recycle flow is made variable since it does not help to recycle more than the amount of easily biodegradable organic matter (in the raw water) can accommodate.

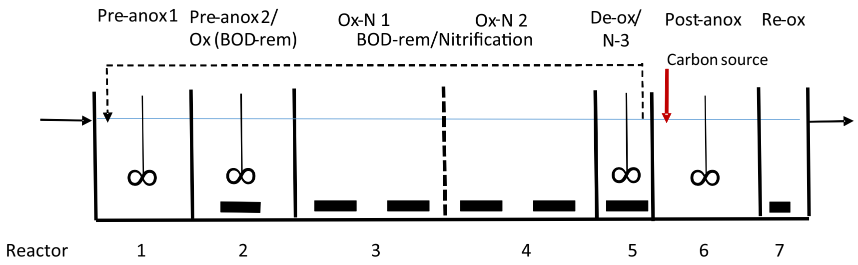

Figure 1.3 Typical build-up of an MBBR based on combined pre- and post-denitrification.

The recycled water contains oxygen (coming from reactor 5) and the more one recycles, the more oxygen will be used to consume the precious, easily biodegradable organic matter intended for nitrate removal.

In plants designed for 'cold water', the recycle will normally not be set higher than $r = 1.5$. Q_{in} $(r = Q_r/Q_{in})$. Theoretically, this can lead to a potential removal of nitrogen in the pre-denitrification of not more than approximately $r/(r+1)$. 100%, that is 1.5/2.5. 100% = 60%. In cold, diluted wastewater (as during snow melt in spring) the availability of easily biodegradable, organic matter can be so low that the recycle may be set even lower, for instance at <1 Q_{in}, equivalent to a theoretical N-removal of <50%.

The dissolved oxygen (DO) in the water of the pre-denitrification stage does not need to be zero. Denitrification takes place inside the biofilm and is experienced that a DO concentration up to 0.3–0.5 mg O_2/l in reactor stage 1 (R1 in Figure 1.3) will not retard denitrification significantly. This fact may be used actively to control the recycle of oxygen-rich water from the nitrification stage.

The second reactor stage (R2 in Figure 1.3) is normally a 'swing reactor', that is it has both a system of aerators as well as mixers. It may be operated with mixing alone, and become a second anoxic reactor, or with aeration alone as a BOD-removal reactor. During summer time (or dry weather flow), the availability of easily, biodegradable organic matter in the raw water (and hence the pre-denitrification capacity) is higher. Inflow is also lower, so a higher recycling ratio may be set – all in all resulting in a higher N-removal in the pre-denitrification stage. The benefit of this, is a lower consumption of external carbon source in the subsequent post-denitrification (step (R6) in order to meet the overall N-removal goal. Together with a smart control system (see below), this makes the combined pre- and post-denitrification MBBR system very flexible and ideally suited for situations with large variations in temperature and flow.

The third and fourth reactor stages (R3 and R4 in Figure 1.3) are aerobic and mainly for residual BOD-removal and start-up nitrification (R3) and full nitrification (R4). Reactors 3 and 4 may be together as one reactor stage, but are often divided into two sections when a very low effluent ammonium concentration is aimed at. In summer time, when temperatures and nitrification

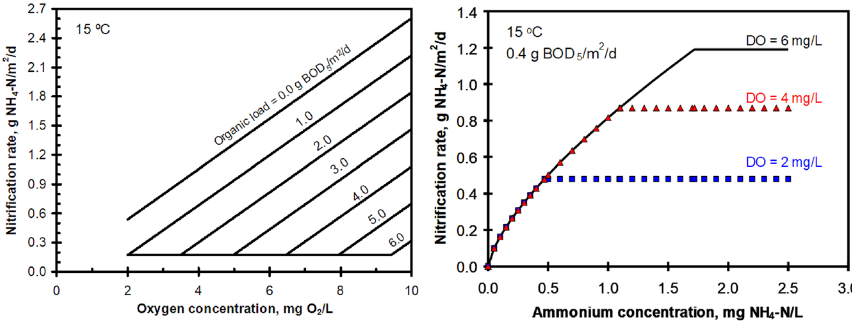

Figure 1.4 Nitrification rate dependency with respect to (a) (left side) organic load and DO concentration and (b) (right side) ammonium concentration and DO concentration. (Source: based on Hem *et al.*, 1994; Rusten *et al.*, 1995a, 1995b)

rates are higher and pre-denitrification is maximized by using R2 for pre-denitrification, R3 and R4 together will have sufficient aerobic capacity to both remove enough BOD to start nitrification and to nitrify to the extent targeted. In the winter and especially in the snow-melt season, however, the nitrification rate is lower, more nitrification capacity is needed and reactor R2 is then operated aerobically with most of the BOD removal taking place here while nitrification takes place mainly in R3 and R4. The key control parameter in the nitrification stage is the DO concentration since the nitrification rate is linearly dependent upon DO all the way up to 10 mg DO/l (see Figure 1.4 left side). DO is overriding ammonium concentration as the primary parameter controlling nitrification rate since ammonium is controlling the rate only at low concentrations (<1–2 mg NH_4-N/l) (see Figure 1.4 right side).

The fifth reactor stage (R5 in Figure 1.3) may be a swing reactor, but is normally not aerated – only mixed. It is still aerobic because of the relatively high DO concentration coming into the reactor from R4. It is thus used as a de-oxygenation reactor stage aimed at reducing the oxygen concentration out of the reactor as much as possible.

This oxygen would consume organic matter that otherwise could be utilized for nitrate removal either in the pre- or post-denitrification reactors. There is, however, not much substrate left for oxygen consumption. But correctly designed, there will be some ammonium left that will consume oxygen, at a relatively low rate, however (design value: 0.225 g NH_4-N/m^2 d). Even though the process may be ammonium-limited at this point, because of low ammonium concentration, one is normally letting enough ammonium through to make DO the limiting parameter even in this reactor stage.

Reactor stage six (R6 in Figure 1.3) is a post denitrification reactor stage where external carbon source is added. The denitrification rate here is much higher than in the pre-denitrification stage, so this reactor is relatively small, even though it may be the most important one in order to achieve a certain treatment goal. If the requirement is a very low nitrate concentration in the effluent, R6 may be divided into two steps, but this is not common when total N-removal of around 70–80% is aimed for. The denitrification rate is dependent on the availability of easily biodegradable organic matter. The nitrate concentration out may therefore be controlled by the dosage of external carbon source.

Reactor stage seven (R7 in Figure 1.3) is normally (when used) an aerated, small reactor with the task to remove any excess organic matter from the added carbon source. If the control of carbon source is good or if carbon is added in an amount that makes it the limiting factor for denitrification, this reactor may be omitted. That is also the case if the MBBR is followed by coagulation/DAF.

The experiences from Norwegian plants show that the wastewater situation that may be encountered in cold and wet weather situations, calls for the use of a post-denitrification step, because this makes one independent upon the wastewater characteristics of the incoming water. Hence, the combined pre- and post-denitrification MBBR process is the preferred one.

1.2.3 The tertiary (biomass/floc) separation step

The tertiary treatment step is there for removing biomass from biodegradation in the MBBR and flocs created by chemical coagulation/precipitation in either the primary or the tertiary treatment step. A metal salt (based on aluminium or iron) is added for the precipitation of soluble phosphates and coagulation of suspended and colloidal particles. The effectiveness of the separation is dependent upon;

- process conditions during precipitation, such as pH, metal dosage and their mixing conditions
- flocculation conditions, such as velocity gradients, residence time and floc volume and possible use of added flocculants
- separation reactor conditions, such as type of separation process and reactor, hydraulic load/overflow rate, as well as the size, strength and density of the flocs

Key control parameters are pH and coagulant dosing. If DAF is used as the separation reactor, the effectiveness may additionally be controlled by the air/solids ratio that requires particle amount monitoring (by SS or turbidity measurement) determining the air flow. This is, however, not implemented in the Norwegian plants with DAF.

1.3 PROCESS SURVEILLANCE AND CONTROL OPTIONS

As predicted by Gustav Olsson already in 1999 (Olsson & Newell, 1999), today, the wastewater treatment utilities have an array of opportunities to make the processes more compact, more efficient and more economical. New real-time sensors are widely available in the market, cost-efficient smart sensor technologies such as virtual/proxy sensors are continuously introduced, process knowledge is increasing, use of advanced SCADA systems have become common, and the embracement of digitalization by the water sector are presenting enormous opportunities. They also present new opportunities for nutrient removal by MBBR in cold climates, to meet various challenges.

1.3.1 Process surveillance using virtual and hybrid sensors

Physical probes are invaluable in real-time process surveillance and process control. They provide rapid and continuous measurement of parameters, often at a fraction of the total costs of lab analysis. However, there are several challenges with them: some sensors are exorbitantly expensive, some require frequent maintenance and for some parameters (e.g., phosphates) there are no real-time sensors. The alternative for the latter is using auto analysers that provide measurements after 10–20 min. They are, however, also expensive and require frequent maintenance.

An alternative to the above is virtual (soft or surrogate) sensors. The simplest form of such a sensor is the measurement of SS as a function of turbidity. Since there is a very good correlation between these two parameters, SS sensors have been available in the market for over two decades. A SS sensor enables instantaneous measurement instead of 2–3 h required by the conventional method. Correlations can be found between UV absorbance and several parameters (Li *et al*., 2020; Nataraja *et al*., 2010). Using scanning spectrometry and pre-calibrated algorithms, several commercial probes are available in the market (e.g. S:CAN, GO Systemelektronik etc.) for an array of parameters using a single probe. However, they do not measure all relevant parameters and are also expensive (20,000–30,000 €).

It is possible to measure more parameters more accurately with hybrid sensors. In this concept, real-time measurements using simple physical probes are combined with historical measurements to develop calibrated algorithms. Since the algorithms are calibrated for local conditions incorporating real-time measurements of pH, conductivity, turbidity and flow, they have been proven to estimate chemical oxygen demand (COD), phosphates and nitrogen compounds more accurately (Nair *et al*., 2020). Such sensors are much more cost-efficient as they do not require any advanced or costly physical probes or maintenance.

Hybrid sensors may efficiently be applied in MBBR plants, both for the possible chemically enhanced primary step as well as for controlling the biological processes in the MBBR. Nair *et al*. (2019, 2020) reported applications of their use in MBBRs. The authors presented the use of principal component analysis as a successful technique in these processes.

Increased understanding of the water treatment processes in combination with the rapid digitalization of the water sector enables further improvement of process efficiencies and economics. For example, flow proportional dosing, at best with overriding pH control, is the most common approach for chemical dosing control in the coagulation processes, which has a significant room for improvement.

1.3.2 Instrumentation, control and automation (ICA) in the CEPT step

If enhancement of the primary step is implemented by coagulant addition, the main purpose is to enhance particulate organic matter removal without removing too much of the soluble phosphate that otherwise might lead to phosphate limitation of the biological processes in the MBBR step.

Wastewater concentrations may rapidly and widely vary during a day or a week. Thus, it is logical to use flow proportional dosing as many plants do. However, if the control algorithm is a simple linear function, it will be far from optimal, resulting in under – or overdosing. The latter will lead to negative impacts such as reduced treatment efficiency, too low pH, too high sludge production and so on. While the increase in flow may follow the pollution loading/concentrations due to daily domestic activities, flow increase due to precipitation and snow melting will often result in a reduction of concentration. In the latter case, it is not advisable to use simple and linear flow proportional control algorithms. The two feasible alternatives could be to have several algorithms calibrated for various flows or to include a parameter describing the pollution load, such as turbidity or SS. Having a pH overriding function is a minimum requirement if none of these two concepts is implemented, at least to avoid negative impacts on the unintentional reduction of pH, while ensuring the performance at coagulant-specific working pH ranges.

Dosing control is currently normally carried out based on flow proportional dosing, at best with overriding pH control. Flow proportional dosing only may lead to under- or overdosing of coagulants. Under-dosing will underutilize the potential benefits, while overdosing may impact the downstream MBBR process with too low PO_4-P values and/or too low pH values impacting the MBBR process. It is possible to derive empirical relationships between the residual PO_4-P after a chemically enhanced primary step, thus the turbidity or SS will function as a surrogate parameter to ensure necessary PO_4-P levels. There are no PO_4-P sensors available in the market yet, but virtual/hybrid sensors are a viable alternative. Promising results and concepts are emerging in the market, resulting in accurate and real-time measurements at a fraction of the auto-analysers costs (Nair *et al.*, 2019). With real-time measurement of PO_4-P, it will be possible to add a feed-back loop before the MBBR, or feed-forward dosing control at the chemically enhanced primary step (Ratnaweera, 2020).

In addition to the flow and pH, some plants use turbidity and phosphate measurements to define the optimal coagulant dosage (Ratnaweera & Fettig, 2015). The authors also report of a more comprehensive system using several parameters and multivariate statistics. For example, a dosing control system provided by DOSCON, has reduced the coagulant consumption by 30% since 2009, at the Nedre Romerike WWTP near Oslo, Norway. This is an example of a combined pre- and post-denitrification MBBR plant operating at low temperatures and excessive infiltration caused by precipitation and snow-melt.

1.3.3 ICA of the secondary MBBR step

Figure 1.5 indicates what kind of parameters can be controlled on-line and used for ICA of the MBBR step.

There are especially three parameters, in addition to flow rates and temperature that are important for on-line control: DO, NH_4-N and NO_3-N.

Some of the plants use an on-line NH_4-N sensor in the inlet water to the MBBR. The purpose of it is mainly to prepare the plant for an increased load by increasing the set-point for DO in the nitrification reactor stage (DO2 in Figure 7). This action will lead to a more stable NH_4-N concentration out of the nitrification stage and into the post-denitrification stage. If depending only on the NH_4-sensor in R5, some time will pass before the increased load in R3 and R4 will be detected in R5 and the control system will react a bit belated.

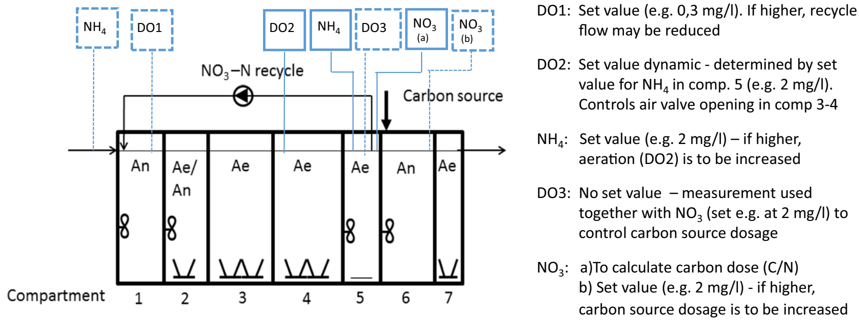

Figure 1.5 ICA of the MBBR step.

In some plants, sensor DO1 is just used as an on-line measurement, but some use it actively to control the recycle of nitrate. As mentioned above, denitrification in the biofilm will proceed even if there is a low concentration of DO in the bulk water of the pre-denitrification stage. Since the DO will be influenced mainly by the recycled DO-rich flow from R5, control of the recycled flow may ensure that pre-denitrification is not hampered by aerobic activity and biodegradable organic matter consumption in the pre-denitrification step. Experiences show that a sensible set-point for the DO1 is 0.3 mg DO/l.

DO2 regulates normally the valve openings to the aeration pipes for reactors R3 and R4 (possibly to R2 when this is operated aerobically). The valve opening in R3 and R4 is regulated automatically in order to keep the DO set-point in R4. The valve openings in R3 (possibly also in R2 when this is operated aerobically) is interlocked so that they open a given percentage of full opening, that is dependent on the valve opening in R4. This percentage is set in the operating system by the plant operators, and may be programmed to vary with several factors. If, for instance, the valve opening in R3 is set at 100%, these valves will get the same opening as those in R4 (the %-value may be set to more than 100). The valves will never open completely, because one needs a defined pressure-loss over the valves in order to have full control of the air flow to each of the reactor stages. Therefore, an upper limit is set with respect to how much each valve may open. When the valves in the reactor stage opens more, resulting in more air supplied to the reactor, the pressure in the main supply pipe will be lowered. The blowers will then increase the speed and will deliver more air in order to keep this pressure constant.

The set-point for DO2 is dynamic and is determined by temperature and NH_4-N concentration measured in R5. In addition there is a maximum value that may be programmed to vary with the temperature. If, for instance, the NH_4-N sensor in R5 shows less than 2 mg NH_4-N/l, the DO set-point will be reduced, resulting in less air supplied. At the same time, a lower limit for the valve openings for air to the reactors is set in order to ensure enough air for sufficient mixing in the reactors. If, for instance, the NH_4-N sensor shows that the NH_4-N concentration in R5 is about to increase, the set-point for DO in R4 will automatically be increased from for example 5 to 5.5 mg O_2/l. If the NH_4-N concentration continues to increase, the set-point for DO2 is automatically increased to for example 6.0. With still increasing NH_4-N concentration, it will continue in this way until the defined maximum value of for example 8 mg O_2/l is reached, or until the ought-to value of 2 mg NH_4-N is reached. The set-point for NH_4-N may be set manually, but one may have an automatic adjustment as well, based on temperature. It may, for example, be set at 2 mg NH_4-N/l during summer/autumn with relatively warm water, and at 5 mg NH_4-N/l during winter/spring with relatively cold water. With 5 mg NH_4-N/l as ammonium set-point, the DO set point in R4 will be reduced if the NH_4-N concentration falls under 5 mg NH_4-N/l.

As mentioned above, for plants with on-line NH_4-N sensor in the inlet water to the MBBR, the system can be programmed to increase the DO set-point for DO3 above the value indicated by the R5 NH_4-sensor if the inlet NH_4-sensor detects an increase in nitrogen load.

Sensor DO3 in R5 is only used in order to calculate the amount of NO_x-N that the recycle of oxygen to the pre-denitrification as well as flow-through of oxygen to the post-denitrification, represents. This will influence the calculation of the amount of external carbon source needed in the post-denitrification step (R6). A NO_3-N sensor is placed in R5. The NO_3-N concentration measured is used together with the DO in R5 (as well as measured temperature) to calculate the necessary C/N ratio from which the speed of the external carbon dosing pumps are regulated. The operators may change several parameters from the control system (within upper and lower limits) and they must programme the type of carbon source and the concentration of the carbon source solution (e.g. g COD/l). Some plants also have a NO_3-N sensor in R6. This is not absolutely necessary but may make the external carbon dosing control even more sophisticated. It is primarily used to control that one does not overdose the external carbon source in a situation where the reactor has reached its maximum denitrification rate and it does not help, for the removal of more NO_3-N, to add more carbon source.

In the models that help control the system and calculate recycle flows, DO-set-points, C/N ratios and so on, flow measurements of both water and air supply are also included. Thus, the smart control systems (such as DOSCON) can integrate real-time measurements of DO, NH_4-N and NO_3-N to ensure optimal conditions of all MBBR chambers, enabling trouble-free automation. Such systems can optimize the flows between the chambers, aeration and C-source supply ensuring overall optimized plants. The cost of real-time sensors can be too high for some plants and the maintenance resources may also be a challenge. In such situations it is worthwhile to consider using virtual sensors (Nair *et al.*, 2019, 2020).

1.3.4 ICA of the floc/biomass separation stage

The tertiary floc/biomass separation stage has three purposes:

- to precipitate residual soluble phosphate
- to coagulate colloidal particles (including bacterial cells)
- to separate the SS created by biodegradation and precipitation/coagulation

This is achieved through three steps: (1) precipitation and coagulation, (b) flocculation and (3) floc/biomass separation. The latter may again consist of two separate stages, a primary settling or flotation stage and a secondary filtration (membrane-, cloth- or membrane) step.

1.3.4.1 Coagulation/precipitation step

The addition of a metal salt (normally Fe^{3+} or Al^{3+}) results in two parallel processes taking place; (a) coagulation of colloids involving precipitation of metal hydroxide and (b) precipitation of phosphate forming, complex flocs that enmeshes the metal, the hydroxides, the phosphates as well as organic and inorganic colloidal matter. The goal is to add just enough to precipitate all the phosphates while at the same time produce as little hydroxides attached, to the colloids, as possible. Nowadays, pre-polymerized metal products are most frequently used as coagulants/precipitants. In order to succeed with this balance, plants will benefit from using the coagulant dosing control system (sensors, models, control units) that was discussed for the primary stage.

In the tertiary stage, the amount of phosphates that is to be precipitated depends on whether or not chemically enhanced primary treatment has been implemented. If so, the coagulant dosage control system would ensure that the coagulant dosage would not remove too much phosphate to prevent retardation of the biodegradation in the MBBR. Typically, a residual PO_4-P concentration after the primary stage of 1–2 mg/l would be aimed at.

In the tertiary stage, however, it is common to overdose coagulant relative to the stoichiometric need (~15–25 mg Fe/l) in order to ensure good floc structure – especially so when chemical enhancement of the primary is not implemented. One solution for solving the challenge of loose, fluffy flocs, is to add an anionic organic polymer as well (~0.5–1 mg/l), to enhance flocculation/separation. An alternative solution is to add a low metal dose, possibly under the stoichiometric need (i.e., ~5 mg Fe/l), and compensate the lack of Fe-cation by adding a cationic polymer (~1–2 mg/l) – typically a poly DADMAC. This will minimize sludge production by minimizing hydroxide precipitation. This solution was demonstrated with success in a pilot-plant (based on MBBR + flocculation + DAF) where both iron and polymer dose were controlled by the on-line measurement of the SS in the water entering the flocculation tank (Helness *et al.*, 2005). The typical dosage was 33 mg Fe/g SS + 5 mg cationic polymer/g SS. So if the sludge production out of the MBBR was typically 200 mg SS/l, the dosage would be 6.6 mg Fe/l and 1 mg polymer/l. This low Fe-dose, that is considerably less than what one finds in the MBBR plants for N- and P removal in Norway (typically 15–25 mg Fe/l), could still precipitate >3 mg PO_4-P, more than enough if CEPT was implemented and most likely enough even if only standard primary had been used. And this would create considerably less sludge production in the tertiary stage.

1.3.4.2 Flocculation step

The flocculation efficiency is dependent upon the hydraulic residence time (HRT), the residence time distribution (i.e., the number of mixed reactors in series), the turbulent velocity gradient (G) and the floc volume fraction (Φ) (Ødegaard, 1979). Once the HRT (typically 20–30 min total HRT), the number of stages in series (typically 2–4) and the coagulant (that determines Φ) are given, the only parameter that might be possible to control, is the turbulent velocity gradient, G (sec^{-1}), that is dependent on the mixer shape and the mixer speed. It is advisable to reduce the speed for a given mixer from one compartment to the other (from around 40 sek^{-1} in the first to around 10 sec^{-1} in the last), in order to form large, dense flocs, if settling is to be used for biomass/floc-separation. If flotation or filtration is to be used, one does not want large, fluffy flocs but rather small, dense flocs and tapering the G-value from one compartment to the next is contra-productive. The optimal G-value then lies in the 70–100 sec^{-1} range.

It is very rare that the mixing intensity is controlled automatically. In the start-up of the plant, one is usually varying the mixing speed manually (using pulleys) but once good flocculation is reached, the mixing intensities are normally kept constant. It is quite common to compensate for suboptimal mechanical mixing in flocculation by using the addition of a flocculant, normally an anionic polymer. This represents an extra cost, however, and an automatic regulation of the mixing speed by using a step-less mixer-motor gear-box, controlled by the flow (HRT) and coagulant dose, or by a floc image device at the end of the flocculation zone, might result in cost savings.

1.3.4.3 Floc/biomass separation step

When settling is used for floc/biomass separation, not much can be controlled in the settling tank as such. The possible control has to be done in the preceding mixing/flocculation tanks.

When flotation is used for floc/biomass separation, however, there are some possibilities for control (in addition to the one in the flocculation tank), since flotation efficiency is dependent upon the air/solids ratio. One may control the air flow (within limits) based on the SS-concentration (or turbidity) of the water that enters the flotation tank.

1.4 CONCLUSIONS

Real-time physical, virtual and hybrid sensors provide unique opportunities for WWTP owners of today to maximize treatment performances at reduced plant footprints.

The MBBR has established itself as a well-proven, robust and compact reactor for wastewater treatment. Experiences presented in this paper, from Norwegian MBBR plants based on combined pre- and post-denitrification, coupled with P-removal by chemically enhanced primary treatment and/or post-precipitation, demonstrate great flexibility of operation and advanced treatment results – even in cold climate situations.

Real-time physical, virtual and hybrid sensors are efficiently used for coagulant dosage control in order to avoid too low pH and PO_4-P after coagulation in the

CEPT step and to minimize PO_4-P after the post-precipitation step, as well as reducing chemical sludge production.

DO sensors are used in combination with on-line NH_4-N and NO_3-N sensors to control nitrification (by regulating air supply), pre-denitrification (by regulating the recycle NO_x-N flow) and post-denitrification (by regulating the external carbon dosage).

With the rapid digitalization of the water sector, a new array of opportunities is available for wastewater utilities. Virtual and hybrid sensors enable feed-forward control systems that may be used in MBBR systems combined with chemical treatment, bypassing the need for conceptual models for coagulation and biodegradation.

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Method for automatic correction of offset drift in online sensors

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ABSTRACT

Successful operation and optimization of water treatment systems hinge on the availability of high-quality online sensor measurements. Ideally, the available measurements should be simultaneously accurate (i.e., unbiased and precise), representative, voluminous, and timely. This remains a pain-point in current water infrastructures, forming a barrier to a wider adoption of advanced and autonomous control systems. While short-lived symptoms, such as outliers and spikes, can be detected or corrected with state-of-the-art tools for fault detection and identification, it is much more difficult to detect, diagnose, and correct the symptoms of slow faults, such as changes in offset or sensitivity due to drift. The time scale of drift is often longer than the time scales of the system dynamics of interest. Moreover, sensor drift has been shown to occur at the same time and with similar rates when sensors are exposed to the same conditions. This challenges data quality management strategies based on redundancy. In this contribution, we develop a new method, including both a hands-off sensor calibration mechanism and an information-seeking control architecture that can handle the unique challenge of simultaneous and similar drift in online sensors.

Keywords: auto-calibration, extremum-seeking control, fault correction, nonlinear optimization, incipient fault, observer, sensor drift

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2.1 INTRODUCTION

Data quality is a long-standing problem in the wastewater sector. It is an important barrier to widespread adoption of adaptive and fully autonomous systems for control and optimization of wastewater treatment plants. Several authors highlight the challenges and costs associated with the need for high-quality data sets (Blumensaat *et al.*, 2019; Cecconi *et al.*, 2019; Corominas *et al.*, 2011, 2018; Rieger *et al.*, 2003, 2010; Rosén *et al.*, 2008). In response to this challenge, multiple studies have evaluated methods for fault detection and identification. Most of these focus on short-lived anomalies, such as outliers, spikes, and step changes, and are based on the application of mechanistic or empirical models (see e.g., Alferes *et al.*, 2013; Le *et al.*, 2018). The automated detection, quantification, and correction of drift proves more challenging. The problem of sensor drift is exacerbated by the fact that exposure of the same type of sensors to the same medium at the same time leads to similar drift effects in water quality sensors (Ohmura *et al.*, 2019). In Hansen *et al.* (2022), it is illustrated that this challenges the use of existing methods based on redundancy (e.g., Aguado *et al.*, 2007; Prakash *et al.*, 2005; Rosén & Olsson, 1998; Rosén & Lennox, 2001). Indeed, existing methods only work well if the symptoms of drift in redundant sensors start at distinct times or progress with distinct drift rates. This is not a realistic expectation, as demonstrated experimentally in Ohmura *et al.* (2019).

In response to the challenge of sensor drift, Chowdhury *et al.* (2021) developed a method for sensor offset quantification without the need for drift-free reference measurements. Central to this method is the deployment of sensors that exhibit a discontinuity in their sensor response curve. In Chowdhury *et al.* (2021), it was shown that the unscented Kalman filter (UKF) can provide offset estimates whenever the process state value crosses the point where one or more sensors exhibits a discontinuity in its response. During the writing of this chapter, we found that this method is rather sensitive to sensor noise and the initial guesses for the offsets, as might be expected (see e.g., Haseltine & Rawlings, 2005; Schneider & Georgakis, 2013). This previous study also relied on natural variation in the process state to cross the sensor discontinuity on a frequent basis. However, one can also develop fault detection methods that are based on the deliberate introduction of dynamic sensor responses. This has been proposed in multiple area of application, including nuclear engineering (see e.g., Hashemian, 2013) and wastewater engineering (see e.g., Samuelsson *et al.*, 2018). Inspired by this, we developed an approach that relies on process excitation to collect the data required for sensor drift correction.

The main contribution of this chapter is a new method for automatic estimation and correction of sensor offsets without the need for offset-free reference measurements. As in Chowdhury *et al.* (2021), we exploit the ability to generate information about sensor offsets when a discontinuity in the sensor response curve is crossed. To achieve robustness against inaccurate initial guesses for the sensor offsets, we solve a nonlinear sensor calibration problem. This calibration is repeated on a regular basis to track slow changes in the sensor offsets. In addition, we develop a change-point-seeking controller aimed at generating measurements that make the sensor offsets identifiable. We demonstrate that the newly proposed method is an effective method for automatic drift correction, even when (1) initial offset guesses are far from the correct offsets and (2) natural process variation alone is insufficient to gather informative measurements.

2.2 MATERIALS AND METHODS

In the following section, the studied case is explained first (Section 2.1). After this, we explain the applied methods and how they are integrated in the studied case (Section 2.2). This section ends with a description of studied scenarios and performance metrics (Section 2.3). All symbols are listed in Table 2.1, together with units and values where appropriate.

2.2.1 Case study

To demonstrate the utility of the approach, we simulate a simple hydraulic reservoir with two pressure-based height sensors that are subject to drift. We explain this model in detail next.

Simulated system model. Figure 2.1 shows a scheme of the simulated system. The reservoir receives water as an unknown and unmeasured water flow into the system ($v = v(t)$). There is a single outlet with a control valve that allows to drain water from the reservoir by gravitation. The outgoing water flow is given as $q = q(t)$ and the controlled valve position is $u = u(t)$. The evolution of hydraulic level ($x = x(t)$) in the reservoir is given by this nonlinear differential equation:

$$\dot{x} = \frac{1}{\tau}(v - q), \qquad x(0) = 0 \tag{2.1}$$

$$q = \kappa u \sqrt{x} \tag{2.2}$$

To simulate v, we construct it as a linear combination of three sine waves, one of which has a randomly varying amplitude:

$$v(t) = a_0 + a_1 v_1(t) + a_2 v_2(t) + A_3(t) v_3(t)$$

$$v_f(t) = \sin\left(2\pi \frac{t - \phi_f}{\theta_f}\right), \quad (f = 1, \ldots, 3)$$

$$A_3(t) = \begin{cases} a_3\, g, & \text{if: } \dfrac{t - \phi_3}{\theta_3} = \left\lfloor \dfrac{t - \phi_3}{\theta_3} \right\rfloor \\ A_3(t - \epsilon), & \text{otherwise} \end{cases}$$

$$g \sim \mathcal{U}(0,1)$$

Table 2.1 List of symbols, units, and values.

Symbol	Description	Value	Unit
$\Delta\vec{\beta}\ (\Delta\beta_j)$	Change in offset estimates (for sensor *j*)	–	m
Δt	Measurement time interval	0.25	h
Δt_{cal}	Calibration time interval	6	h
$\Sigma\ (\tilde{\Sigma})$	Covariance matrix (estimated)	–	m^2
α	High-pass filter coefficient	0, 2	–
$\beta\ (\beta_j, \beta_j^*)$	Offset estimates (for sensor *j*, last known value)	–	m
γ	Regularization parameter	$1e-3$	–
δ_1, δ_2	Change-point locations	0, 5	m
$\in$	Small, positive value	$1e^{-12}$	–
$\theta_1, \theta_2, \theta_3$	Periods of feed flow rate oscillation	360, 1.0, 0.5	d
κ	Valve gain	4	$m^{5/2}/d$
ρ	Correlation coefficient	–	–
σ_0	Standard deviation of shared sensor drift	$5e-3$	m
σ_j	Standard deviation of sensor drift for sensor *j*	$1e-3$	m
$\sigma_{i,j}\ (\tilde{\sigma}_{i,j})$	Covariance between sensor *i* and *j*	–	m^2
τ	System parameter	0.04	m^2/d
ϕ_1, ϕ_2, ϕ_3	Phase angles of feed flow rate oscillation	90, 0.0625, 0	d
$\vec{\chi}$	Level estimates	–	m
$\psi\ (\tilde{\psi}, \psi^\star)$	Similarity index (measured, filtered)	–	–
A_3	Effective, randomized amplitude	–	m
K_y	Proportional coefficient for level control	0.5	m^{-1}
I_y	Integral coefficient for level control	0.1	m^{-1}
I_ψ	Integral coefficient for change-point-seeking control	0.1	–
J	Number of sensors	2	
L	Number of samples for sensor calibration	96	
a_0	Average feed flow rate	2	m^3/d
a_1, a_2, a_3	Amplitudes for feed flow rate oscillation	0.5, 0.1, 0.1	m^3/d
a_p	Amplitude of dither signal	0.25	m
$b_j\ (b_{j,0})$	Sensor *j* offset (at $t=0$)	–	m
d	Control error	–	m
e	Random measurement error	–	m
f	Feed flow rate component index	–	

(*Continued*)

Table 2.1 List of symbols, units, and values (*Continued*)

Symbol	Description	Value	Unit
f_p	Frequency of dither signal	6	d^{-1}
g	Random uniform variable	–	–
i, j	Sensor index	–	
k, l	Sample index	–	
p	Dither signal	–	m
q	Effluent flow rate	–	m^3/d
r_j	Drift rate for sensor j	–	d^{-1}
t (t_k)	Time (sample time)	–	d
t_p	On-set time of dither signal	–	d
u	Control action, that is, valve opening	–	–
u_L, u_U	Lower and upper limit for u	0, 1	–
v	Feed flow rate	–	m^3/d
w_j	Wiener noise for drift component j	–	m/d^2
x	Reservoir level	–	m
$\tilde{y}_j$ (y_j, y_j)	Measurement for sensor j (error-free, corrected)	–	m
y^* $(y^\#)$	Level setpoint	–	m
y_L, y_U	Lower and upper limit for y^*	0, 10	m
$\tilde{z}$ $(\tilde{z}_j)$	High-pass filtered signal (for sensor j)	–	m

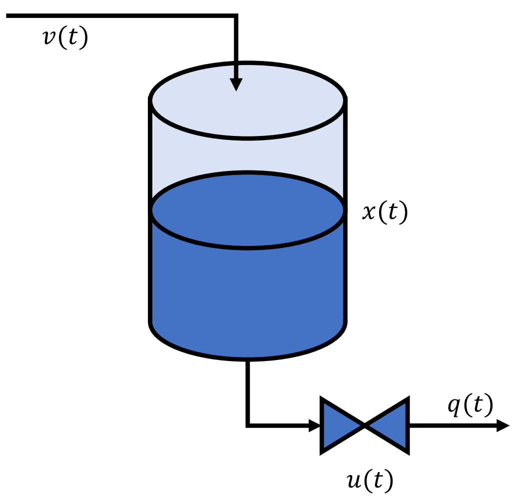

Figure 2.1 Scheme of the simulated system, including reservoir, valve, and key variables.

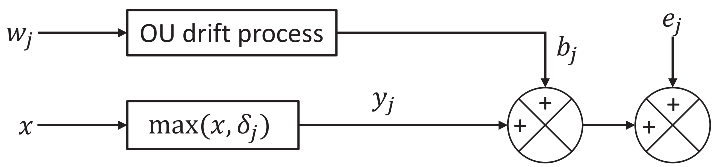

Figure 2.2 Scheme of the sensor signal flow. The measured variable (x) is nonlinearly transformed to produce the recorded signal (y), after which the accumulated drift (b_j) and noise (e_j) are added. The drift (b_j) is the result of an Ornstein–Uhlenbeck (OU) process, which corresponds to the integration of Gaussian input noise (w_j). Critical for the proposed method to work is that the drift (b_j) is not affected by the sensor nonlinearity while the error-free signal (y) is.

With a_f, θ_f, and ϕ_f are the amplitude, period, and phase angle of the fth sine wave component, a_0 is the mean flow rate, and ε is an arbitrarily small positive number. The expression $\lfloor\cdot\rfloor$ specifies the floor function and $\mathcal{U}(0,1)$ specifies the standard uniform distribution. $A_3(t)$ is a time-varying amplitude changing with each increasing zero-crossing of the corresponding sine wave.

We assume that there are $J=2$ pressure sensors ($j=1,2$) placed in the reservoir at distinct and known heights in the reservoir (δ_j). The error-free signals ($y_j = y_j(t)$) thus are:

$$y_j = y_j(t) = \max(x(t), \delta_j) \tag{2.3}$$

Without loss of generality, we assume that $\delta_{j-1} < \delta_j$, i.e., the sensors are indexed according to increasing height.

The actual sensor measurements, with drift and noise, are obtained at discrete time instants and simulated through the following equation:

$$\tilde{y}_{j,k} = y_j(t_k) + b_j(t_k) + e_j(t_k) \tag{2.4}$$

$$t_k = t_{k-1} + \Delta t \tag{2.5}$$

where $b_j(t_k)$ is the offset in the j th sensor at time t_k due to drift, $e_j(t_k)$is the random measurement error at time t_k, and Δt is the time difference between consecutive measurements. Figure 2.2 gives an overview of the signal path from the measured variable (x) until the noisy measurement by sensor $j(\tilde{y}_j)$. Most important for this study is that the drift term (b_j) is added after the nonlinear signal transformation.

The sensor offset drift is simulated such that it is stochastic yet similar in all sensors. To this end, we simulate the drift rate in each sensor as a linear combination of Ornstein–Uhlenbeck (OU) processes (Ohmura *et al.*, 2019; Thornton & Chambers, 2017):

$$dr_j(t) = \frac{1}{\tau_d} r_j(t)\mathrm{d}t + \mathrm{d}w_j, \qquad r_j(0) = 0, \qquad r_j(0) = 0 \qquad (j = 0, \ldots, J) \tag{2.6}$$

where the signals w_j represent $J+1$ Wiener noise inputs. We note that an OU process can be thought of as a continuous-time analogue of the discrete-time

AR(1) process. We assume the same time constant τ_d for all sensors. The offset in sensor j is then obtained by solving:

$$\dot{b}_j(t) = \sigma_0 r_0(t) + \sigma_j r_j(t), \qquad b_j(0) = b_{j,0} \qquad (j = 1,\ldots,J) \tag{2.7}$$

In this form, $\sigma_0 r_0(t)$ is the drift rate shared by all J sensors while $\sigma_j r_j(t)$ is the drift rate unique to sensor j. Values of σ_j ($j=0,\ldots, J$) are set so that the shared drift is dominant. This creates an unfortunate yet realistic situation where the deviation between two sensor signals cannot be used as a reliable indicator for drift. For examples of such sensor behavior, see Ohmura *et al.* (2019). In addition, the initial offsets ($b_{j,0}$) are set to non-zero values to simulate the effect of a calibration error at time of installation.

2.2.2 Methods

In what follows, we explain the method for automatic sensor calibration first. Then the proposed control system to obtain informative measurements is explained.

2.2.2.1 Sensor auto-calibration

The main idea underlying our approach to drift correction is that the discontinuous response curve in the sensors can be used to identify their offset without resorting to manual or otherwise cumbersome reference measurements or any form of on-site maintenance. Figure 2.6b shows measurement pairs obtained in a situation where both sensors exhibit a significant offset and the true level x oscillates around the location of the second sensor (δ_2). As one can see, this results in hockey-stick-like profile for the measurement pairs. Importantly, the location of the bend in this profile corresponds to the coordinate pair(δ_2+b_1, δ_2+b_2). Key to this behavior is that the drift is added after the nonlinear signal transformation, as explained above. As a result, one can obtain time-local estimates for b_1 and b_2 if sufficient data points can be collected within a time window short enough to assume constant offset values. Estimation of these offsets is practically equivalent to re-calibrating the sensors, as the estimated offset can be subtracted from the sensor readings as soon as they are available.

The detailed procedure used for sensor re-calibration follows next. As no manual effort is needed, we name this the auto-calibration procedure from here on. We assume the L most recent measurement pairs $(\tilde{y}_{1,l}, \tilde{y}_{2,l})$ are recorded and available ($l=1, \ldots, L$). Then auto-calibration is executed by solving the following optimization problem.

$$\hat{\chi}, \hat{\beta} = \arg\min_{\chi,\beta} Q(\chi, \beta)$$

$$\text{subject to: } Q(\chi,\beta) = \frac{1}{L}\sum_{j}^{J}\sum_{l}^{L}\left(\tilde{y}_{j,l} - y_{j,l}\right)^2 + \gamma\frac{1}{J}\sum_{j}^{J}\left(\beta_j - \beta_j^*\right)^2$$

$$y_{j,l} = \max\left(\chi_l, \delta_j\right) + \beta_j \quad (i = 1,\ldots,L, j = 1,\ldots,L)$$

where $\hat{\chi}$ is an L-dimensional vector of level estimates, $\hat{\beta}$ is the J-dimensional vector of sensor offset estimates, and β^* is the J-dimensional vector containing the most recent estimates of the sensor offsets. The values $y_{j,l}$ are predictions of the jth sensor measurement in the lth sample. The first term in the objective function Q is the sum of squared residuals between the measurements and these predictions and measures the quality of the fit. The second term is a regularization term, measuring the magnitude of change between the new offset estimates and previous ones. The relative importance of the two terms is defined by the user-specified regularization parameter γ. In this study, we set $\gamma = 10^{-3}$. This second term prevents making extreme changes in the estimated offsets from one calibration event to the next. It also prevents updating the offset estimates when the measurement pairs do not contain information about the offset values, as will be illustrated below.

The above problem, while nonlinear, exhibits some favorable properties. First, the values for $y_{j,l}$ are (non-strictly) monotonic in the optimization variables (χ, β) while the objective function is quadratic in $y_{j,l}$ and $\vec{\beta}$. As a result, the optimization problem is a non-smooth convex optimization problem (Nesterov, 2004). This means a global optimum exists and can be found through a local search. Note however that the global optimum is not necessarily unique, that is, the global optimum may be attained in a convex region rather than a single point. The exact conditions that lead to a unique solution are yet to be specified precisely and is out of scope for this chapter. Second, the above optimization problem can be reformulated as a mixed-integer quadratic program (MIQP), for which robust optimization software exists. This reformulation is achieved through the *big-M* approach (Hooker, 2011) and is detailed in the Appendix. Solving the MIQP produces estimates for $\hat{\chi}$ and $\hat{\beta}$.

The auto-calibration procedure is repeated at a regular time interval, Δt_{cal}, starting at the first time L measurement pairs are available. We write the most recent estimates for β available at time t_k as $\hat{\beta}_k$. In what follows, the momentary change in the estimates $\hat{\beta}_k$ is key to achieve a smooth control and is written as

$$\Delta\hat{\beta}_k = \hat{\beta}_k - \hat{\beta}_{k-1} \tag{2.8}$$

At any time, the measurements, corrected with the most recent offset estimates are always available:

$$\underline{y}_{j,k} = \tilde{y}_{j,k} - \hat{\beta}_{j,k}$$

2.2.2.2 Change-point-seeking control

As will be illustrated below, successful auto-calibration of both sensors requires access to a set of L measurement samples that includes (a) multiple samples for which the level x is above the location of sensor 2 (δ_2) and (b) multiple samples for which x is below this location. For this reason, auto-calibration requires that a control system is in place that can bring the true level x close to the change-point δ_2. However, since both sensors may exhibit a significant offset, one cannot know a priori which value for y_1 or y_2 will correspond to the change-point. Consequently, this cannot be achieved with a conventional setpoint control structure. In what follows, we describe a feedback control aimed at finding the change-point. The resulting controller is interpreted as a special form of extremum-seeking-control (ESC, Ariyur & Krstic, 2003; Trollberg *et al.*, 2014) and named change-point-seeking control structure.

Master controller. The most important element of the change-point-seeking control structure is the development of an indicator variable that quantifies how close the current level x is to the change-point δ_2. To this end, first consider the three sine waves of x shown in Figure 2.3a–c, following the equation

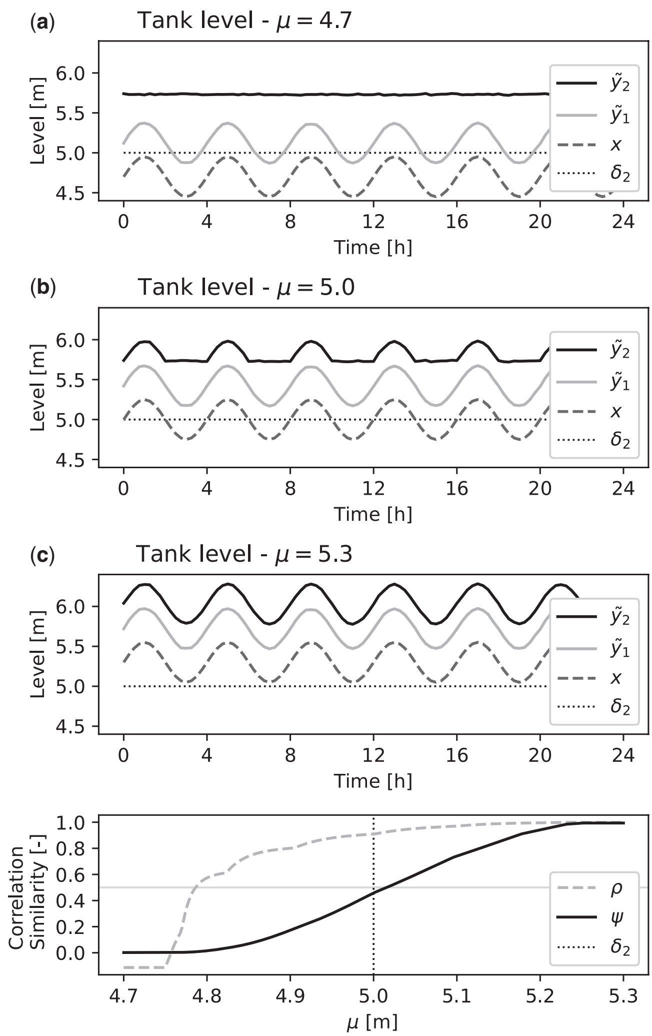

Figure 2.3 Illustration of the similarity index for change-point-seeking control. Panels (a)–(c): Sensor readings ($\tilde{y}_1$, $\tilde{y}_2$), true level (x), and change-point location (δ_2); Panel (d): Correlation (ρ) and similarity index (ψ) as a function of the mean level (μ).

$x(t) = \mu + A_d \sin(2\pi f_d t)$ with $A_d = 0.25$ m, $f_d = 6d^{-1}$, and μ ranging from 4.7 to 5.3. These sine waves are (i) below δ_2 (Figure 2.3a); (ii) centered at δ_2 (Figure 2.3b); and (iii) above δ_2 (Figure 2.3c). The same figure also shows measurements of sensors 1 and 2, using the parameter values for δ_1, δ_2, σ as in the case study explained above and using the initial offsets ($\beta_{1,0}$ and $\beta_{2,0}$). Despite the offsets, one can see in panel (a) that sensor 1 is sensitive to x while sensor 2 is not. The correlation between both measurement time series is very low in this case ($\rho = 0.084$). In contrast, both sensors are sensitive in the case shown in panel (c) and the correlation between the time series is very high in magnitude ($\rho = 0.99$). In panel (b), one sees that sensor 2 is sensitive to change in x about half the time, particularly when x rises above δ_2. In this case, the correlation becomes 0.91. Figure 2.3d shows the correlation coefficient (ρ) as a function of the mean level (μ). The correlation coefficient rises monotonically with μ, which illustrates that correlation between y_1 and y_2 could be used as an indicator of the closeness of x to the change-point. However, the profile lacks the smoothness and symmetry that is needed to formulate a simple control law.

Figure 2.3d shows another measurement of similarity (ψ) designed to achieve better smoothness and symmetry through trial-and-error. This similarity index ψ is computed as

$$\psi = 1 - \frac{\left|\sigma_{1,0}\left(\sigma_{0,0} - \sigma_{1,1}\right)\right| + \epsilon}{\left|\sigma_{1,0}\left(\sigma_{0,0} + \sigma_{1,1}\right)\right| + \epsilon} \tag{2.9}$$

$$\Sigma = \begin{bmatrix} \sigma_{0,0} & \sigma_{1,0} \\ \sigma_{1,0} & \sigma_{1,1} \end{bmatrix} \tag{2.10}$$

where Σ is the empirical variance–covariance matrix and ε is an arbitrarily small positive number. As can be seen in Figure 2.3d, this similarity index exhibits a sigmoidal response that ranges between 0 and 1 and that is close to anti-symmetric around the point $x = \delta_2$. While other indicators are likely to be useful as well, we use ψ as the indicator of choice for change-point-seeking control.

To achieve change-point-seeking, we name ψ^* the setpoint for ψ and set it to 0.5. The change-point-seeking controller manipulates y_1^*, the setpoint for y_1 through use of the following integral control law:

$$y^{\dagger} = y_{1,k-1}^{*} - I_{\psi} \cdot \left(\tilde{\psi} - \psi^{*}\right) - \Delta\hat{\beta}_{1,k} \tag{2.11}$$

$$y_{1,k}^{*} = \max(y_{\mathrm{L}}, \min(y^{\dagger}, y_{\mathrm{U}})) \tag{2.12}$$

with I_{ψ} a control tuning parameter and y_{L} and y_{U} defining the permitted range y_1^*. Note that this control law acts as a filter on the value of $\tilde{\psi}$, which is the online estimate of ψ as discussed below. The change in offset estimate for sensor 1 ($\Delta\hat{\beta}_{1,k}$) is subtracted in Eq. 15 to achieve bumpless transfer (Åström & Hägglund, 1995; Olsson, 1992). The same bumpless transfer feature will be implemented throughout the remaining components of the control system. The value for $\tilde{\psi}$

is computed as the outer product of a high-pass filtered measurement vector, specifically as follows:

$$\tilde{z}_{j,k} = \alpha \tilde{z}_{j,k-1} + \alpha\left(\tilde{y}_{j,k} - \tilde{y}_{j,k-1}\right)$$
$$\tilde{\Sigma} = \left[\tilde{z}_{1,k} \quad \tilde{z}_{2,k}\right]^T \left[\tilde{z}_{1,k} \quad \tilde{z}_{2,k}\right] = \begin{bmatrix} \tilde{\sigma}_{0,0} & \tilde{\sigma}_{1,0} \\ \tilde{\sigma}_{1,0} & \tilde{\sigma}_{1,1} \end{bmatrix}$$
$$\tilde{\psi} = 1 - \frac{|\tilde{\sigma}_{1,0}\left(\tilde{\sigma}_{0,0} - \tilde{\sigma}_{1,1}\right)| + \epsilon}{|\sigma_{1,0}\left(\tilde{\sigma}_{0,0} + \tilde{\sigma}_{1,1}\right)| + \epsilon}.$$

Note that $\tilde{\psi}$ is a noisy estimate of ψ, as will be shown below. However, the change-point-seeking control law (Eq. 2.11) acts as a low-pass filter, similar to extremum-seeking control. To illustrate this, we compute ψ^*, a low-pass filtered version of $\tilde{\psi}$ using the same parameter I_ψ:

$$\psi^\star_k = \psi^\star_{k-1} + I_\psi\left(\tilde{\psi}_k - \psi^\star_{k-1}\right). \tag{2.13}$$

Although $\psi^\star$ has no role in the feedback control system, it can be used as a tool to tune the value of I_ψ. We discuss further possible refinements of the control strategy in Section 2.4.

The above change-point-seeking controller is activated on an intermittent basis. When this controller is not active, the setpoint for $y_1\left(y^*_{1,k}\right)$ approaches a user-set level setpoint (x^*) as follows:

$$y^\dagger = y^*_{1,k-1} + I_\psi\left(x^* - y^*_{1,k-1}\right) - \Delta\hat{\beta}_{1,k} \tag{2.14}$$

$$y^*_{1,k} = \max\left(y_\mathrm{L}, \min\left(y^\dagger, y_\mathrm{U}\right)\right). \tag{2.15}$$

The tuning parameter I_ψ used for this control law is the same as in the change-point-seeking control law in view of simplicity, although this is not a requirement.

Inspired by extremum-seeking control techniques, a dither signal is added to the setpoint $y^*_{1,k}$ to promote unbiased estimation of $\tilde{\psi}$. The perturbed setpoint is:

$$y^\#_{1,k} = y^*_{1,k} + p_k \tag{2.16}$$

$$p_k = \begin{Bmatrix} A_p \sin\left(2\pi f_p(t - t_p)\right), & \text{if } t_p \le t \\ 0 & \text{otherwise} \end{Bmatrix} \tag{2.17}$$

where the amplitude (A_p), the frequency (f_p), and the time of activation of the dither signal (t_p).

Slave controller. Finally, the measurement $\tilde{y}_1$ is brought close to its setpoint with a conventional proportional-integral (PI) controller. This controller

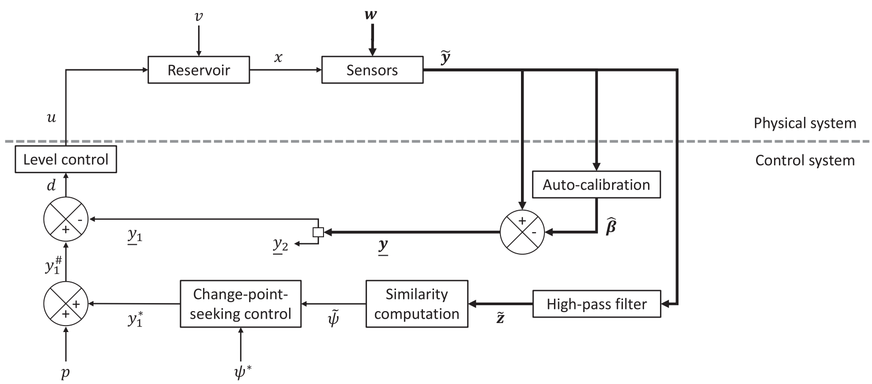

Figure 2.4 Scheme of the complete control system, including auto-calibration and change-point-seeking control. Multivariate signals are indicated with thick lines. Univariate signals are indicated with thin lines.

manipulates the valve opening (u) and is implemented in the following incremental form:

$$\begin{aligned} d_k &= y^{\#}_{1,k} - \underline{y}_{1,k} \\ \Delta y^{\#}_{1,k} &= y^{\#}_{1,k} - y^{\#}_{1,k-1} \\ u^{\dagger} &= u_{1,k-1} - K_y\left(d_k - d_{k-1} - \Delta\hat{\beta}_{1,k} - \Delta y^{\#}_{1,k}\right) - I_y d_k \\ u_{1,k} &= \max\left(u_{\mathrm{L}}, \min\left(u^{\dagger}, u_{\mathrm{U}}\right)\right) \end{aligned}$$

where K_y and I_y are the control tuning parameters and u_{L} and u_{U} define the feasible range for the valve opening. The term $\Delta y^{\#}_{1,k}$ is the momentary change in the level setpoint and is used to ensure bumpless transfer when the setpoint changes. The complete control system, with auto-calibration and change-point-seeking control is shown in Figure 2.4.

2.2.3 Simulated scenarios and performance analysis

We simulate the system and controllers in four scenarios. The first two scenarios (A and B) consist of a 6-day simulation period to illustrate the methods. In both scenarios, the dither signal is activated after 1 day and deactivated again after 5 days. The change-point-seeking control is active from the start of day 3 to the end of day 4. In scenario A, auto-calibration is never executed to focus on the performance of the change-point-seeking control. In scenario B, auto-calibration is always active and executed as explained above. This allows to illustrate how significant sensor offsets can be estimated and accounted for through the combined effect of change-point-seeking control and solving the auto-calibration optimization problem. Two additional scenarios (C and D) consist of 360-day simulation periods to study the performance of the complete control system over long time periods. In scenario C, dither signal and change-point-seeking control are applied during every 15th day in the simulation (i.e., day 15, 30, …) and the auto-calibration feature is always active. Scenario D is the same, except that the sensors are never re-calibrated in any fashion. Scenarios A, B, and C are discussed in detail in the main text, while results obtained with scenario D are discussed in the Appendix. Scenarios C and D are also used to compute several performance measures. We compute the median absolute error (MAE) and the root mean-squared error (RMSE) for the corrected measurements ($\bar{y}$), relative to the error-free sensor values (y). We do this for both sensors separately. We also compute the MAE and the RMSE for the true state (x) relative to its setpoint ($y^{\#}$).

2.2.4 Software implementation

All software used to produce our results is written in *Python* (Python Software Foundation, 2021) and uses several open-source packages, such as *Matplotlib* and *Numpy* (Harris *et al.*, 2020; Hunter, 2007). We use the commercially available Gurobi optimization software (version 9.5.1, Gurobi Optimization, LLC, 2021) to solve all MIQPs and interface it via the the related *Gurobipy* package. The code needed to reproduce all results is added as a separate. zip-file.

2.3 RESULTS

2.3.1 Demonstration of the change-point-seeking control mechanism

To illustrate the feedback control system locating the change-point in sensor 2, we inspect the results of scenario A in detail. Figure 2.5a shows the level (x), the measurements obtained with sensor 1 ($\tilde{y}_1$), and the setpoint for the sensor 1 reading ($y_1^{\#}$). The setpoint for sensor 1 reading is set equal to 3 m, whenever the change-point-seeking controller is inactive. At the start of the simulation, the sensor 1 reading is maintained around this setpoint, despite unknown changes in the feed flow rate. These changes in feed flow rate are compensated by changes in the outlet valve position, as shown in Figure 2.5e. Note that the real value of the level is 0.73 m lower due to the presence of a sensor offset (of magnitude 0.73 m). At $t = 1d$, the dither signal is activated and the level setpoint, measurement, and true level start to oscillate with a frequency of $6d^{-1}$. Note that the measured value does not track the oscillating setpoint perfectly during this time, mainly because the controller was tuned manually to achieve good disturbance rejection when the change-point-seeking control is inactive. At $t = 2d$, the change-point-seeking control is activated. At $t = 2.7d$, the level crosses the change-point for the first time. After that, the level oscillates around the change-point until $t = 4d$, when the change-point-seeking control is deactivated and conventional setpoint control is resumed. At $t = 5d$, the dither signal is also deactivated and a steady setpoint, measurement, and level is obtained. Figure 2.5b shows equivalent results for sensor 2. In this case, the sensor saturates when the true level (x) reaches a value lower than 5. One can observe that this sensor is indeed sensitive to changes in x during day 3 and 4, particularly when the true level is above 5. One can also observe an offset in sensor 2, equal to 0.42 m. Figure 2.5c shows the effects on the high-pass filtered

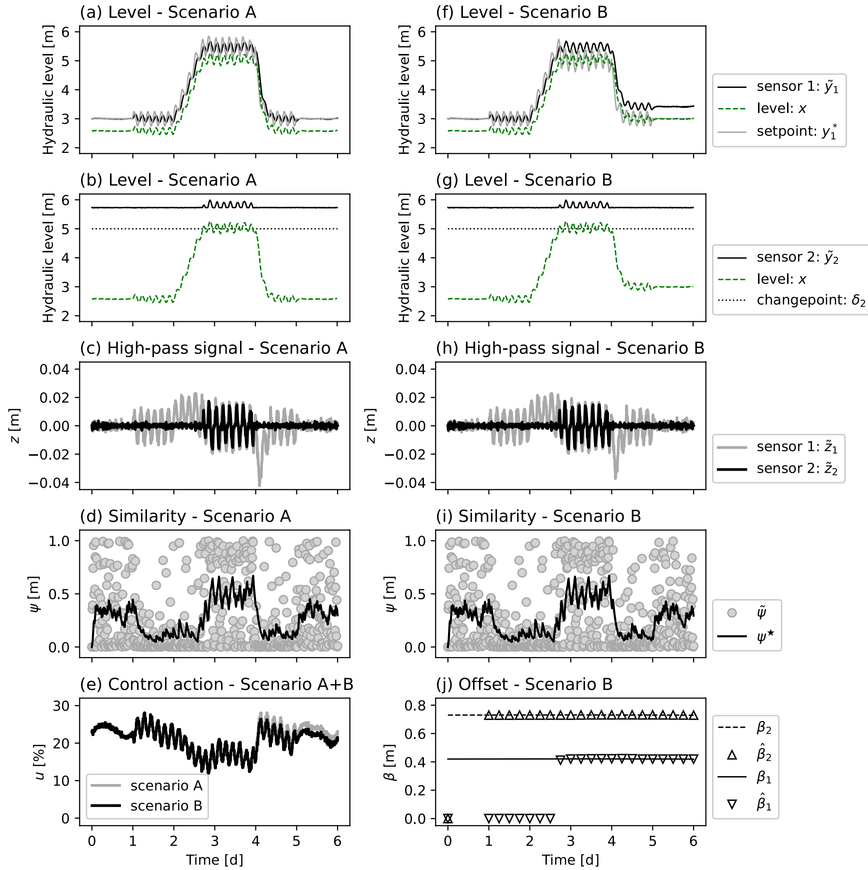

Figure 2.5 Short-term simulation results. Left panels: Scenario A; Right panels: Scenario B. Panels (a) and (f): Sensor 1 readings, true level, and setpoint; Panels (b) and (g): Sensor 2 readings, true level, and change-point value; Panels (c) and (h): high-pass filtered sensor readings; Panels (d) and (i): Similarity index ($\tilde{\psi}$) and its filtered values ($\psi^\star$); Panel (e): Valve opening; and Panel (j): True and estimated offsets as a function of time.

sensor signals ($\tilde{z}_1$ and $\tilde{z}_2$). One can see that applying a dither, starting on day 1 leads to oscillations in the sensor 1 readings while sensor 2 remains insensitive. During this time, the coefficient $\tilde{\psi}$, as shown in Figure 2.5d, is noisy but is close to zero on average. As a result, the change-point-seeking control increases the setpoint for y_1 following its activation at $t = 2d$. At $t = 2.7d$, the values $\tilde{\psi}$ fluctuate between 0 and 1. Its filtered version ($\psi^\star$) hovers around 0.5 however. The net effect is that the reference setpoint remains stable from this point onward, with the true level (x) oscillating around $5m$ as observed above. Once the change-point-seeking control is deactivated, x drops below the change-point and the values for $\tilde{\psi}$ are again closer to 0. Before and after the application of dither, the

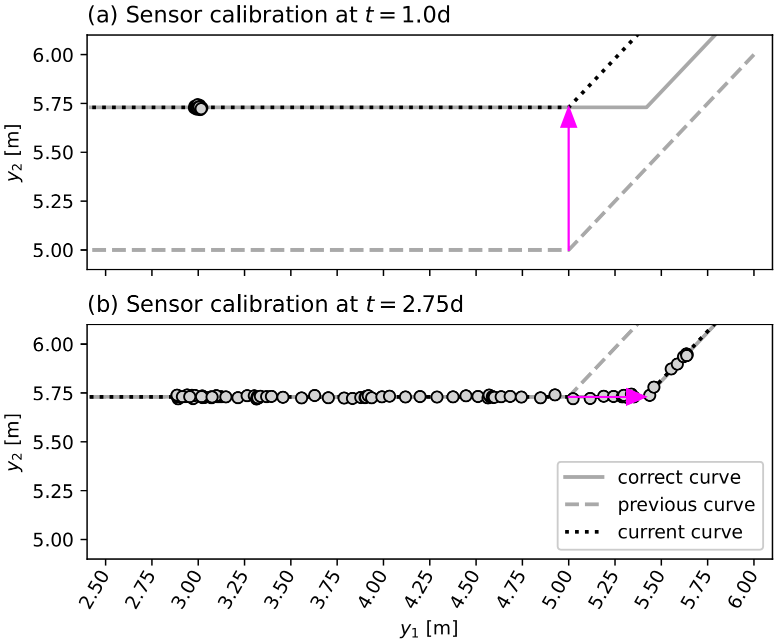

Figure 2.6 Illustration of the auto-calibration method. Top: Auto-calibration at time $t = 1.0$ d in scenario B; Bottom: Auto-calibration at time $t = 2.75$ d in scenario B. Panels show the available data for auto-calibration, as well as the previous and updated calibration curve.

values for $\tilde{\psi}$ are fairly noisy and are close to 0.5. This indicates that excitation of the level setpoint is important to estimate $\tilde{\psi}$ reliably, in turn being important for the change-point-seeking controller to work as intended.

2.3.2 Demonstration of the sensor calibration mechanism

The auto-calibration method is illustrated through scenario B. The dynamic behavior of key variables is shown in Figure 2.5e–i, analogously to the results obtained with scenario A. The most important difference with scenario A is that the level control does not suffer from the biased measurements from $t = 4d$ onward. Indeed, its level is controlled around $3m$ as intended. In addition, one can also see that the feedback control system behaves smoothly despite drastic changes in the measurements following re-calibration, thanks to provision of bumpless transfer features. Figure 2.5j shows the estimated sensor offsets as a function of time. At $t = 1d$, the minimum number of data points ($w = 96$) to enable auto-calibration is reached and the nonlinear calibration problem (Eq. 10) is solved for the first time. Figure 2.6a shows the sensor 2 readings as a function of the sensor 1 readings. All measurement pairs hover around the point (3,5.73) reflecting the steady conditions shown during day 1 in Figure 2.5. It also shows a curve according to the original estimates for the sensor offsets (both zero). In this case, all measurements are closest to the flat segment of curve. As a result, the re-calibration procedure shifts the original curve (with zero offsets) upward to fit the cloud of data points better. The resulting estimate for β_2 equals 0.7301 m, which is close to the true offset for sensor 2, whose mean and standard deviation during day 1 are 0.7304 m and 11.29×10^{-6} m. In contrast, the estimate for β_1 equals -3.138×10^{-12} and is far from the true offset values (0.4204±0.00003545 m). The estimates for β_1 and β_2 do not change significantly until $t = 2.75$ d.

The first time sensor calibration is executed after the initial crossing of the change point (at $t = 2.7$ d) occurs at $t = 2.75$ d. Figure 2.6b shows the $w = 96$ measurement pairs available for calibration at this time. In contrast to earlier time points, these data points now form a hockey-stick profile that enables to locate the discontinuity in the response curve for sensor 2. Both β_1 and β_2, essentially corresponding to the discontinuity in the hockey-stick profile, are now identifiable. As a result, the auto-calibration procedure can shift the curve describing the relationship between y_1 and y_2 to an accurate location. The estimates for β_1 and β_2 are now 0.4174 and 0.7304. These values are close to the true offset values, whose means and standard deviations are 0.4205 ± 0.000110 m (sensor 1) and 0.7304 ± 0.000150 m (sensor 2) during the 24 h period preceding $t = 2.75$ d. Clearly, this approach based on discontinuous sensor response curve enables automatic calibration of sensor offsets without manual or cumbersome reference measurements.

2.3.3 Long-term performance evaluation

We now study the long-term performance of the control system with change-point-seeking control and auto-calibration (scenario C). Figure 2.7a and b shows the level, measurements, and setpoints as a function of time. Every 15 days, one can see a spike in each of these, due to the change-point-seeking control that is active then. Most importantly, the true level is maintained close to the setpoint (3 m) between periods of active change-point-seeking control as soon as the first period with active change-point-seeking control (day 15) has ended. Clearly, the combined system can maintain accurate setpoint level control in presence of sensor drift and unmeasured and unknown fluctuations in the feed flow rate. For a comparison of the performance in the absence of change-point-seeking control and auto-calibration, refer to Section A.1 in the Appendix. Figure 2.7c and d shows the measurement errors after correction with the estimated offsets. During day 1, both sensors are off with more than 0.4 m, reflecting the initial offset. After 1 day, sensor 2 is re-calibrated (as observed in scenarios A and B). Sensor 1 is corrected effectively on day 15, when the change-point-seeking control is activated for the first time. After that, the measurement error of the corrected sensor readings remains below 0.15 m for both sensors. This deviation is less than 8% of the maximum offset (2.4 m, for sensor 2). In addition, one clearly sees that the error in sensor 1 drops towards zero each time the change-point-seeking control is activated. This is also visible in Figure 2.7e. Here, the offset estimate for sensor 2 ($\hat{\beta}_2$) moves in a stepwise fashion, with each step occurring during periods with active change-point-seeking control. This means that even better accuracy could be achieved

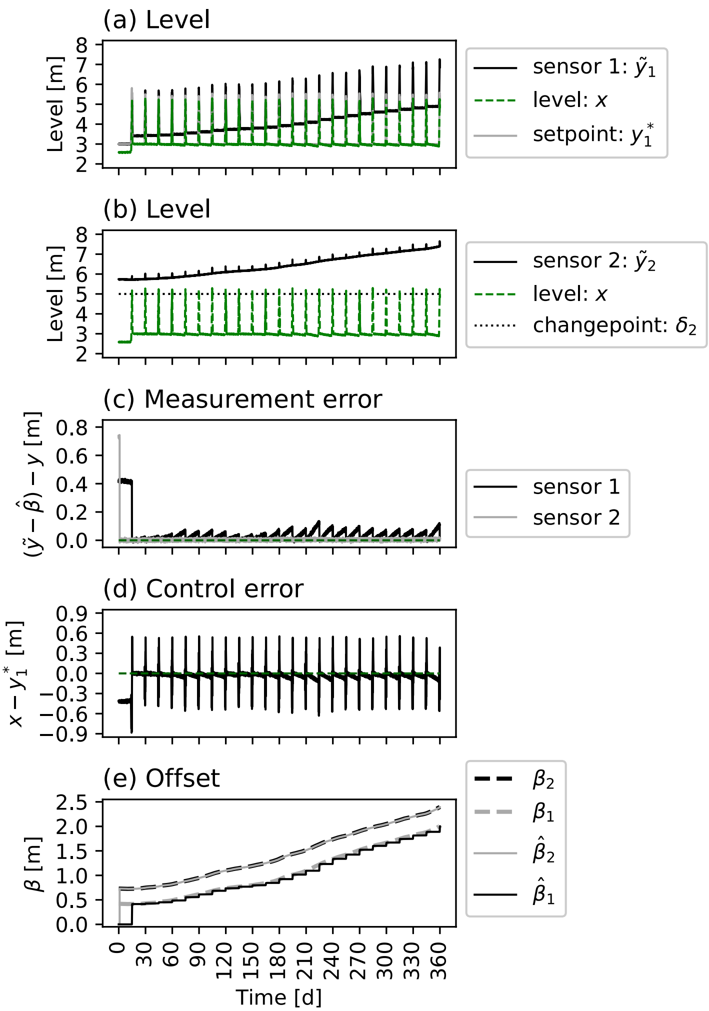

Figure 2.7 Long-term simulation results in scenario C. (a) Sensor 1 readings, true level, and setpoint; (b): Sensor 2 readings, true level, and change-point value; (c) measurement error accounting for auto-calibration; (d) control error; (e) true and estimated offsets as a function of time.

by decreasing the time interval between periods with active change-point-seeking control. We return to this point in Section 2.4. Figure 2.7d shows the deviation between the setpoint for $x\left(y_1^{\#}\right)$ and the true level (x). One can see the effect of the change-point-seeking control as periods of increased magnitude in control error, as was observed in scenarios A and B. In between these periods, the control error remains close to zero as soon as the first period with change-point-seeking control has passed.

Table 2.2 Measurement and control performance metrics evaluated for scenarios C and D.

Performance Metric	C (m)	D (m)	Reduction from D to C (%)
MAE sensor 1	0.0281	0.919	96.9
MAE for sensor 2	0.00406	1.34	99.7
MAE for level control	0.0329	0.904	96.4
RMSE for sensor 1	0.0804	0.495	83.8
RMSE for sensor 2	0.0384	0.517	92.6
RMSE for level control	0.400	0.509	21.5

Table 2.2 shows summary statistics describing both measurement and control performance in scenarios C and D. All statistics are computed over the whole simulated time window, thus including the initial 14 days before change-point-seeking control is activated for the first time. Most importantly, scenario C, during which change-point-seeking control and auto-calibration are executed regularly, reduces all error metrics relative to scenario D, where neither change-point-seeking control and auto-calibration are ever active. We record improvements with a factor 20 or more for the median-based summary statistics. These are most dramatic as they are less sensitive to the measurement and control error during initial 14-day period and the periods of change-point-seeking control. In contrast, the root-mean-square-based statistics are heavily influenced by the initial 14-day period and periods of change-point-seeking control, leading to a factor 1.2 improvement for the control error. Still, the root mean-squared measurement errors improve with a factor 5 or more.

2.4 DISCUSSION

In what follows, we discuss the main aspects of the proposed method that require further investigation.

2.4.1 Sensor calibration as a nonlinear optimization problem

With this chapter, we showed that sensor calibration is feasible without reference measurements if at least one of the sensors has a change-point in the sensor response curve at a precisely known value for the measured variable. This discontinuity allows re-calibrating the sensors by solving a nonlinear optimization problem. This nonlinear optimization problem can always be solved to a globally optimal solution thanks to a mixed-integer quadratic program formulation. However, such a solution may not be unique. The exact conditions under which a unique solution will be obtained need to be identified still.

An interesting feature of the sensor calibration method is that it does not rely on a dynamic model of the process, in contrast to an earlier approach based on the UKF (Chowdhury *et al.*, 2021). Should a reliable model be available however, then joint estimation of the process states and the sensor offsets could be achieved through moving horizon estimation (Rao & Rawlings, 2002), which solves similar optimization problems repeatedly as new data arrives. We also note that the proposed method enables quantification of the sensors' offsets but not their sensitivities. Although we believe a similar method could be developed to simultaneously estimate both offsets and sensitivities, this remains to be developed.

2.4.2 Refinements to the change-point-seeking control structure

A change-point-seeking control structure has been proposed to bring the process to a state where information about the sensors' offset is contained in the collected measurements. We consider this control structure a special case of extremum-seeking control. In this study, we have aimed to make the complete control structure as simple as possible. This means that low-pass filters for the measurements ($\tilde{y}$) or the similarity index ($\tilde{\psi}$), although probably beneficial, were deliberately avoided in favor of a simpler representation. In addition, control tuning parameters were tuned manually to obtain sensible results but not optimized. Naturally, real-world systems may benefit from inclusion of additional features, such as low-pass filters, and a more careful and systematic tuning. Methods for online optimal experimental design or active learning (De Pauw & Vanrolleghem, 2006; Mesbah, 2018; Vanrolleghem & Van Daele, 1994) may be used to obtain control actions that produce measurements that are optimally informative about the sensor offsets and sensitivities.

2.4.3 Nonlinearity is a feature, not a bug

In the water sector, it is typical to include a maximally linear response curve as an important specification for sensor design and manufacturing. Nonlinearity of any kind is often regarded as a bug, that is, something to avoid (if possible), or to correct for (if needed) (ISO, 2003). In contrast, this chapter illustrates that deliberate introduction of nonlinear features in a sensor's behavior produces tangible benefits for data quality management. A key requirement for the proposed method to work is that the drift process must act on the nonlinear signal, that is, the drift cannot affect the sensor signal before the measured variable is translated nonlinearly into the sensor signal (see Figure 2.2 and related discussion).

We note that some sensors available in the market already feature the nonlinear response curves that could be exploited for this purpose. For example, level sensors exhibiting this or similar types of nonlinearity include sensors based on the measurement of conductivity, pressure, or vibration (Wani *et al.*, 2017). Similarly, several light sensors and thermocouples for temperature measurement exhibit nonlinear response curves that may enable autonomous drift correction (Bentley, 1984; Salim *et al.*, 2011). To the best of our knowledge, most water quality sensors are designed and manufactured to achieve a response that is as linear as possible. Given that these are most prone to drift, we believe water quality sensor design and manufacturing practices should move away from specifying linearity as a requirement and consider the benefits of nonlinear features in the produced signal, especially when considered for remote or unstaffed systems (Schneider *et al.*, 2019, 2020).

2.5 CONCLUSIONS

The most important conclusions of our work are:

- Automatic drift correction is feasible in (a) absence of complete or precise understanding of the causes of drift and (b) absence of trusted reference measurements.
- Data that are useful for automatic drift correction can be collected by letting the measured variable oscillate around a discontinuity in one of the sensor response curves, which is named the change-point.
- Feedback control can be used to bring a process state to a change-point of interest without prior knowledge of the location of this change-point. This is named change-point-seeking in this work and a working example has been presented in this study.

At this time, several directions of future research have been identified, including:

- The development of a method that can track drift in multiple parameters of the sensor calibration curves, such as offset, sensitivity, and curvature.
- The development of sensors, including water quality sensors, that exhibit nonlinear features facilitating the automatic re-calibration without human intervention or reference measurements.

A APPENDIX

The supplementary information contains (1) results obtained with scenario D, as described in the main text, (2) detailed formulation of sensor calibration problem as a mixed-integer quadratic program (MIQP), and (3) the software used to produce all results in this study.

A.1 Results obtained with scenario D

Figure A.1 shows the sensor measurements and process dynamics obtained in scenario D. In this case, the sensors are never calibrated. As expected, this severely degrades the data quality and control performance of the system. First, the sensor offsets are never corrected, meaning that the measurement error ranges between 0.4 and 2.5 m over the course of the simulated period. Since sensor 1 measurements are used for feedback control, this also means that the true tank level is always below the desired setpoint, with magnitudes of the control errors matching the offsets in sensor 1. This control error ranges from 0.4 at the start of the simulation to 2.0 m after one year.

A.2 Sensor calibration formulated as mixed-integer quadratic program (MIQP)

To reformulate the sensor calibration problem in MIQP form, we first introduce an $J \times$ L-dimensional matrix ζ containing binary variables, $\zeta_{j,l}$. These binary variables indicate whether sensor χ_l is above or below δ_j. The optimization problem Eq. 10 then becomes:

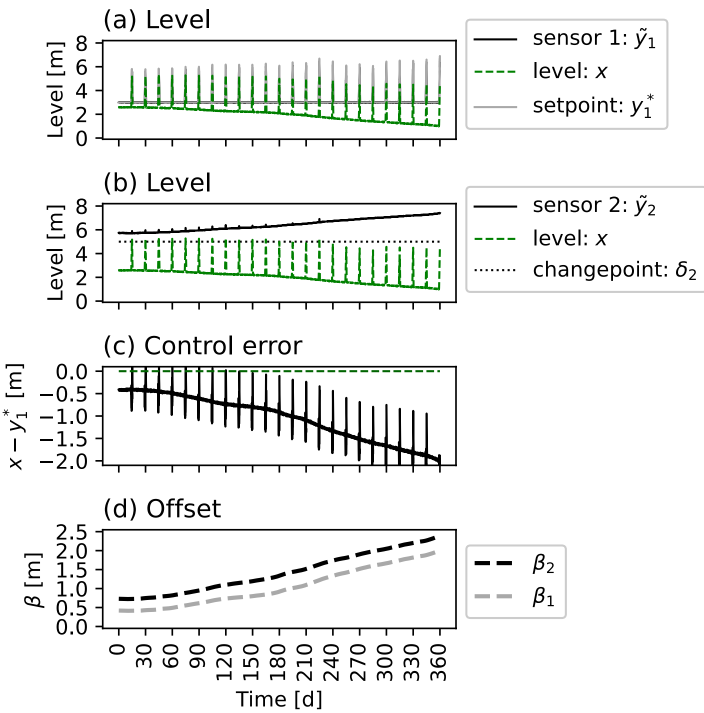

Figure A.1 Long-term simulation results in scenario D. (a) Sensor 1 readings, true level, and setpoint; (b) Sensor 2 readings, true level, and change-point value; (c) control error; (d) true offsets as a function of time.

$$\hat{\vec{\chi}}, \hat{\vec{\beta}}, \hat{\zeta} = \arg\min_{\vec{\chi}, \vec{\beta}, \zeta} Q(\vec{\chi}, \vec{\beta})$$

$$\text{subject to:} \quad Q(\vec{\chi}, \vec{\beta}) = \frac{1}{L} \sum_{j}^{J} \sum_{l}^{L} \left(\tilde{y}_{j,l} - y_{j,l}\right)^2 + \gamma \frac{1}{J} \sum_{j}^{J} \left(\beta_j - \beta_j^*\right)^2$$

$$y_{j,l} = \delta_j + \zeta_{j,l}\left(\chi_l - \delta_j\right) + \beta_j \quad (i = 1, \ldots, L, j = 1, \ldots, L)$$

$$\zeta_{j,l} = \begin{cases} 1 & \text{if: } x_l \geq \delta_j \\ 0 & \text{otherwise} \end{cases}, \quad (i = 1, \ldots, L, j = 1, \ldots, L)$$

In this form, the optimization problem is a mixed-integer bilinear program. The bilinear terms in the equality constraints are products of a binary and a continuous variable. As a result, one can obtain a relaxed version of this problem through the *Big-M* approach. Each bilinear equality constraint is transformed into four linear inequality constraints. This leads to the following mixed-integer quadratic program (MIQP) formulation:

$$\hat{\vec{\chi}}, \hat{\vec{\beta}}, \hat{\zeta} = \arg\min_{\vec{\chi},\vec{\beta},\zeta} Q(\vec{\chi},\vec{\beta})$$

$$\text{subject to: } Q(\vec{\chi},\vec{\beta}) = \frac{1}{L}\sum_{j}^{J}\sum_{l}^{L}\left(\tilde{y}_{j,l} - y_{j,l}\right)^2 + \gamma\frac{1}{J}\sum_{j}^{J}\left(\beta_j - \beta_j^*\right)^2$$

$$y_{j,l} - \beta_j \geq \delta_j \; (i = 1,\ldots,L, j = 1,\ldots,J)$$

$$y_{j,l} - \beta_j \leq \delta_j + \zeta_{j,l} M \; (i = 1,\ldots,L, j = 1,\ldots,J)$$

$$y_{j,l} - \beta_j \geq \chi_l \; (i = 1,\ldots,L, j = 1,\ldots,J)$$

$$y_{j,l} - \beta_j \leq \chi_l + \left(1 - \zeta_{j,l}\right) M \; (i = 1,\ldots,L, j = 1,\ldots,J)$$

$$\zeta_{j,l} \leq \zeta_{j-1,l} \; (i = 1,\ldots,L, j = 2,\ldots,J)$$

In this formulation, M is an arbitrary large positive value. This problem formulation is equivalent to Eq. 30 if M is chosen such that (a) Eq. 34 is never active when $\zeta_{j,l} = 1$ and (b) Eq. 36 is never active when $\zeta_{j,l} = 0$. When $\zeta_{j,l} = 1$, it follows that $y_{j,l} - \beta_j = \chi_l$. This means that Eq. 34 will be inactive as long as $\delta_j - \chi_l$ is smaller than M. When $\zeta_{j,l} = 0$, it follows that $y_{j,l} - \beta_j = \delta_j$. As a result, Eq. 36, will be inactive as long as $\zeta_{j,l} = 0$ if $\delta_j - \chi_l$ is always smaller than M. Thus, if all estimates for χ_l lie between $\delta_j - M$ and $\delta_j + M$, solving the MIQP is equivalent to solving the original calibration problem. A sensible value for M can be set based on the physical understanding of the system. This is the strategy taken in this work by setting $M = 100$. Alternatively, the value of M can be adjusted by solving the optimization problem repeatedly for increasing values of M until M is large enough so that $\delta_j - M < \hat{\chi}_l < \delta_j + M$.

A.3 Software

The code needed to reproduce all results is located in this online repository: https://gitlab.com/krisvillez/drift_correction.

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The story of Gustaf – from the early days to his emeritus adventures

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3.1 OUTLINE

In this contribution we try to chronologically summarize some highlights from Gustaf's outstanding research career within the water sector. We tell his story from a Swedish perspective, since it is in Sweden he started his career and his early research with the water utilities. It is also here he had his long career as professor and also remained most of the time as professor emeritus. Although written with a Swedish perspective, his contributions surpass any national boundaries. Needless to say, this is not a complete review but it should hopefully give the reader a feeling for Gustaf's extraordinary research career.

3.2 THE EARLY YEARS (1970S AND 1980S)

Gustaf's interests in wastewater engineering began already in 1972 when a student pointed out the potential to apply more automatic control strategies in wastewater treatment plants (WWTPs) (Olsson, 2012a). Possibly inspired by this, Gustaf and a colleague made a study visit to the US and Canada in 1973 (Ulmgren & Olsson, 1973). They visited several WWTPs and had meetings and discussions with plant personnel and researchers. One person Gustaf met was professor John Andrews who he later wrote several papers with, for example (Olsson & Andrews, 1978), and also visited several times as a visiting professor. The travel report (Ulmgren & Olsson, 1973) is very comprehensive but let us here just mention the process computer used in one of the plants: An IBM version 7, which had 1 kB of memory left for writing control algorithms. The code of the controller had to be written in assembler!

Already from the beginning, Gustaf had close collaboration with Swedish WWTPs. In his first research projects related to WWTPs he collaborated with personnel from two Swedish WWTPs; Käppala WWTP in Stockholm and the treatment plant in the city of Gävle. The collaboration with Käppala continued for many years. In Olsson and Hansson (1976), for the time novel, a system identification approach was used to estimate the dissolved oxygen (DO) dynamics using a dynamic black-box model consisting of a first-order ARMAX model. Also DO control and settler dynamics modelling experiments are described. Here one could see a lot of creative analysis and thinking, including emerging ideas related to data-driven monitoring.

The 1980s was certainly the heydays of adaptive control (at least in academia). In Sweden, ASEA (today ABB) released an adaptive controller named Novatune around 1983. The self-tuning controller used in the Novatune was based on the research from Gustaf's department at the time, led by Professor Karl-Johan Åström during the 1970s. The first adaptive controller for DO concentration in an activated sludge process was most likely implemented in Käppala by Gustaf and coworkers (Holmberg *et al*., 1988). The self-tuning controller was running for some time even after the research project was finished but was later replaced for reasons which are unknown to us. It could have been that a simple PI-control strategy did the job equally well for this control task.

In general, 'classical' adaptive control faces robustness problems including the task to recursively estimate a feasible model for control design in a closed-loop system, which is affected by unmeasured disturbances. It is interesting to note that more recently adaptive control applied to WWTPs has gained renewed interest using the reinforcement learning concept. It is not unlikely that some researchers in that field may not be aware of the very extensive early research in adaptive control including fundamental robustness problems hiding in the adaptive control paradigm when dealing with dynamic systems, disturbances and noisy data.

A challenging modelling problem is to estimate the respiration rate and the oxygen transfer rate from closed-loop data. The problem was tackled by Gustaf and co-workers by an on-line estimation of a grey box model of the DO dynamics (Holmberg *et al*., 1988). The on-line parameters of the estimated model were used to linearize the real plant nonlinearity (this is adaptive control!). Furthermore, the linearized system was controlled by a relay in order to achieve good excitation of the plant. The strategy was evaluated at the WWTP in Malmö (Sjölundaverket). The results in Holmberg *et al*. (1988) were a key inspiration for the last author of this paper when writing his first paper related to WWTPs (Carlsson, 1994).

Already from the start, Gustaf was a role model also in summarizing research works and putting results in a larger context. Already in 1977 (when two of the authors of this text were not even born) Gustaf published a state-of-the-art paper on control of WWTPs (Olsson, 1977). He also published papers not only with national and international research colleagues but also with professionals from WWTPs (e.g., Olsson *et al*., 1985a, 1985b, 1988).

It is fair to also mention that applying automatic control and automation techniques to WWTPs was not always easy in these early days. In some sense one may argue that Gustaf was too early in bringing his new ideas of control and monitoring (adaptive control, on-line estimation of parameters and variables etc.) into the wastewater sector. A common comment was 'Who is this academic and control engineer trying to teach us how to operate our plants? We have worked with these processes for decades and we know how it should be done!'. He often had to fight hard to get the industry to listen to his novel ideas of how the new technology could actually provide benefits for the daily operation of WWTPs. Both plant managers and operators were often sceptical and one important part of Gustaf's work was to make sure that the on-line controllers he had implemented and activated in full-scale applications were not shut down by the plant operators after he had left the premises. It is a well-known fact that the water- and wastewater industry was (and maybe still is?) conservative and also different from many other process industries in terms of financing, limited financial incentive to improve the operation and no need to go beyond the legal requirements in relation to product quality. However, Gustaf knew from examples from many other types of process industries that he was on the right track and sooner or later the water industry would realize this.

3.3 PROFESSOR IN INDUSTRIAL AUTOMATION (1987 TO 2005)

In 1987 Gustaf's professional platform changed. He left the department of Automatic Control at Lund University and was inaugurated as full professor in Industrial Automation and head of the new department Industrial Electrical Engineering and Automation (IEA) in Lund. Thereby he could extend his research group with a number of new PhD students and push his work and ambitions forward at a higher speed. Gradually, the water industry also started to change its view in terms of the potential usefulness of on-line control and monitoring of WWTPs. Around this time Sweden was planning/starting to implement full nutrient removal at all its larger plants and the idea that smart control could help reduce the amounts of extra reactor volumes needed to be constructed became a prominent part of the discussions.

Immediately Gustaf realized that this was a great opportunity. He was consequently one of the creators of a new six-year national research programme (1991–1996, financed by the Swedish National Board for Industrial and Technical Development (NUTEK)) called 'Control and Operation of Wastewater Treatment Plants – New Methods and New Process Technology (STAMP)', which involved several universities in Sweden and also many of the larger national water and wastewater organizations. The purpose of the programme was to (1) strongly enhance the collaboration between academia and the water industry, (2) develop and extend methods for advanced control and optimization for the operation of WWTPs, (3) develop new process technology and instrumentation and (4) increase the knowledge of microbiology related to wastewater treatment. Also the changing working environment for operators and other staff categories at WWTPs as a result of increased automation was studied (Figure 3.1).

A major influence of Gustaf is visible both in the title of the programme and in goals 1, 2 and partly 3. Needless to say, under the enthusiastic and knowledgeable leadership of Gustaf, the entire programme was a great success

Figure 3.1 Gustaf relaxing with some good friends after a long day at the ICA2009 conference in Cairns, Australia. (Henri, Ingmar, Peter, Gustaf, Quim, Stefan, Alessandro, Ulf). Who will get the last glass of wine?

and significantly changed the view on the need for instrumentation, control and automation for operation of WWTPs in Sweden. Moreover, an entire session at the IWA World Water Congress in Singapore 1996 was devoted to the Swedish STAMP programme. In the same year, Gustaf was awarded *Vattenpriset*, the highest national award in the field, by the Swedish Water (then the Swedish Association for Water Hygiene) and humbly entered the 'Swedish Hall of Fame for Water'. Some 25 years of tireless efforts to bring modern control tools to WWTPs had finally been properly acknowledged.

Towards the end of the 1990s it was more and more sustainability issues that came into focus. Energy efficiency, cost effectiveness, resource recovery, systems analysis, life-cycle assessment, green-house gas emissions, risk assessment for the urban water and wastewater system as a whole and also including economics, organizational and legal matters were now on the agenda. The goal was to develop a more holistic view on overall urban water management. Once again Gustaf, together with several colleagues, was able to create a national research programme on Sustainable Urban Water Management (1999–2006, financed by the Swedish foundation for strategic environmental research (MISTRA)). The programme involved some 100 persons including municipalities, governmental agencies, water and wastewater organizations and companies together with several universities and was coordinated by Chalmers University of Technology. Also within this programme modelling, control, simulation and so on had an important role to play but this time it was clear to everyone from the beginning that the research programme needed to include and work with such tools. Gustaf had left his mark on the national research community.

Towards the end of the above research programme (in 2005 at the age of 65) Gustaf chose to formally retire from IEA and pass the torch on to his younger colleagues. The reason for this was certainly not lack of interest or ability but rather that as an emeritus he could take on a much more free role and really focus on the research topics closest to his heart, without having to spend 50% of his time on administrative issues. More on this will be discussed in the next section.

Gustaf has for many years been one of the most (maybe the most?) active Swedish researchers in the water field also on the international arena. His extensive involvement in the International Water Association (IWA, formerly IAWQ, formerly IAWPRC) and IWA Publishing should be briefly mentioned. Between 1997 and 2001 he served as chair of the IWA specialist group on instrumentation, control and automation (ICA) and he was a member of the IWA Strategic Council between 2002 and 2006. He has also been part of the IWA Board of Directors. In 2001 he organized the international IWA conference of ICA (ICA2001) in Malmö, Sweden, and for many years he was editor-in-chief for the IWA journal Water Science & Technology. Also within organizations such as International Federation of Automatic Control and the Institute of Electrical and Electronics Engineers he has been heavily involved. He has served on more scientific committees, programme committees and PhD evaluation committees than can be mentioned. Moreover, he has been a visiting professor at the University of Houston, Kyoto University, University of Brisbane, University of New South Wales, University of Wisconsin and so on and a consultant on automation of wastewater systems for Reid Crowther Inc., EMA Inc., city of Houston, Weyerhaeuser Company and so on (Figure 3.2).

3.4 WITH HIS OWN MEANING OF 'EMERITUS' (2005 AND ONWARDS)

'Emeritus' was in Latin used to describe soldiers who had completed their duty – 'one who served out his term'. After a long and successful academic career serving the academic society and the water and wastewater community, Gustaf embraces his new freedom as professor emeritus – but he has by no means served out his term.

Gustaf's duty to society and to the community is not finished. He is as dedicated as ever to progress towards a sustainable society for future generations. As emeritus, Gustaf embraces the new independence and his work takes a new and more free form. He is invited as guest professor at Chalmers University of Technology in Gothenburg, the Technical University of Malaysia (UTM) and at the Tsinghua University in Beijing. He is also an honorary faculty member of Exeter University in the UK.

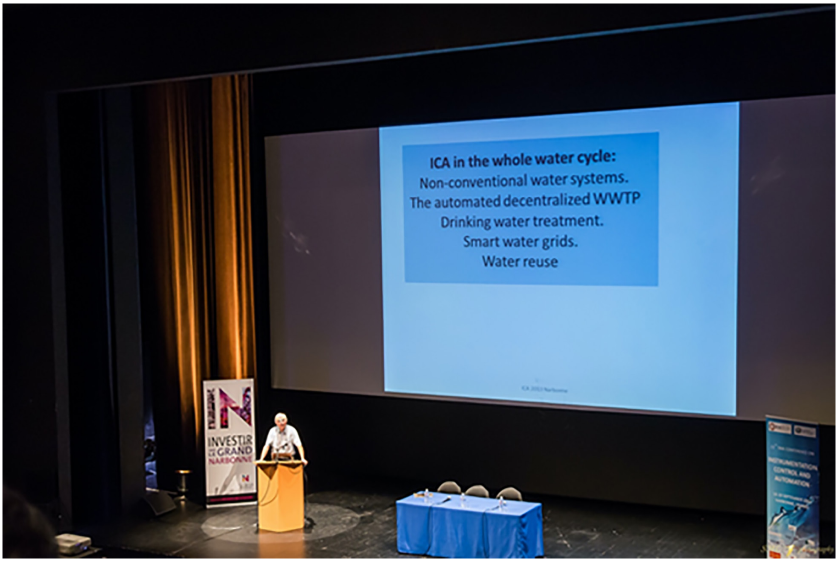

Figure 3.2 Gustaf giving one of many invited keynote presentations. Here at the ICA2013 conference in Narbonne, France.

Gustaf can focus his time and mind on what he finds most important for the future and on the things in the world that need more attention. As an *author*, *mentor* and *thinker* he shares his time between the calm island Vrångö in the Gothenburg archipelago, and travelling the world. As an author, Gustaf shares insights and new angles through his writing. His writing is focused on technology on different levels: The *discipline level* (automation and instrumentation within water and sanitation) is still at his heart, but the *utility or tactical level* (what is a smart water utility?) and the *strategic and international level* (how does food, water and energy interact?) are now more in focus.

Over the years as professor emeritus, he has always stayed close to the technology and research he pursued for so many years: the hidden technology of instrumentation, control and automation, with special application to the water and wastewater systems. In 'ICA and me – A subjective review' (Olsson, 2012b), Gustaf shares his personal experiences of the development of ICA from the early start in the 1970s and onwards. He reflects on why ICA is still not considered as natural as it should be in the water and wastewater systems – arguing that the lack of driving forces at the utilities and lack of ICA in education can be two explanations. Apart from giving his personal reflections on the topic, he also helps summarizing and sharing knowledge within the field to others, both academics and practitioners. See for example Rosso (2018) and Åmand *et al.* (2013) just to mention a few (Figure 3.3).

Gustaf does not stop by concluding that utilities lack driving forces and the right tools to emerge from the present state of mind. Perspectives on this

Figure 3.3 Gustaf and Magnus in front of Gustaf and Magnus, World Water Congress, Busan South Korea (2012), The photograph of the two printed on the wall is from the IWA Water & Energy Congress in Dublin, Ireland (2011).

challenge are something that Gustaf also put down in writing. Together with his co-author Pernille Ingildsen he wrote the book 'Smart Water Utilities: Complexity Made Simple' (Ingildsen & Olsson, 2016) asking how we can create value from all this information that utilities hold? Another example of Gustaf being involved in the development of utilities is the WISE initiative: Water Intrapreneurs for Successful Enterprises (Vitasovic *et al.*, 2021). WISE is a standard method for improving utilities' performance and to encourage system thinking.

The series of books focusing on 'Water and Energy' (Olsson, 2012a, 2015, 2019) teaches us that 'the global energy challenge depends on water'. Adding food to water and energy, he provides us with examples on how energy security, water security and food security are interlinked. In his work, Gustaf argues for a paradigm shift where this is viewed in a systems perspective and decisions are taken recognizing the impact and value of all aspects. Furthermore, he throws light on the impacts fossil fuels have not only on climate, but also on water; emphasizing the urgency of a fossil free society. In the most recent book 'Water Interactions – A Systemic View' (awaiting publication; Olsson, 2022), Gustaf challenges his readers even further by looking beyond the classic nexus: 'Why we need to comprehend the water – climate – energy – food – economics – lifestyle connections'. Ultimately this new book comes down to the very core of this challenge: we are all human beings who depend on one another to solve our future. This is an example of how Gustaf as a thinker can literally think outside the box.

As a mentor and PhD advisor, Gustaf has focused on helping and inspiring so many young researchers. By his humble and attentive attitude to all people he meets, from the new students to the most senior researchers, Gustaf helps junior colleagues at their level by providing insights from his extensive experience. He has mentored PhD students in Sweden and abroad and supported them to make their way into the water and wastewater community. He has also taught scientific writing to students and young water professionals, among other places in Malaysia and South Africa. Gustaf is a part of the Swedish Water Research School, teaching the new generation of scientists in the water sector in Sweden. As a mentor, Gustaf is encouraging as always, but can also challenge and ask fundamental questions.

The students and how they challenge Gustaf's own thinking are also an important motivation for Gustaf to stay within academia. 'Many times I have reflected on why I have still stayed at the University. After many years it became obvious that a main reason is that I meet young people all the time. They are willing to try the impossible. They never tell us that this has already been tested and we know it cannot be done. They force me to think along new lines and I can never just rely on old experiences' (Olsson, 2012b).

During Gustaf's time as professor emeritus, he received several awards, celebrating his achievements in teaching, science and society. Gustaf received the 2010 IWA Publication Award and in 2012 IWA awarded him with an Honorary Membership at the Busan World Water Congress. Also in 2012 he was awarded the Honorary Doctor degree at University of Technology Malaysia. In 2014 he was appointed Distinguished Fellow by IWA.

As a thinker, Gustaf has, as emeritus, taken on a free role pursuing sustainable solutions through a systems perspective. Many times, challenging conventional thinking and current practice. Throughout his career, Gustaf has been engaged in matters of funding for research in the water field. Water utilities, as municipal organizations, have traditionally low attention, knowledge and budgets for research and development. The main development in the sector was instead driven by private vendors and consultancies. Gustaf argued and lobbied for an increased direct funding for water research. In line with this, Gustaf also worked for a strengthened national research collaboration between academia and utilities.

When four national consortia for research and education were established within water and wastewater research, Gustaf was involved in the Stockholm and Mälardalen consortium (VA-kluster Mälardalen) from the start. VA-kluster Mälardalen is a regional network for collaborative research and education between academia and water utilities within the area of sustainable and digital wastewater treatment. He was invited to join the steering committee, a mission he took part in for over 13 years. Over the years, the consortium has grown in size, consolidated research collaborations and progressed in research topics towards sustainable and smart wastewater systems. Gustaf has been

Figure 3.4 Gustaf in the ceremonial gaune received as an honorary doctor at University of Technology, Malaysia. Photograph taken at the doctoral inauguration ceremony at Lund University 6 May 2022.

instrumental in pushing the members of the consortia forward by consistently arguing for a vision beyond current standard (Figure 3.4).

When Gustaf finally retired from being a solid supporter and member of the research consortium VA-kluster Mälardalen, he did so by summing up the journey he himself has taken part of over the decades. At his last meeting in the steering committee he stated ‘It is today completely natural to collaborate between academia and utilities. This was not always the case. We are also founded on trust today, and we do not need any ‘agreement of collaboration’. This trust is precious and something to value highly. The informal contacts are very much alive’.

3.5 SUMMARY

Summarizing Gustaf's career from a Swedish perspective, he has been ahead of his time, pushing the community forward from the very start. It took time for his early research on control and automation to get accepted and implemented to start with and the adaptive control that Gustaf tested in the 1980s are only now being picked up and explored as innovative ideas. Maybe the industry and water systems are more mature to adopt it now?

Gustaf also realized at an early stage the necessity of a holistic systems perspective. He was an early advocate for an integrated system perspective of water, energy, food and our lifestyle to solve the complex environmental and social challenges of our time. The importance of these perspectives for mankind cannot be overestimated and the problem of understanding starts to sink in to some extent. However, implementation of relevant solutions and measures still remains.

Gustaf has been greatly acknowledged for his achievements in research and importance for the industry. Numerous prizes and awards are tangible evidence for this but the many students and fellow water professionals being inspired and picking up ideas and research are an even more important legacy.

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Gustaf Olsson and me: mentorship at its best

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This tribute is really about Gustaf and me. Others will have written eloquent appreciations of the scientific and practical merits of Gustaf's professional career, but I want to use this contribution to exemplify how Gustaf profoundly impacted my life and in this way illustrate how he may have impacted the lives of so many others that don't get a place in this Festschrifft (thanks, Pernille, for the initiative by the way: it is just a wonderful way for some of us, in the name of many, to try to express our affection to Gustaf).

To start with a boutade: Gustaf is the reason Annick and I embarked on learning a fifth language, Swedish (next to the three official Belgian languages and of course (I guess), English). Why? Because we wanted to really take part of his culture, really feel what made him such a wonderful person. In the meantime, Annick and I have lived over a year in Sweden and if it weren't for the really short days in winter, we'd probably be retiring there.

Let's go back to where Gustaf's mentoring of me as a person and a scientist all started. In fact, it is thanks to one of the best research programs the European Union ever funded: the COST program. At no point has research gotten more bang for the buck. COST was meant to create networks of researchers across Europe around certain strategic research areas. Wastewater modelling was one of these areas and my other main mentor, Willy Verstraete – what an impact he had! But that is worthy of another tribute… – pushed me to become the second representative of Belgium, searching for the equilibrium between the Flemish and Walloon representation. Together with Denis Dochain, of Université Catholique de Louvain, who has also had a significant contribution to my early career, we got in touch with the European wastewater modellers. Well, Gustaf Olsson was one of them and he literally took me under his wings. One cannot imagine how this COST program, with relatively little means, has catapulted a whole group of young European researchers to the top. So many of the young PhD students or postdocs I got to know then, are now leaders in the field. It would just be nice to line them up once and see how efficient research funding can actually work.

But let's go back to Gustaf! My research then was about respirometry (they still call me 'respiroPeter' now and then) and I was already collaborating with my Dutch brother in arms, HenRi Spanjers, who Gustaf had started mentoring as well. In 1991, only one year into my PhD, Willy Verstraete (again!) sent me to Sweden to work with HenRi and Gustaf, because he knew this would help me move forward, give me the independent view, get new insights. It sure did! By 1992, my relationship with HenRi and Gustaf was such that I dared to ask him to chair a workshop that Willy Verstraete (the visionary he was!) had suggested me to organize in the framework of the local Forum for Applied Biotechnology (FAB). Willy just created an opportunity for me, and I grasped it fully: he must have felt I would love organizing conferences (and I did)! Having Gustaf then as a chairman of the workshop made that it got traction, it got the structure it needed, it got top-notch discussions going and gave me the confidence to start a series of FAB Workshops on Monitoring, Modelling and Control of Wastewater Treatment Plants. Talking about giving a young person the chance to shine! Gustaf not only gave me confidence, but was a true mentor on how one should make such workshops truly work. Together with the Kollekolle modelling seminars in which he was involved as well, it has eventually lead to a number of, I think, successful workshops and conferences on modelling and control, where water professionals around the world could come together to learn about each other's experience and expertise, and ultimately to make significant progress, together. Gustaf, consider this part of your legacy!

The picture I have added in this tribute is a truly important one to me. It is taken in Bruges, September 1992, almost 30 years ago, and immortalizes three truly important people in my personal and professional career. From right to left, Denis Dochain, young me, Gustaf Olsson and HenRi Spanjers.

Next to our shared eternal optimism, enthusiasm and the joy of a good laugh, something else that people in the profession may not know, made us resonate: Gustaf and I have a similar (schizophrenic) interest in two completely different domains: nuclear engineering and biological processes. When I stood in front of one of the most important choices in a person's life: what studies will you embark upon, I hesitated a lot to go into nuclear engineering myself. However, in secondary school my math results were not very strong (to say the least), so, given the very math-oriented entry exam for the nuclear engineering studies, I bifurcated to the very promising new area of biotechnology, and this brought me eventually into microbial ecology and technology (and its modelling). So, at all times, Gustaf and I enjoyed talking about the interplay between quantitative methods for nuclear power systems and biological wastewater treatment. But the huge differences between these two fields inspired us: Nuclear power systems are (luckily) pretty well understood whereas biological wastewater systems are much less. For nuclear power systems, control is key and part of life, while it was (and still is) not for wastewater systems. But inter-disciplinary transfer of knowledge, experiences and technologies is surely possible and full of potential. It gave us a vibe to ride on.

By 1993, my first IWA international specialized conference on instrumentation, control and automation, which brought me (and Annick) to the 'promised land', Canada, Gustaf had become a true mentor of my research and he, I think, started to look beyond my PhD: he pushed HenRi and me, to join Peter Dold, another iconic member of the wastewater modelling community, to embark on an IWA Task Group on Respirometry for Control of the Activated Sludge Process. He went in fully himself as he wanted to support us. Little did I know that this would keep part of me busy for the next 20 years (until we published the third in a series of three Scientific and Technical Reports: the Benchmarking STR). It was Gustaf, together with the visionary ideas of Ulf Jeppsson and Bengt Carlsson, that got us going on a journey of finding methods to objectively evaluate control ideas (first based on respirometry, but later way beyond that). And Gustaf has been by our side all the time, helping us like a father that helps his child to learn how to ride a bicycle, giving it the confidence it will make it till the end of the street, but being around in case it would fall and hurt its knees or elbows.

As I grew in my career, Gustaf was around on a regular basis, thanks to the COST money that allowed us to see each other in workshops on relevant topics, discussing next challenges and increasingly helping me with research management: how to organize research, get research funding and supervise graduate students. Indeed, by 1997 I had become professor myself, but there is no dedicated school for that and Gustaf (and Willy) were there to mentor me through this daunting learning phase. I have been able to pick up so many good ideas and ways of doing from them and I hope that my collaborators realize that they have to thank Gustaf for the way I have been working with them. Talking about a legacy again…

I want to give two more examples of what Gustaf contributed to in terms of training: Together with Helmut Kroiss, another one of those legends of the water profession, he developed the journal paper writing course in the early 2010s. The first of these was in Kuala Lumpur, I think, and one of my PhD students had the benefit of taking part in it. She came back completely transformed, had had the theoretical training that Helmut and Gustaf had given, but more importantly, she had her draft paper thoroughly worked through and transformed, and rather than being derailed by the considerable changes they made to her draft paper, she got so much confidence from the way that Gustaf had been working with her, that she was just ready to write scientific papers.

The second example of the influence Gustaf has had on training young water professionals originates from a summer course on wastewater system modelling that Giorgio Mannina organized for a few years in Palermo, Italy in the mid-2010s, with Gustaf, George Ekama and Hallvard Ødegaard. While the students learned a lot of technicalities about each of the disciplines covered by these mastodonts of the field, the added value the students gained in terms of personal development has been such a source of inspiration, probably for the rest of my life. Gustaf has the gift to talk to a student in a way that makes them come out of such personal meeting, even if it is only a few minutes long, in an energized way, plenty of confidence, with new ideas and ready to tackle the next challenge. During one of his visits to Quebec, I asked him to spend a day at university with my students spending time with each of them, one-by-one. What an energy boost and injection of new ideas this has been for the team. It were truly inspiring encounters that so many of us have been able to enjoy as well, because Gustaf always makes time (where does he find it?) to inspire young water professionals (and not so young ones too – I still get the thrills when I'm discussing with him!).

To finish, I think it is essential to look beyond the impact he has had on me (and my collaborators) and recognize that Gustaf is a true giant in the whole water profession field. He not only made so many people succeed in the field, each contributing in their own way, but each of them basically also amplifies the seeds of ideas he plants in them. He is of course a key contributor to the fields of modelling and control of wastewater treatment, but he has in the later stages of his career gone way beyond these rather technical disciplines: think of his contributions to the water–energy nexus, and sustainable development overall and I heard he is writing yet another book. What will this one be about. Keep surprising us with your guidance, Gustaf!

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Gustaf Olsson, ICA and me

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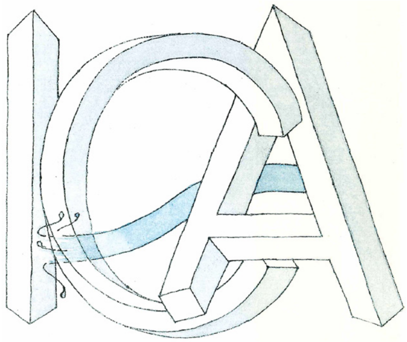
It was in 2001 that I had the pleasure to meet Gustaf Olsson for the first time, at the IWA conference on Instrumentation, Control and Automation (ICA) in Malmö, Sweden. I was a starting PhD student, this was my very first conference, and I did not know many people around. At the conference dinner, I ended up sitting on the same table with Gustaf Olsson and his wife Kirsti. I will never forget how they made a really pleasant conversation, genuinely interested in me and in the other young researchers around the table. Gustaf was kind and most modest – I am not even sure if it was mentioned that he was the conference chair, or the chairman of the ICA specialist group.



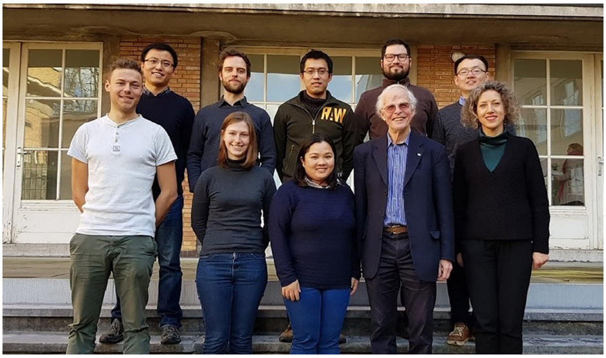
I still have this souvenir from the Malmö 2001 conference: an original drawing for each participant (132/220).

The Malmö conference was the first in a series of ICA conferences, on which it was always a pleasure meeting Gustaf.

Years later, I myself became member and also chair of the ICA specialist group management committee.

This picture unites the ICA specialist group chairs in historical order (from right to left): Gustaf Olsson, Zhiguo Yuan, Alejandro Vargas, me and Juan Baeza. It was taken at the ICA conference in Québec 2017. That was also the conference where Gustaf gave a live piano concert.

In March 2018, Gustaf paid a visit to Ghent University, where he gave a lecture on 'Water-Energy-Food-Climate: they are all connected', for the Centre of Environmental Science & Technology.



On that occasion, Gustaf also took the time to listen to the talks of the young researchers in my BioCo research group and give them some feedback on their research. As always, he was very open, interested, and encouraging.

So, dear Gustaf, besides the bright insights on ICA, that attitude is what I would like to take from you.

Thanks for everything!

Eveline

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Love and art: key requirements for modeling and control of wastewater treatment plants

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Wastewater treatment plants – or water resource recovery facilities (WRRF) as they are now called – involve a magical world: microbial ecosystems. Microbes constitute the Earth's most ancient, abundant, and diverse form of life. To a large extent, we humans are indebted to microbes for our continued presence on Earth.

Among the many useful functions performed by microbes, their role in producing some of our finest foods (bread, cheese and wine among others) is worth a mention. Healthwise, gut microbes (i.e., our gut microbiota) provide us with the energy needed to breath, move and think and from a sanitary perspective, they guarantee the treatment and valorization the residues (i.e., dejections, waste and wastewater) of human activity.

Almost 30 years ago, I was recruited as a research scientist in a small lab in the south of France. My mission was to start a research group working on process modeling and control. At that time, my host laboratory was composed of microbiologists and bioprocess engineers working on carbon, nitrogen and phosphorus removal from wastewater. Therefore, I was the only mathematician in the whole laboratory. The hiring of my first master student heralded the foundation of my group, which I baptized 'Process Engineering and Control Engineering group'. This name was chosen, not just for the catchy acronym (i.e., PE[a]CE), but to emphasize the fact that modeling and control research must relate to real processes. Indeed, the message that I have always communicated to students is that if you want to discover something that is both useful and beautiful, you first have to understand the intimate workings of the application, in this case the process.

Over the years, one of my main sources of scientific inspiration has been Water Science and Technology (WS&T). Indeed, the content of this journal is grounded in real-world problems and written by practitioners. In particular, I believe that I have read cover to cover all of the special issues devoted to the ‘Instrumentation Control and Automation’ (ICA) conferences. The first ICA conference was held simultaneously in London and Paris in 1973 (it must have been a nightmare to organize a conference in two different locations!), while the 7th edition (1997) was held in Brighton. For the latter, a paper that I enthusiastically submitted to the conference was accepted… as a poster. Unfortunately, the rules in my laboratory stated that to attend a conference you had to be accepted for at least an oral communication. What a disappointment it was! I had to wait four more years for the next one, organized in Malmö in 2001. This time, to increase my chances of success, I submitted no less than 6 papers! All were accepted…….as posters. Of course, my proposals dealt with modeling and control of anaerobic digestion processes, while most ICA attendees at that time were working on activated sludge. No oxygen, no interest from the ICA community! However, to my great surprise the Chair of the 2001 ICA conference (a certain Gustaf Olsson) contacted me by email. He told me that he really appreciated my published work and encouraged me to attend the meeting in Malmö. To help convince my lab director, he invited me to chair a session during the conference. Eureka, it worked! The conference was memorable, not only for the science presented but also for the encounters I experienced. Among these, was my encounter with Gustaf. I was proud and flattered to be invited by Gustaf to dine at his table for the gala dinner! Gustaf, you probably do not realize, but your generous gest toward the young scientist that I was at that time has influenced me ever since. As a senior scientist, I try to emulate your example in my relations with younger colleagues. Clearly Gustaf, your generosity and humbleness, are manifestations of your love of both science and people. Those are very inspiring and noble qualities.

Twelve years after my ICA baptism in Malmö, I had the honor to organize and chair the 11th ICA conference held in Narbonne. Fittingly Gustaf, you accepted to deliver the opening talk at the conference. I was immensely proud, because you are an iconic figure of ICA, having attended every edition since 1973. Moreover, your ability to foresee future trends is always so accurate and so appropriate! Your talk resulted in a paper published – of course – in WS&T (Olsson *et al.*, 2014), the journal you saved a few years earlier when the world of the scientific edition decided it could no longer be referenced as an international journal because of its specific policy regarding the selection of papers presented at international conferences (Figure 6.1).

Building a model and calibrating it to accurately represent experimental data is a subtle art. Over the years, I have battled to reconcile experimental

Figure 6.1 Pictures of Gustaf Olsson at the opening of the ICA conference in Narbonne in 2013.

Figure 6.2 Gustaf and me after a PhD defense in Girona, Spain.

data with simulations. When it all comes together, when the structure of the equations reflects the biological reactions involved and when parametric values reflect the experimental kinetics and the sensitivity to variations is low…..in a nutshell, when the model is precise, reliable and robust – it is like music to my ears. Finding and assembling the different pieces of the puzzle, in this case the model, is a major undertaking. However, when one is successful, it is like a musician that discovers music that matches the lyrics of a song.

My analogy to music provides the opportunity to recall a lasting memory of the ICA conference in Quebec in 2017. For the opening session, we were all gathered in the amphitheater, waiting for the conference to begin. As participants waited in expectation, they were treated to piano music. Everyone assumed that it was recorded. However, when the curtains opened we discovered that it was the multi-talented Gustaf, playing the piano!

Last but not least, another memory comes to mind. A few years ago, Gustaf and I were invited to a PhD defense in Girona, Spain. Following the defense, during the lunch a waiter approached our table and said 'be careful, the plate is hot'. So, what was Gustaf's reaction? He reached out and touched the plate. He immediately exclaimed 'whaoooh, it's hot!'. At that moment, your basic curiosity got the better of you, rather like a child thirsty for new discoveries! That day, the only thing that separated you from childhood was the fact that it was you first day of retirement!

For all of these great memories and for everything you did to promote ICA and the cause of WRRF all over the world, *tack så mycket*, Gustaf. I already miss your presence, but I know you'll always be around if needed (Figure 6.2).

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A humble, generous and inspirational mentor

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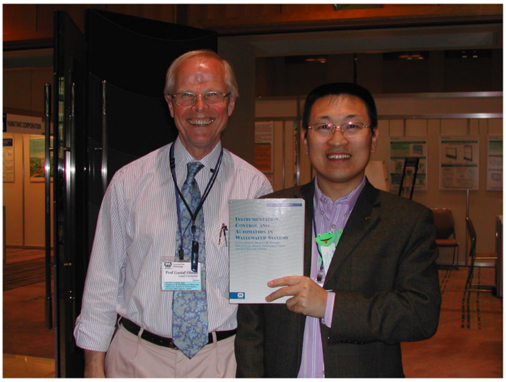
Anyone who has met Gustaf, however briefly, would know that he embraces life with enthusiasm. He is passionate about his work and the people around him. Although he has made an incredible intellectual contribution to the field of instrumentation, control, and automation (ICA), he is equally respected for his kind nature and genuine approach. His generosity toward others made a big impression on me as an early career researcher, and I have strived to model his optimistic outlook in my career, and return that generosity of spirit to the next generation.

I met Gustaf in 1994. In the spring of that year, I arrived at Ghent University in Belgium to commence research on water system automation, after saying goodbye to aviation control, which I had studied for more than 10 years. Early in my Ghent appointment, I came across Professor Olsson's landmark 1976 ICA discussion paper, which was a major influence on my academic direction. Later that year, among a few hundred other researchers, I attended the 1994 Forum on Applied Environmental Biotechnology, led by my postdoctoral advisor, Professor Willy Verstraete. At the time, I didn't recognise the gentleman who asked many wise questions at the meeting, leaving a deep impression on me. It was only later, when I saw his name tag that I realised the gentleman was Professor Olsson. During the seminar break, I summoned the courage to approach Gustaf, who took time to discuss ideas with me, a complete novice with limited language skills, and he warmly encouraged me to pursue my ideas. Gustaf does not remember our first encounter, but I gained a great deal of confidence and inspiration from our conversation. I am sure a great scholar such as Gustaf, with his positive attitude and enthusiasm for knowledge exchange, has unknowingly influenced many of the next generation.

Gustaf can be called a living treasure in the field of water system automation. Gustaf's exciting ICA work laid the foundation for my generation of automation scholars. Gustaf is the only scholar who has attended all the conferences in the ICA series of the International Water Association (and predecessor). From the first conference held in London, England in 1973, Gustaf has tirelessly and enthusiastically shared his passion for ICA. I look forward to welcoming Gustaf to the 13th IWA ICA Conference in Beijing in October 2022, of which I am a co-chair. Unfortunately, this will be a virtual conference due to the pandemic, and I will miss an opportunity to show Gustaf around in the city in which I studied for 11 years.

Not long after I joined The University of Queensland's Advanced Wastewater Management Centre (AWMC) in 1998, Gustaf arrived for an academic sojourn. During these few weeks, we often met to discuss ICA issues. Also participating in the discussion was Pernille Ingildsen, who was then a PhD student of Prof. Olsson, and now an internationally leading water professional. These discussions were inspirational, and I gained great benefit from the intellectual challenge and stimulation. At this time, Professor Olsson gave me my first big break by inviting me to give a keynote presentation at the upcoming 8th IWA ICA meeting to be held in Malmö, Sweden in 2001. This keynote opportunity proved to be a turning point, raising my international profile and boosting my career immeasurably. With the guidance and support of Gustaf, I gradually joined the IWA ICA leadership team, my first major research leadership position, and subsequently I was elected as the chair of the IWA ICA Specialist Group in 2005. In that year, Gustaf and I published our joint book 'Instrumentation, Control, and Automation in Wastewater Systems' (IWA Publishing), in collaboration with Marinus Nielsen, Anders Lynggaard-Jensen, and Jean-Philippe Steyer. The idea was initiated at the 8th ICA Conference in Malmö, 2001. It was a challenging job, but owing to Gustaf's genuine leadership and tireless effort, we were able to launch the book four years later at the 9th IWA ICA Conference in Busan in 2005. In 2009, I successfully hosted the 10th ICA Conference in Cairns, Australia. It was my great honour to present Gustaf with a lifetime achievement award at the closing ceremony, a small token of appreciation for his inspirational leadership.

Gustaf has been a humble, generous mentor who greatly supported my professional growth throughout my entire career. However, I am just one of many people who owe much of their success to Gustaf's ongoing guidance and support. In retirement, Gustaf continues to embrace life; he is still productive and giving back to our community. Here, I would like to express my heartfelt gratitude to Professor Olsson on behalf of all the colleagues who he has helped.



Gustaf Olsson and Zhiguo Yuan at the 9th IWA Conference in Busan, Korea in 2005, following the launch of their joint book 'Instrumentation, Control and Automation in Wastewater Systems' (IWA Publishing).

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Gustaf Olsson is a water science and system thinking super hero

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It is with a great sense of external gratitude, humility, admiration, and solidarity that I write this tribute to honour Emeritus Prof. Gustaf Olsson, a borderless mentor of smart water science and an advocate of system thinking (water–energy–economy–climate–lifestyle nexus) for sustainability. I presume that my piece is a lone contribution from the Niger Delta, Nigeria, a region where Gustaf has written copiously about the human rights consequences of unprecedented degradation of the total environment and poor management by the oil industry. Thus, I elect or volunteer to convey the united thanks of the peoples of the Niger Delta, on whose behalf Gustaf has passionately exposed the sufferings caused principally by poorly regulated oil spills and their avalanche impacts on water, food resources, and livelihoods. His consistent advocacy for immediate, sustainable cleanup, remediation, and restoration of the extensive oil-degraded ecosystems in the Niger Delta has started to yield tangible results.

My background is in zoology, with a focus on hydrobiology, specifically benthic and restoration ecology. On the contrary, Gustaf is an emeritus professor of automation engineering. These specialties are far apart, but we have been bonded by the common water trait of our studies. His towering posture, contributions, and mentorship in the water–energy nexus are outstanding and have had great influence on water management, and will continue to impact on current and future water sustainability designs, policies, and practices.

As part of my doctorate, I researched community ecology of intertidal macrozoobenthos (animals >0.5 mm that live in or on sediment) of the Bodo Creek, collecting field samples for two years (May 2006–April 2008). Four months after the end of my sampling campaign (August 2008), Bodo Creek was hit by two major oil spills. Thus, the data I had collected became useful pre-spill baseline with which the Bodo oil spill impact was assessed and the data continue to serve as valuable reference for monitoring water quality recovery in the creek.

Given poor oil spill management regime in Nigeria, the 2008 Bodo Creek oil spill was almost swept under the carpet – despite the heavy impact on livelihoods of the local population. I took the initiative of documenting the post-spill conditions and talked about the spill's human rights consequences in many international fora. I eventually introduced the spills to Leigh Day & Co law firm in the United Kingdom for prosecution. The case was formally filed in a London court in April 2011. The welter of evidence forced the liable company, the oil giant, Shell, to settle out of court in 2015. Consequently, 15,601 claimants who suffered losses and the Bodo community were compensated with 55 million pounds. Given the long walk to justice, Gustaf wrote a compelling letter in support of my nomination that led my being the recipient of the Association for the Sciences of Limnology and Oceanography (ASLO) 2022 Ruth Patrick Award.

On April 27th, 2009, I was invited as a guest speaker at the conference 'Petroleum and Pollution – How Does That Impact Human Rights?', co-organized by Amnesty International, Forum Syd, and Friends of the Earth, Sweden, which was held at Kulturhuset, Stockholm, Sweden. In my lecture paper titled 'Impact of oil pollution on livelihood in Nigeria', I highlighted the impact of the Bodo Creek oil spill on water quality. A few months after the conference, Anna Gustafson, one of the conference organizers, emailed to introduce Prof. Olsson to me. This was how our paths intersected and I got to know and continue to learn from this great teacher and advocate of smart water use.

In his seminal book that ensued, 'Water and Energy – Threats and Opportunities', published in its first edition in 2012, Prof. Olsson amplified access to water as a fundamental human right and highlighted the consequences of a lack of access to sustainable, safe water, using the Bodo Creek spill as a case in point. He uses the textbook to plead for cleanup, remediation, and restoration of the creek. In 2015, he published a significantly upgraded second edition of the book. This coincided with the above out-of-court settlement and payment of 55 million pounds as compensation to the impacted people in the Bodo communities. Prof. Olsson discussed the relief and sense of justice achieved by the compensation and, again, reminded water professionals of the urgent need to clean up the degraded waterways. Clean up (free phase oil removal) of the Bodo Creek started in September 2017. The remediation and restoration of mangroves that followed the initial phase is ongoing for over two years now. The anticipated planting of 1000 ha of mangroves in the Bodo Creek would make it the world's largest restoration of oil-degraded mangrove. These have created direct jobs for about 2500 locals.

Prof. Olsson has had an uncommon and outstanding impact on the advancement of water science and water-wise technological development. He flags the problems and challenges, exposes the drivers of the challenges, and proposes smart and innovative solutions to fix the problems. He is a mentor par excellence. He introduced me to the International Water Association (IWA), a gesture that has helped to push back the frontiers of my water career. I have had the privilege and honour of co-authoring two conference posters and a refereed journal article with him (Olsson & Zabbey, 2012, 2014; Zabbey & Olsson, 2017).

Our latest submission 'Water science and human rights: a case study from the Niger Delta' has been accepted as a poster presentation at the September 2022 International Water Association (IWA) World Congress in Copenhagen.

I'm eternally grateful to Gustaf for the superb lessons and skills I and countless other mentees garnered from his mentorship. In the Niger Delta, as in similar developing lands, we conduct field research in very challenging circumstances – poor funding, limited state-of-the-art sampling and analytical equipment, and insecurity due to armed militancy, kidnapping, and demands for 'matching ground', a kind of bizarre, illegal entry permit levy that some local youths collect. The below personal experience I had and have shared with Gustaf graphically illustrates the risks that researchers in conflict-prone regions are exposed to.

> I was offered the 2016 British Ecological Society (BES) Ecologist in Africa grant to study Polychaete diversity in varied health-integrity habitats in different reaches of the Bonny Estuary, Niger Delta. The study involved collecting polychaeta samples from oil-degraded and relatively undegraded areas in the upper, middle, and lower reaches of the Bonny Estuary, and identifying the specimens under expert supervision at the Los Angeles Museum of Natural History, USA. While collecting the polychaete samples with some of my students in 2018 at the middle reaches of the Bonny Estuary, we were once intercepted by an armed gang. The boys had three AK-47s in their speedboat. They seized our Eckman grab, water quality multi meter, and some of the benthic samples we had collected and towed our boat ashore to the Seato fishing camp where they were residing then. We begged them to free us and they insisted we should've obtained permission from them before coming to collect samples. I responded that we are only trying to preserve the environmental legacy of the region and that I am a native of Bodo City (the community that owns the Seato fishing camp), but to no avail. The incident occurred in the waters contiguous to Seato, the mouth of one of the four main channels that connect the Bodo Creek complex to the Bonny River. Luckily, our boat driver phoned another gang leader who talked to our captors, and we were released with a stern warning. After the grisly incident, I've been brooding over how we can collect environmental data in the Niger Delta in conjunction with non-science citizens or build the latter's capacity to collect useful data from remote insecure areas. Thus, with a few colleagues, we developed a framework for the region's community science. On August 4th, 2020, we tested the community science framework with several undergraduate volunteers and youths from the Bundu Waterfront neighborhood to document mangrove biodiversity in the Bundu Creek, Port Harcourt. Interestingly, I met in Bundu one of the boys that had held my students and I hostage for a few hours in 2018 on the Bonny River. He has expressed regret and informed me that, of his gang, he is the sole survivor. He claimed that a rival cult group attacked the place where they brought us and massacred all of his gang members while he managed to escape. He is a

potential citizen scientist! He is currently collaborating with my team at the Center for Environment, Human Rights, and Development (CEHRD) on a modest Global Green Grant-funded project in Bundu for sustainable waste management and mangrove restoration.

In sum, great efforts and sometimes risks to personal safety go into collecting sound temporal field data in the Niger Delta, especially in the wilderness or remote mangrove areas. Thus, until I started to co-author with Gustaf, I usually got upset and seemingly frustrated when I received uncomplimentary peer-review feedback on my manuscripts that contained 'hard-acquired' datasets. As the correspondent author, in fact, the *de facto* lead author of our joint paper above 'Conflicts – oil exploration and water', Gustaf taught me a life-long lesson in the virtues of scholarly patience, humility, and tolerance. I was amazed by the incredible calmness and humility with which Gustaf responded to what, in my estimation, were rude review remarks. This changed the way I perceived reviewers' comments. It makes me appreciate the importance of blind peer review even more. It's more likely that the reviewers of our paper are his juniors or mentees. Had they known the manuscript was Gustaf's, their review comments would have been less critical, but kinder all-round commendations that wouldn't have added value to the paper!

Prof. Olsson's 2016 classic book, 'Smart Water Utilities', which he co-authored with his former PhD student, Pernille Ingilsen, will continue to influence water professionals' and policymakers' water-wise innovative thinking, system design, judgment, and practice for a long time. As a trusting mentor, Gustaf is, he gave me the rare privilege of contributing a case study in the book titled 'The Risk of NOT Measuring—Oil Exploration in the Niger Delta' in the book; pp. 227–230. The book chapter analyses state-of-the-art technologies for surveillance and monitoring of oil facilities for early warning signals and detection of oil spills for prompt contingency response. It also highlights the long-term benefit of investing in the seemingly expensive technologies as being superior to the cost of catastrophic oil spills due to poor or inadequate pipeline monitoring, maintenance, and leak-detection regimes in regions with poor oil spill management such as the Niger Delta.

Gustaf had shared with me the draft of his latest book (in press) 'Water Interactions – A System View', in which he expounds the intricate connectivity between water–climate–energy–food–economics–lifestyle. This was quite providential. A couple of days afterwards (in April 2022), the revered Niger Delta environmental rights activist, Rev. Nnimmo Bassey, asked me to write a review paper on the relationship between climate change, environmental degradation, insecurity, and conflict in the Gulf of Guinea, using the Niger Delta as a case study. I'm not yet very familiar with the terrain of climate change science, but Gustaf's new book, the insights and suggestions he shared with me via email, and the literature he provided bolstered my confidence to write the paper, and I delivered it on time. With the enormous time commitment Gustaf dedicates to younger professionals like me and the speed with which he responds to our ongoing requests for his scholarly thoughts and guidance to navigate contemporary water science issues, I frequently wonder if he operates on a daytime length longer than 24 hours! With his proactive literature provisioning and personal insights, I'm extremely glad I wrote the paper because it evokes in me a sense of guilt that I'd paid little attention to the impacts of climate change on my region. The Niger Delta, according to the research, is one of the regions that has felt the impact of climate change, particularly coastal flooding and erosion. It demonstrates to me how the double whammy of environmental degradation and climate change weakens resilience, adaptation, and mitigation capacity and exacerbates insecurity and conflict in the region. When I delivered the paper to Rev. Bassey, who commissioned me to write it, I shared it the same day with Gustaf, the unseen towering personality behind the article.

Prof. Gustaf Olsson's career has contributed remarkably to the body of knowledge on water systems engineering, the connection between water and energy, innovative water-wise technologies, and the human rights impact of poor water quality. He continues to evolve and communicate system-thinking solutions. His work has had a huge impact on the water science community, as well as water managers and policymakers. In 2018, I was extremely delighted to have written one of the letters in support of his nomination for the Stockholm Water Prize. Honestly, by my estimation and that of countless colleagues across the world, Gustaf would be a worthy recipient of the Stockholm Water Prize! I hope his priceless contributions to water science system thinking will be duly rewarded in the near future. Whether he wins the Stockholm Water Prize or not, he is the hero of heroes of water science! His contributions will continue to inspire us.

Gustaf Olsson and Nenibarini Zabbey before the presentation on "Rehabilitation of mangroves degraded by oil spills in the Niger Delta" at the World Maritime University, Malmo, Sweden, in July 2022.

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Gustaf Olsson and me: ICA and hydroinformatics – a subjective view

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The overarching and enduring quality of Gustaf Olsson's career is the enjoyment with which he works in water and automation research and practice, his international outreach and his capacity to bring others along on the journey. My personal feeling, with which I agree, is that Gustaf truly believes that the ICA (*instrumentation, control and automation*) technologies involved with water and wastewater engineering are important to the future of humanity.

Gustaf's attitude to research in automation was confirmed by his seminal paper 'ICA and me – a subjective review' (Olsson, 2012), providing an eyewitness account of the four decades of evolution of ICA in the water sector, something as of late known as *digital water* transformation. In addition to the focus on ICA technological advances, he has also devoted himself to supporting his students and early-career engineers involved in ICA research and practice. The integration of these two dimensions of his career – technological and human – is what made me think of and write this personal view of the links between ICA solutions for wastewater and water systems and developments in a related field of *hydroinformatics*.

As a young engineer, I believed that engineering and technology have profoundly changed the world we live in and that they will continue to improve our lives in the 21st century. Proof of that widely accepted belief was the poll conducted by the British Medical Journal at the turn of the century, where its readers were asked to vote for the greatest medical milestone of the previous 150 years. Sanitation, brought about by the construction and operation of wastewater facilities and systems, was the undisputed winner (Ferriman, 2007). While that confirms the importance of technology, later on in my professional career I realised that future progress is not only about technology. Gustaf identified that, equally, if not more importantly, as the '*human factor*' that possibly creates more problems than technology but is often neglected (Olsson & Newell, 1998).

The field I work in, *hydroinformatics*, is often identified by its technological dimension through applications of information and communications technologies (ICT) and artificial intelligence (AI) methods to complex water and societal challenges (Makropoulos & Savić, 2019). We are witnesses to modern digital technologies transforming our society by improving the planning and management of complex systems (e.g., banking, transportation, marketing, entertainment and tourism), but progress in automation of the water sector is slow. Comparisons with industries that have made significant strides towards full automation, for example, car and aviation industries, show that the water sector could learn from the experiences of those early adopters (Savić, 2022).

I have recently made such a comparison and identified the need to always keep humans in the loop as operating complex systems that require the highest possible level of safety, such as aeroplanes and cars, still rely on trained airline pilots and vehicle drivers. For the water sector, this means that automation systems will still require a highly skilled workforce to ensure safe future operation of water and wastewater systems (Savić, 2022). The other key conclusion from that comparison is that more automation requires more education and training, not less. At the University of Exeter, together with colleagues from three other UK universities, we identified the need to train engineers and scientists at the intersection of water informatics, science and engineering. In 2014, the Water Informatics in Science and Engineering Centre for Doctoral Training (CDT) was established (Wagener *et al*., 2021). The CDT has recruited over 80 PhD students since October 2014. As a visiting professor at the University of Exeter, Gustaf has been also involved in and contributed to the activities of the CDT.

As I am approaching a similar career milestone that Gustaf reached and reflected on in the 2012 paper, I'm contemplating more often how he influenced my views and attitudes towards engineering technology. In order to do that, I have to comment first on the different educational backgrounds of Gustaf and me. While we both have been educated in the broad field of engineering, Gustaf's specialisation is in control engineering while I have studied water engineering as a specialisation in a more general civil engineering discipline. This is important as different specialisations are defined by educational and institutional boundaries constructed by the needs of teaching, research, funding, administration and professional development. These boundaries can and do introduce fundamental differences in epistemologies, ways of knowing, methods and language, a mixture that can create tension.

Gustaf has recognised that in his 2012 paper, stating that '… there is still a lack of understanding between control engineers and design [civil] engineers'. I am glad to say that despite those differences, there have been no tensions between us as Gustaf combines the sharpest of scientific minds with a gentle personality and a great sense of humour. He has been an incredible role model not just for me, but for many other academics and practitioners, and serves as an inspiration across countries, regions and disciplines.

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A legacy driven by curiosity and generosity

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Gustaf Olsson has generated an impressive volume of scholarly work that includes many articles and books. Many contributions to this Festschrift will reflect on the significance of Gustaf's work and the impact of *what* Gustaf has done during his long career as an engineer, scientist, and educator. I feel honored by the opportunity to make my own contribution to a document that would recognize Gustaf, and I am also humbled by the challenge to add a perspective that would not be redundant with the content from other contributors. To provide a different perspective, instead of focusing on *what* Gustaf has done I will focus on *how* he has done it. My notes will be about personal reasons why Gustaf has been an important part of my life.

I was fortunate enough to meet Gustaf some 40 years ago in Houston, where I was studying for my Ph.D. with Dr. John F. Andrews. On a couple of occasions, Gustaf stayed as a guest with our family, so I had a chance to also get to know him personally. I also feel fortunate that in the following years, our professional and personal relationship grew and strengthened.

As a researcher, Gustaf has several qualities that have enabled him to make an extraordinary impact on many lives. He has retained the curiosity of a child: always exploring, continuously learning, with apparent pleasure and enthusiasm. Gustaf truly enjoys learning: his thirst for knowledge remains unquenchable. One can see the excitement about learning on his face, in the smile and the twinkle in the eye. When encountering a new idea, when introduced to a new concept, Gustaf is immediately eager to dive into it. This enthusiasm is infectious, and very rewarding if you are the person introducing ideas to Gustaf. He does not shrug them off, does not ignore them, is never too tired to attack some new concept. This encourages young people (as I used to be) to approach Gustaf and share their ideas and thoughts. Gustaf listens, considers, and almost always thinks of related things that he has read somewhere else. The conversation blossoms, and the young person ends up feeling that learning can be joyous and feel like an adventure. This way Gustaf can transform the experience of learning from being a required chore to becoming a fun game: Gustaf seems to be having more fun with your ideas than you thought possible!

Another valuable quality that makes Gustaf excel at research is that his mind is not constrained, it is always open; he is not locked into rigid frameworks or dogmas. If one has a truly different and perhaps 'crazy' idea, Gustaf is the best person to speak to. Gustaf seeks and finds knowledge in many different and diverse places; he does not lock himself into a narrow area of expertise where one 'knows more and more about less and less until he knows everything about nothing'. On several occasions I have approached Gustaf with some 'crazy' ideas and I always felt encouraged after our conversation. I believe that Gustaf in fact prefers the 'crazy' ideas because they provide an opportunity to take a different look at things. Even if the idea turns out to truly be crazy, the experience of testing it and questioning it can be rewarding because it tests the boundaries.

Gustaf also has a natural ability that enables him to be a great educator. His curiosity and eagerness to learn, his energy and his focus, are inspirational and aspirational to his students. They are infectious!

Gustaf also knows how to nudge a person in a different direction, prod them to do something that is different, unusual, or unexpected. Some years back, when I was working for a Danish firm (Danish Hydraulic Institute), I was spending a lot of time in 'Gustaf's neighborhood'. Several times Gustaf asked me to 'swing by Lund' and give a lecture to his students. This would give us a chance to discuss our research and enjoy some food and each other's company. One time, Gustaf invited me to give a lecture but made a special request on the content of the lecture. In the past, my lectures had a narrow focus on a specific subject, such as real-time control of sewer networks, using computational fluid dynamics to model secondary clarifiers, or integration of information systems. Gustaf gave me a challenge: 'This time, give a lecture that is not about technical subjects'. I accepted this challenge, and initially I truly struggled to step off my own railroad tracks. I rewrote that lecture and rebuilt the slide deck several times. Somehow, I would always veer off into the known, safer territory of technical subjects. In the end, I gave a lecture that had very little to do with technology. I have done many lectures and presentations in the past 40 years, but the one I gave at Lund that day is the one that I am most proud of. I believe that I learned more from developing that lecture than perhaps students have learned from it; and it would not have happened without Gustaf.

I have always enjoyed Gustaf's sense of humor: it is never aggressive, it is always insightful, and there is typically some kind of a lesson hidden somewhere.

As we are trained to be scientists, engineers, or managers we are taught to observe and measure different things and to act based on those measurements. The same is true on a personal level: we have to decide how to measure our own life. The choices about what to measure, what to value, and what to desire determine the path of a person's career and life. In my experience, those whose goal is acquisition (e.g., of money, influence, power) are seldom happy, because they never feel that they can acquire enough. Gustaf's goal is based on giving: and he can be at peace because there are often ways for him to give more to others. One can feel this sense of calm and peace when talking to Gustaf.

In the early last century, there were three famous people who studied human nature: Freud believed that man seeks pleasure, Adler believed that man seeks power, and Frankl believed that man seeks meaning, a purpose. We can observe these three types at work: the 'Freud group' comes in a bit late, takes a long lunch, and enjoys chats at the water cooler. The 'Adler group' pays a lot of attention to who is getting promoted, dreams about the corner office, and carefully chooses who to take out for lunch. The 'Frankl group' can be observed because in meeting they may ask probing questions that others do not date to ask, they may be oblivious to the hierarchy, and they always try to do what is best for the company. Gustaf is firmly in the 'Frankl group' because he is driven by a higher purpose: a search for truth and knowledge.

Henry Miller (author) said that 'you only have problems if you care'. Gustaf cares a great deal about the important things: people, environment, truth, justice. He cares about this planet, which is threatened by the profoundly dysfunctional groups of people who have the power to spoil the world we all live in. Gustaf is doing his part as a tireless voice of reason and compassion. His work inspires many and gives me a sliver of hope that perhaps reason and compassion may have a chance. I am deeply grateful to Gustaf for giving me that hope.

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Gustaf Olsson – teacher, supervisor, inspirer, friend

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11.1 OUTLINE

The three authors of this short Festschrift have had the privilege of working together with Gustaf Olsson for several decades in numerous roles: as undergraduate students, as Ph.D. students, as postdocs and as senior researchers. Most importantly, we are all very close friends to Gustaf. Below, each of us provide a few personal reflections related to how Gustaf has been a beacon of light for us and has had great influence on both our professional and personal lives.

11.2 SOME OF STEFAN'S ENCOUNTERS WITH GUSTAF

When you think about Gustaf, you smile. He seems always so happy, enthusiastic and positive, but also in a hurry. One gets the impression it is because there are so many things in life and research still to be discovered. He is genuinely interested in the people he meets. Even if he has met someone only once before, he remembers details about that person and asks relevant questions about that person's interests.

My first impression of Gustaf was in the undergraduate course on automatic control when he held the weekly seminar classes. Right on time, he rushed into the class room and seemed to find out during the first couple of seconds what the topic was that day. He then caught our total attention when explaining how to think about abstract concepts and what is really going on in the problem at hand in addition to solving it on the blackboard. We learned a lot during these seminars, and above all, that automatic control is fun. He was an authority in a positive way and gave us plenty of questions during his lectures so that one had to stay alert.

A wastewater treatment plant contains several different subprocesses that need different types of models to describe. Gustaf's interest and knowledge about all of them is known through all his books, publications, courses and talks. In the mid-1980s, the ASM1 model was published and gave a valuable and satisfactory description of the biochemical reactions in a biological reactor. It was possible to simulate all concentrations as functions of time, since the model was a system of ordinary differential equations. One complicated process in the treatment plan that occurs in the secondary clarifier, or sedimentation tank, where the activated sludge (living bacteria) coming from the biological reactors is separated from the purified water and recycled to the reactors. The process of sedimentation by gravity had been used since the beginning of the 20th century; however, it was known to be difficult to predict and control. In the mid-1980s, there was no mathematical satisfactory model for the process. The few simulations that had been made easily showed instabilities, in particular near the so-called sludge blanket – a visible large concentration discontinuity in the tank. Since the concentrations in the tank depend on both time and space, a mathematical model necessarily consists of a partial differential equation (PDE). Such nonlinear equations are difficult to solve, and it is difficult to create reliable simulation methods that give approximate solutions.

Gustaf approached his colleague Dr Gunnar Sparr at the Department of Mathematics, who thought the problem was interesting. I was at the time a curious student attracted to the problem, which therefore became my master's thesis project. Once the PDE model of the sedimentation process was established, we found that there was neither any textbook nor any publication that had treated a similar mathematical problem. The sedimentation of particles in a liquid is a nonlinear process that gives rise to shock waves (look at a glass of squeezed orange juice and you will after a while see a layer of high concentration at the bottom rising upwards while the juice particles settle downwards). In addition to this, an essential difficulty is the feed inlet and the upward and downward flows, which means that the PDE has coefficients that are discontinuous functions of the depth in the tank. It turned out that fundamental research in mathematics had to be done. This rich problem gave rise to both an MSc thesis and a PhD thesis for me, and I still today produce results on the application to wastewater treatment with the ironic comment from my math colleagues: 'So, you are still stuck in the sludge'.

I am so happy that Gustaf brought this problem to the mathematicians' attention and I am grateful for the support he has given me during all these years. It has been an excellent problem in applied mathematics, rich of challenges in both modelling, mathematical and numerical analysis, control aspects, and creation of reliable simulation methods.

When I was a fresh doctoral student, Gustaf took me to the impressive IAWPRC (today IWA) conference in Yokohama and Tokyo in Japan in 1990. I am very grateful for the way he treated me when introducing me to the 'big guys' in the field and pushed for our new results in my first publication (Diehl *et al.*, 1990). Gustaf was able to handle all situations, even the awkward one when the big opening ceremony was about to start and one of the Japanese organizers of the conference bumped into Gustaf with his wife Kirsti, Gilles Patry with his wife and me, dressed in shorts and T-shirts on our way to do sightseeing. All of us more or less hid behind Gustaf and let him do the talking, explanation and giving the excuses. We thought this was the best opportunity we had for sightseeing, but quickly learned how important official ceremonies are in Japan.

Gustaf has many abilities of different kinds to look up to and I will mention only two more. If you have not yet heard Gustaf play the piano, I advice you to do so! Often when Gustaf arrives to a new city somewhere in the world one of his first tasks is to check if there is some organ in a church (or other official building) close by that he may be allowed to try out. Another 'other fact', which I think is part of his success and large network, is that Gustaf is a great connector. He connects people in a friendly and positive way. This is particularly valuable at conference, where many people meet and greet most everybody knows Gustaf and he also seems to know so many people at any conference. In a group of people chatting, he introduces people to each other with some cleverly concluding sentence of a key achievement of each person, so that a new connection between two previously unknown people occurs.

Gustaf has always been busy with a full schedule. After his official retirement, I met him in the queue at the local lunch restaurant at the Faculty of Engineering in Lund and asked how he felt and what he did now. He replied: 'It's wonderful, I can do what I want and I have now reduced my workload considerably down to 100%!' Still today, he works more than most and spreads wisdom, happiness and hope around the world and we are happy with whatever percentage (Figure 11.1).

Figure 11.1 Gustaf relaxing with some friends at the Lund University International Guest House in 2004 (from left: Quim Comas, Erik Lindblom, Christian Rosén, Krist Gernaey, Ulf Jeppsson, Gustaf Olsson).

11.3 A LIFE-CHANGING MEETING FOR ULF

'What is wrong now?', I thought to myself after visiting the IEA bulletin board in the early summer of 1988 to find out the results of my very last exam at LTH before concluding my MSc education. The result itself was good enough (actually above the maximum grade, which is hardly possible nowadays) but there was also a special marking after my name. Checking the end of the page the marking was explained as: 'Please contact professor Gustaf Olsson'. I was just about to finish my MSc thesis project and then I was off to some industry to start working in the real world. At least that was my plan. But as Gustaf was the examiner and head teacher (and of course did a remarkable job) on this final course I could not just ignore the request. A few days later I stepped into his office, somewhat worried about what this meeting would be about. He greeted me with the words: 'Have you ever considered enrolling as a PhD student?'. My own knowledge on that issue was fairly limited and the idea had never really crossed my mind. But after a two-hour meeting with Gustaf where he spoke with great enthusiasm about wastewater treatment (a topic I new absolutely nothing about) in combination with automatic control, on-line state estimation, artificial intelligence (AI), knowledge-based systems and so on, I was ready to sign just about any paper he would have put in front of me. I had been recruited by Gustaf and started my PhD studies a few months later with Gustaf as my main supervisor. Thirty-four years later I am still at Lund University working with water and wastewater within that very same department. And no regrets whatsoever!

Seven years later I defended my PhD on modelling of wastewater systems. Note, the topic of my thesis changed somewhat because the world (including computer hardware and sensor data quality) was not ready to do the things Gustaf had intended during this early first hype of AI. But the ambition to do research in the forefront of what is possible is one of Gustaf's excellent characteristics. In the world according to Gustaf nothing is impossible, but some things simply take a bit longer time. When this text is written (2022), I have two PhD students of my own working in the field of AI, machine learning and digital twins for wastewater systems. So you were right Gustaf! We are gradually getting there but it took somewhat longer time than initially expected.

During my years as a PhD student Gustaf was the best supervisor one can imagine. Always kind, positive and encouraging, with great knowledge in the field and a huge network of international researchers which he so willingly introduced me to. He also taught me to always do the best I possibly can, take initiatives, the importance of loyalty and ethics towards science and colleagues and the necessity of hard work and never to give up on a topic. Very limited research is the result of 'divine inspiration' but rather of 'massive transpiration'.

Obviously there have also been some drawbacks of working close to Gustaf for so many years. 'This is the final call for passenger Gustaf Olsson. Proceed immediately to gate number X' is something I have heard several times when nervously waiting for Gustaf at some gate to fly off to some conference around the globe. When it was later time to go to bed in a joint hotel room it was always a good idea to bring a set of ear plugs as his snoring could (can) be quite offensive.

And when it was time for breakfast he had (has) a strange tendency to prefer a McBreakfast at some local burger joint rather than a prepaid extravagant hotel buffe breakfast. I have never been able to figure out the reason for this odd craving.

It is surely amazing how Gustaf has been able to accomplish all he has done – developing new courses, teaching (teacher of the year already in 1993 at Lund University and still active teacher), head of department, 100++ MSc and 45+ PhD supervision tasks, writing an almost infinite number of applications for research funding, project manager for a huge number of research projects, extensive publication including 12 books (IWA Publication award 2010), leading functions at Lund University and on national level boards and committees, highly active within IWA (former chair of the ICA specialist group, former member of the Strategic Council and Board, Honorary member (2012) and Distinguished Fellow (2014)) and many other international organizations, editor-in-chief for *Water Science & Technology* and *WST: Water Supply* and the on-line journal *Water Practice and Technology* (2005–2010), arranging national and international conferences, guest professor and advisor at several universities across the globe, and so on, and so forth. And all of this has been done with the same enthusiasm and willingness to do good. It is indeed a most remarkable career. However, Gustaf also has the great ability to bring out the very best of his co-workers and hopefully that can partly explain how the above is at all possible.

I personally have Gustaf to thank for so much, both professionally and otherwise. But I am most proud and happy to have Gustaf as my close friend.

11.4 A FEW THINGS CHRISTIAN WANTS TO THANK GUSTAF FOR

'Not again!', I remember sitting at my desk at the department of Industrial Electrical Engineering and Automation, Lund University wondering what just happened and how it could be that I yet again did not get the answers I needed in the relatively rare student/supervisor meeting I just had. Although frustrated, I also remember feeling happy and full of enthusiasm in contrast to how miserable I felt before the meeting. All the frustration with my lack of progress was gone and the confidence in my abilities was back. But no perfect answers…

This is what it was like to have a Gustaf as my PhD supervisor. He rarely gave me direct answers to my problems but always gave me the tools and the confidence to find the solution on my own. After a meeting with Gustaf, no challenge was too big or impossible and although no solution was yet found, the feeling was that finding it was just a matter of time. Sometimes a lot of time afterwards and sometimes in unexpected places but when the answer was eventually found, the solution *was my own*. This was a feeling that was extremely rewarding and confidence building for a PhD student. Gustaf's ability to be patient and trust me to find my way forward is probably one of the most important factors for my development as a young engineer and researcher and something I still benefit from when I approach new and sometimes seemingly insurmountable challenges.

I mentioned that my student/supervisor meetings with Gustaf were quite rare. This does not mean that Gustaf was not available. His door was always open and I cannot even remember that he ever said that he did not have time for a chat about work or just about anything. And in these informal and spontaneous talks Gustaf did answer a lot of questions, from questions about being a young PhD student and wondering about the future to more broad and even existential questions about being a human being and how to see the world we are living in.

In the competitive world of research, Gustaf always advocated collaboration before competition. From the early years of my PhD work, he encouraged me to collaborate with other researchers and engineers. In the beginning, this was limited to local or national contacts but it was soon expanded to international collaborations. Gustaf seemed to know everyone (both in his own field but also in other fields) and he introduced me to his contacts from all over the world, from Australia to North America. The very open and inclusive way Gustaf headed the department meant that we had a lot of visiting researchers bringing ideas and experiences from all corners of the world. This exposed me to an academic and industrial world more international than national and expanded the horizon for me on a personal level. This ‘internationalism’ became a natural state for me in a way I only realized when I, after leaving academia, no longer

Figure 11.2 Gustaf being honored by Professor Zhiguo Yuan in 2009 for his life-long achievements in bringing ICA to the wastewater community (ICA2009, Cairns, Australia).

had it. Fortunately, I soon learned that similar ways of working and exchanging experiences do exist in industry as well.

My years at Lund University as a PhD student and young researcher to a large extent shaped me into what I am today. The opportunities I had and still have in my professional life are a direct consequence from working for and with Gustaf and my other colleagues during these years.

For this and so much more I am forever grateful to Gustaf (Figure 11.2).

11.5 SUMMARY

Numerous prizes and awards are tangible evidence for Gustaf's achievements but the many students and fellow water professionals being inspired and picking up ideas and research are an even more important legacy. We know that many more colleagues have similar experiences as we (the authors) to share about Gustaf as a mentor, inspirer and friend. However, we have had the privilege to experience the great knowledge and even greater enthusiasm and positivism that is the signum of Gustaf on an almost daily basis for 2–3 decades. We are forever in your debt, Gustaf! Thank You so much for all You have done and given us over the years!

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My digital water journey with Gustaf

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12.1 ON MENTORSHIP

When looking back at one's own life and career, the red thread is the people that inspire you and assist you in making decisions that determine your path, your mentors. This influence is vastly underrated and I recommend everyone to build in ample reflection time in every workweek.

In my specific case, my journey was carved out starting with my math teacher in high school that triggered my interest in STEM. Later on, I got inspired by a professor that further triggered this interest, more specifically in system optimization and control, in modelling and control courses and came to be my MSc and PhD thesis supervisor as well as inspiring me to embark on a scientific mission. And more recently, there were two former PhD students with whom I co-founded a company and that are truly inspirational. Note that these are all people in my close vicinity, that is living close by. But then there are the mentors that you meet when travelling the world. And when I'm asked that, the first name that pops up in my mind is Gustaf.

I physically met Gustaf for the first time during my postdoctoral stay in Lund back in 2005. And later on, I had the honour to meet him at many locations around the globe, mostly at modelling or control conferences, or more higher level events such as the world water conference. The remarkable thing about Gustaf is his accessibility. As a newbie in the field, one read his work and you immediately understood the massive contribution he has made to the water field. Yet, at an event he was the person that likely spent most of his time talking to what we nowadays call Young Water Professionals and also the water professionals from Third World countries. That is truly remarkable and he had a clear mission doing so: inspiring and stimulating those people that will have to 'push forth the water (sector)' (allow me the pun), the next generation. He did this by actively talking to people, setting up mentoring sessions on several topics and foremost by listening to the people's story and providing his feedback, typically leaving you with a ‘keep up the good work, it makes a difference for the industry, for the world’. You could see the passion in his eyes when he said that, he truly meant every single word. The value of such behaviour is so crucial for the development of young people in the sector. They go back home with confidence and tons of energy to pursue the next step in their research or project. I admire this behaviour and try to apply it myself. It is this scarce ability to put aside the ego and all the things you have established in your long career and truly care about the person in front of you and making that person shine. Just beautiful.

When looking back, I remember several of those encounters with Gustaf. They happened during coffee breaks, receptions, exhibitions and dinners. Some of them were so intense that I even remember when and where they took place. Foremost, Gustaf has stimulated my steps to take on leadership in several IWA structures, such as the Specialist Groups on Instrumentation, Control and Automation and Modelling and Integrated assessment. And furthermore, the task groups on benchmarking control strategies and monitoring and mitigating greenhouse gas emissions. Many of these were close to his heart, coming from the control angle into the water field. Whenever you were doubting if you were ready to take up this responsibility, he was there to convince you that you were up for the job and would have a great impact. Even when this meant going out of your comfort zone and being exposed to ‘easy criticism’. Not only was this helpful when taking such decisions, I also remembered those words and moments when times got a bit tough. It just gave you tons of energy to accomplish things. There is always a way to make it work.

Let’s turn now a bit to scientific content. Of course there are the many inspiring keynotes and lectures to remember. Every one of them was truly inspiring and what I liked most about them is their ‘out of the box’ content and the multidisciplinary nature. He doesn’t get stuck in the details, but provides the context and how the current work fits into the ‘big picture’. He showed what T-shaped leadership is about. Not just looking at your own area of expertise, but also look over the fence to other areas and try to connect them. The water–energy nexus book is a great example of that. This is in my humble opinion what true vision is all about. Not being stuck in the now and focus on incremental progress, but also see the big milestones ahead. The true inspiration comes from people that are able to zoom out and give a high level view on developments. Gustaf did just that and I was always all ears when he got on stage to address us.

And now some words on digital, given its ‘recent interest’ in the water sector. Well, I would say that Gustaf has pioneered this field and the digital journey the sector has been going through was vastly influenced by his work. Given his control background, he saw the need for reliable sensors and models to develop controllers. He has pushed the field to develop all these building blocks that will eventually lead to digital twins in the near future. So, in essence, he is the godfather of the digital twin as he already had the vision back then of how this could work and which building blocks needed to be developed. He always reminded us about the early days of modelling and control, showing pictures of the first computers and SCADA systems. It made us realize that we had already made a long journey to be where we are today. And he stimulated us to keep developing.

And that is what I'm still doing today in my research work, based on the inspiration Gustaf has given me over the years. So I'll end with some vision that I have with regard to the continuation of the digital journey, which might be inspirational.

At the plant level, further development of models that will be needed when digital twins will be implemented is needed, that is compartmental models based on computational fluid dynamics (CFD) models, settler models and hybrid models. If not, the predictive power will stay too low, which will require frequent recalibration and loss of trust with the plant operators (that will also be the digital twin operators by the way). Also, in this context, I would like to remind people about the usefulness of mechanistic models in an era where it seems that data analytics is going to solve all problems. They will not! And besides, why would we throw away all the knowledge we have gathered over the last 200 years? Let it go hand in hand, hybrid, and exploit the best of both worlds.

Just like the T-shaped thinking of Gustaf, I am convinced that we need to start zooming out in order to not end up with suboptimal systems. And that has to do with system definition and scale. In an era of transitioning to a circular economy, where water reuse is key, the two different continents of wastewater and drinking water (as one of my co-founders likes to call them) really need to start communicating. Not only the people, but also the models. Furthermore, we have to start thinking about cross-sectoral optimization. Gustaf already mentioned energy–water is highly connected, but to date the sectors are not. They still operate as separate silo's. Starting up communication between sectors will become key. And again, not only by people, but also by models and data exchange. In this area, I see ontologies to play an important role to make this happen. It would be a nice example of zooming out, just as Gustaf has inspired us many times to do.

I'd like to end by thanking Gustaf for all he has given to the water sector and to me personally. You are a true inspiration and visionary. Tusen tack!

Ingmar
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About Gustaf Olsson

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Probably different from many authors in this book, I am not a control engineer, nor in any way related to the field of water research. I am an electrical engineer who came to know Gustaf when he hired me as a PhD student in 1989. I graduated with a MSc degree in electrical engineering from Chalmers in 1986, specialized in control of electrical drives, and had also a 'Licentiate degree' from Chalmers in 1989 when Gustaf approached me. Me and my family looked for a place in a smaller city than Gothenburg, and Gustaf's offer to let me continue my PhD education in Lund was a perfect opportunity in all respects.

Gustaf had in 1987 taken over the responsibility for a department in Lund named Industrial Electrical Engineering and Automation (IEA). IEA originated partly from another department named 'General Electric Power Engineering' (Swedish: 'Allmän elkraftteknik') that since establishing Lund University, Faculty of Engineering (in Swedish: Lunds Tekniska Högskola, LTH) had taken the responsibility for all 'electrical power'-related teaching at LTH. It was located in the Electrical Engineering building but moved to the Mechanical Engineering building when Computer Science and Mobile Communications grew, and merged with Industrial Electrical Engineering, led by Professor Hermann Helgesen. Hermann was struck by a brain tumor and when Gustaf Olsson, who had a professorship in Automation, took over the department from Herman, it was renamed as Industrial Electrical Engineering and Automation, the name it still carries – however today as a division, not a department. Since the department had a lot of responsibility for Electrical Power Engineering, and Gustaf had no specialty in that subject, he relied to a large extent on other senior staff to carry the teaching burden in electrical engineering subjects.

This is where it starts to become interesting. Here we have Gustaf alone, Herman died, responsible for a department where he was free to develop the topic of Automation according to his interests but also had to develop the electrical engineering part, not least electrical power engineering, and lift a slumbering level of research in this area. Gustaf realized that he needed to hire competence and reestablish a professorship with the main responsibility in electrical power-related topics. When proposing this to LTH the response was that Gustaf should be able to do this himself. At this stage Gustaf was able to document that he was not specialized in electrical power engineering and could not be expected to lead a scientific development in that area. Eventually, LTH granted the continuation of Herman Helgesen's professorship. Meanwhile, Gustaf had started to hire PhD students and seniors who developed the research topic of first electrical drives and later also electrical power systems engineering. This said, Gustaf did not just hand over the responsibility to the people he hired. Instead, Gustaf lead the development of new and updated courses and course materials, hired and supervised PhD students and very much developed the area of electric power engineering, despite his documented lack of expertise in the subject. The reason that this could happen is very much the result of Gustaf's personality and attitude, and what I want to emphasize in this text about Gustaf.

When Gustaf retired, LTH arranged a day about him called the 'Gustaf Olsson Symposium'. I was one of the speakers and had to consider what to say. I concluded that it all boiled down to one word, 'enthusiasm'. That is the first word that came to my mind when I think about Gustaf.

This word 'enthusiasm' derives from the Greek words 'enthousiasmos', meaning 'inspiration or possession by a God' or from 'entheos' which means 'the God within', variations of interpretation depending on what source is used. To me this makes sense very much. As created by God, the creator who gives and energizes life, human beings feel joy and excitement in the creative process and are, when in that process, perceived as enthusiastic by others. The energy they possess, however, not measurable in any scientific unit, is contagious and spreads to anyone who comes near. After having known Gustaf for about 35 years, this is as much true for Gustaf today as it was the very first day that we met in 1987.

In his effort to blow life into research in the electrical drives area, Gustaf created an organization named 'the Electronic Motor Group' (Swedish 'Elektronikmotorgruppen') in the end of the 1980s, abbreviated EMG. This group was formed to engage anyone and everyone that in some way, industrially or academically, was related to electrical machines and drives. EMG (read: Gustaf) arranged annual meetings where invited speakers from as far as Japan presented a topic of common interest and the events attracted a lot of participation. I remember in several of those meetings thinking of the remarkable situation I was in. There were maybe 50 people gathered, almost all of them dealing directly with electrical drives, people who all must be considered as some kind of specialists in the topic area. There was also one who had documents proving that he was NOT a specialist in the topic of electrical drives – Gustaf. I was contemplating how it could be that among this relatively large group of specialists, that all considered EMG a good arrangement, the only one who had taken the initiative to organize something like EMG was Gustaf. It was very clear to me then, as it is today, that the energy and enthusiasm that Gustaf both possesses and radiates was the main driving force, that made all the participants come back, year after year. Of course, the selection of topic and speakers were important, but that was not enough to make EMG fly the way it did. This is just one example of how Gustaf significantly contributed far outside what may be considered his scientific specialty.

When hired, I considered that the lab resources at IEA were unsuitable as a base for the research in electrical drives, that we were building. I designed a modular ‘LEGO’ system for electrical drives, not least for control purposes, that I presented to Gustaf. Without any hesitation, he showed me the confidence to spend time and money on building this modular system, most of it under one year but subject to continued development in subsequent years. It of course delayed my PhD studies a bit, something that is much more difficult to allow today’s PhD students. Vital parts of the system are still being used in both teaching and research at IEA. This is another side of Gustaf that I appreciate a lot, the confidence that he shows and his ability to build self confidence in people around him.

The only time that I can recall that Gustaf showed some not so good judgement, was when he promoted me (during my PhD studies) to IT-responsible at IEA. He however quickly realized his mistake and I was never asked again.

As Gustaf’s PhD student, later as a colleague (I applied for the professorship in Industrial Electrical Engineering in 1994 and was appointed) and as his friend, I have had the privilege to live and work near the seemingly endless source of enthusiasm that Gustaf is. What it has meant to me cannot be described in words. His wise advice, his personal consideration and his personality has affected my life to the better in so many ways. When I applied for the professorship that I have today, I did not consider myself suitable for the role, but saw the application as a chance to get my CV evaluated. When the shock I got after being appointed had settled a bit, I realized again that Gustaf believed in me more than I did, and his support along the way has always been invaluable. – Thank you, Gustaf!

I know that this text is published in a context mainly made by people who in some way related to Gustafs work in the water area. Unfortunately, despite having spent so much time near Gustaf, his knowledge of water treatment has not proven contagious on me. I am just a novice in water science. I can only imagine how powerful Gustaf’s energy and enthusiasm combined with his deep expertise in that field of science can be. It is obvious in his strategic roles in the International Water Association (IWA), as chief editor for Water Science and Technology, as a guest researcher and guest professor in many universities across the globe, author of numerous books etc. that his impact on the world and on a lot of people is enormous.

One of the impacts that Gustaf has made on me, is that I every day try to be enthusiastic about what I do. I notice that when I am, it affects people around me a lot more than my scientific knowledge and skills. This is a realization that I think applies to all of us. It is for me the most important legacy of Gustaf – to search inwards for my own driving forces, not limited to the scientific area that I am responsible for at LTH and share them with enthusiasm in every situation in life.

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Mats Alaküla

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A tribute to Gustaf Olsson

Pernille Ingildsen
Hillerod Utility

As I contemplate the organisation of this paper about the description of Gustaf Olsson's contribution to the world, I understand that the headlines could be many and remarkably varied.

From my perspective, however, four headlines stand out:

- Research contributions in the field of instrumentation, control and automation (ICA) and water
- Philosophical contributions to sustainable systems thinking in water
- Humanistic contribution from the heart
- Personal contribution to my life

These four key contributions only cover a fraction of Gustaf's contributions. They do not cover the contributions within the field of energy, contributions as an active member of International Water Association (IWA)/ International Water Association Publishing (IWAP), the political supportive contributions in for example Niger and to charitable organisations as Smile and Doctors Without Borders, his musical contributions on organs and pianos, his contributions as a husband, father, grandfather and great grandfather, his contributions as soul counsellor for hearts broken in many varied ways, his local church contributions, his contributions to Lund University and the surrounding start-up environment, his contributions to Universities such as Tsinghua, Queensland, Exeter, Laval (Quebec), his contributions to the students who's life he has touched – and to the many more people and organisations he has generously inspired and influenced over the years.

But so it is: not all can be or should be described.

14.1 RESEARCH CONTRIBUTIONS IN THE FIELD OF ICA AND WATER

Gustaf Olsson has been part of the ICA community in water from the early 1970s. Even though he started out as a student of nuclear technology with a specialisation in control, water is where his key contribution lies. After being asked his opinion on the opportunity for control in wastewater treatment plants in Sweden he turned to the topic of water and remained with that challenge from the 1970s and up until today. The first written reports on this topic were *Control problems in wastewater treatment* (Olsson *et al.*, 1973) and *Measurement and control in chemical and environmental engineering* (Olsson, 1974).

After these initial reports where he identified a clear potential, he progressed to deepen his understanding through papers such as *Modelling and identification of an activated sludge process* (Olsson & Hansson, 1976a) and *Stochastic modelling and computer control of a full-scale wastewater treatment plant* (Olsson & Hansson 1976b) and *State of the art in sewage treatment control* (Olsson, 1977).

Then he turned his attention to a key issue in wastewater treatment plants: the control of oxygen in the wastewater treatment process. This control not only handles both the performance of the biological processes, but also the energy consumption which received global attention during and after the years of the energy crisis in the 1970s. The research was published in papers named: *The dissolved oxygen profile – a valuable tool for the control of the activated sludge process* (Olsson & Andrews, 1978) *and Self-tuning control of the dissolved oxygen concentration in activated sludge systems* (Olsson *et al.*, 1985). Then he turned to the difficulties of controlling the clarifier with the paper *Modelling the dynamics of clarifier behaviour in activated sludge systems* (Olsson & Chapman, 1985).

In 2001, Gustaf presented his paper to the ICA community (Olsson, 2002) when it visited Malmö in 2001. A few years later in 2004, he lead the group of Ingildsen, Jeppsson, Kim, Lynggaard-Jensen, Nielsen, Rosen, Spanjers, Vanrolleghem and Yuan in an effort to summarise 'all of it' in a leading edge paper in Prague named *Instrumentation, control and automation – hidden technologies in wastewater treatment* (Olsson *et al.*, 2004).

The year after, he wrote the paper '*Plant wide control – dream, necessity or reality?*' (Olsson & Jeppsson, 2005) to conceptualise a vision of not just managing various single-loop optimisations but to rather optimise all control handles and variables for an overall optimised plant performance.

Gustaf has been a professor in Industrial Automation at IEA (Industrial Electrical Automation) at Lund University since 1987 and continued this position until his retirement to Professor Emeritus in 2005. During this time countless students went through the courses that he taught. Gustaf wrote several books to teach and inspire his students. The key titles are the control technical textbooks *Computer Systems for Automation and Control* (Olsson & Piani, 1992) and *Industrial Automation – Applications, Structures and Systems* (Olsson & Rosen, 2005) and his books directed towards water and control, that is *Wastewater Treatment Systems* (Olsson & Newell, 1999), *Instrumentation, Control and Automation in Wastewater Systems* (Olsson *et al.*, 2005) and for practitioners *Get More Out of Your Wastewater Treatment Plant: Complexity Made Simple* (Ingildsen & Olsson, 2001).

It is difficult to capture the essence of Gustaf's research in a few lines, but an attempt would be something like this:

Control and automation can be helpful in especially the following three priorities: keep the plant running, satisfy the effluent requirements and maximise the efficiency.

There are three key driving forces for control and automation in water, the foremost is a technical driving force, where sensors, actuators, control equipment and control algorithms has developed and become increasingly available since the 1970s and up until today. The second driving force is regulatory. In a sense there is a communication between regulations and technology as stricter demands provide a space for better technology to come and solve the challenge and as technology makes it possible to be more precise, regulation can be made more intelligent and complex to meet the environmental issues that the regulation is attempting to address. The third driving force is the human factor. Gustaf always insists that this field is about people. Clever process operators can make a plant sing, process educator without proper knowledge can make a plant crash. Hence motivation, training and experience are key.

Control and automation are about addressing various timescales in the different control loops. The key loops are dissolved oxygen and SS control, which are controlled in two different time domains. By means of models it is possible to make control much more advanced and taking care of all the interactions in the plant, the ultimate goal is plant-wide control. There are many clever control strategies and ideas, the key idea in control is however first and foremost feedback, that is, the ability to understand where the process is right now and act accordingly. The second most important principle is feedforward, that is, to understand where the process is heading and prepare the process to provide optimal conditions for high performance.

14.2 PHILOSOPHICAL CONTRIBUTIONS TO THE FIELD OF SUSTAINABILITY

The year 2005 marks the time when Gustaf retired from IEA. Gustaf had been a much-loved professor at the department, and I am sure he enjoyed his role. But at this point of time, he grasped the opportunity of being Professor Emeritus and the freedom to do the kind of research he personally felt inspired to do and that he felt was important. Hence, 2005 also marks a transition in his research efforts towards water sustainability and systemic understanding in a global context.

During these later years we have often discussed what it means to be a human being in this time. What is our duty and how can we succeed in changing the world from the perspective of sustainability and water stewardship – and how do we even interpret what we see? Gustaf has followed the environmental debate since before the Club of Rome.

> Inspiring quotes from some of his preferred books on sustainability are:An attitude to life which seeks fulfilment in the single-minded pursuit of wealth – in short, materialism – does not fit into this world, because it contains within itself no limiting principle, while the environment in which it is placed is strictly limited.

From '*Small is Beautiful*' (Schumacher, 1973).

> The difference between a sustainable society and a present-day economic recession is like the difference between stopping and automobile purposefully with the brakes versus stopping it by crashing into a brick wall. When the present economy overshoots, it turns around too quickly and unexpectedly for people and enterprises to retrain, relocate, and readjust. A deliberate transition to sustainability would take place slowly enough, and with enough forewarning, to that people and businesses could find their places in the new economy.

From Limits to growth (Meadows *et al*., 1972).

> I said earlier that my first message to you is that the kind of leadership we have must be changed. The second message I bring you is that global warming is real. It is imminent. It is upon us. It's a lot closer than you think, and I don't believe we're ready for what's coming. from the speech 'The ice is melting' (Lyons, 2004).

> In an incredibly short period of time we have endangered a world that took billions of years to evolve. We are just a tiny link in the great chain of living organisms, so who are we to put it all in jeopardy with our ecological blindness and deadly technologies? Don't we have an obligation, a responsibility, to our planetary future and the generations of humans and other species to come? from The good ancestor (Krznaric, 2020).

He has expanded the systemic approach as the years progressed and still does. In his research more energy themes were included such as in the paper *Smart water and power grids – drivers, opportunities and challenges* (Olsson, 2011). However, most obvious is the transition to be seen in his book publications, which starts off with the best seller '*Water and Energy: Threats and Opportunities*', which has been published in two editions. The book describes the systemic connections between water and energy, never before described with this conceptual clarity. The book shows '… how energy is used in all the various water cycle operations and demonstrates how water is used and misused in all kinds of energy production and generation. Population increase, climate change and an increasing competition between food and fuel production create enormous pressures on both water and energy availability. Since there is no replacement for water, water security looks more crucial than energy security' (Olsson, 2012).

In 2016, Gustaf and I wrote '*Smart Water Utilities – Complexity Made Simple*' (Ingildsen & Olsson, 2016) attempting to describe how far instrumentation, Control and Automation and other levels of digital intelligence could bring water and wastewater utilities in the direction of being smart – in principle regardless of overall goals, but with a nudge towards a water stewardship approach.

In 2019, Gustaf looked at how to provide water sustainably outside the power grid through using solar and power to provide water in the book '*Clean Water Using Solar and Water*' (Olsson, 2019).

In 2022, Gustaf will have two books published on systemic understanding of the water system, '*Improving Utilities with Systems Thinking – People, Process and Technology*' with Cello Zdenko, Scott Haskins and myself is the first book and will be published as a collaborative effort between WEF and IWAP. The second book is his own '*Water Interactions – A Systemic View*' describing the evolvement of the sustainability crisis over the course of his life from the 1940s until today followed by a recounting of the interconnections between the sustainability crises of climate, water, energy, health, economics and lifestyle.

An important insight from this work is that it appears that understanding control theory prepares you well for systemic understanding of larger sustainability issues. Which is also indicated in James Lovelock's Gaia (Lovelock, 1979), who's main thesis was that the world operates and makes the world inhabitable by means of a myriad of feedback loops that keep conditions balanced in such a way that humans and other lifeforms thrive – he may even indicate that the intricate interactions between these life forms are a major part of the intelligence that keeps the huge earth process or life process within the scope of Gustaf's three aims of 'keep the earth running', 'keep within regulatory limits (limits enabling life)' and 'do so as efficiently as possible'.

The books can be seen as a kind of dialogue he is having with himself and the rest of us about the sustainability crises and how they interact with our job as water professionals. Through his writing he is initiating a field of technical water sustainability understanding and emphasis mixed with moral understanding and a growing concern and alarm about the direction the world is heading in.

In this work he strikes both a moral and a technical chord – and we need both to succeed. We need to evolve from short-term thinking to long-term thinking and Gustaf is showing us how.

14.3 HUMANISTIC CONTRIBUTION FROM THE HEART

Even after these great contributions, I believe that at the end of the day, what most people remember is not the science, it's not the alarm rather it's his person and how he manages to make you feel. His distinguished personality exudes warmth, enthusiasm, passion, generosity, kindness, intelligence, ability to explain, ability to listen, grasp and appreciate your ideas and concepts.

There are many examples where I have experienced what he 'does to people' firsthand. But especially two episodes come to mind.

In 2017 he opened the conference 12th IWA Specialized Conference on Instrumentation, Control and Automation 11–14 June 2017 in Québec City, Québec, Canada by playing the most beautiful piano concert for an amazed audience of researchers and practitioners of ICA. It was as surprising as it was soothing and uplifting. After finishing he stood up and gave an inspiring lecture on the last 5 decades of development of instrumentation, control and automation and provided everybody with a vision of what he believes was to come in the near and not so near future of ICA. This uplifted the whole conference for a great both reflective and enthusiastic start of the conference.

Another incident, that illustrates how he can make everybody do their best through inspiration and listening, is from a workshop, I held at Kalundborg

Utility. The purpose was to develop an innovative drinking water plant and we had invited three professors from Denmark, Norway and Sweden – the Swedish being Gustaf. We had also invited a number of other internal and external project participants and stakeholders amongst which were the three key operators of the currently running plant. They felt a bit out of place in the beginning with the three professors, but whatever strangeness they may have felt was completely obliterated by Gustaf. In a short time, he changed the situation, so that the three operators became the lead actors of the workshop. He asked, listened and marvelled at the insights he gained from the three experienced operators. This meant that the project was profoundly inspired by their point of view and their concerns and aspirations. This turned out to be a great experience for everybody – and everybody learned something new in the happy, curious and constructive way that we all love.

I have experienced this magic many times with Gustaf. So much that at conferences I tend to find a place near Gustaf at lunch – just to hear the conversations that come out of it when he questions and thinks together with those, he has lunch with.

14.4 PERSONAL CONTRIBUTIONS AND INFLUENCE ON MY LIFE

Gustaf constitutes a whole part of my world to me. I often as a shorthand explain to people that he is like 'a second father to me'.

I met him in Sweden in 1998 to discuss the opportunity to seek the Danish Academy of Technical Sciences to fund a PhD project on control of wastewater treatment plants using Danfoss' newly invented in situ online nutrient sensors – having him in the central role as the supervisor. I didn't know much about Gustaf besides having read a few papers. Little did I know what an incredible fortunate event it would develop into, that he happily accepted the task.

In 1999 we visited the Advanced Water Management Centre at University of Queensland in Brisbane. Almost every lunch we enjoyed together followed by chocolate topped with mini marshmallows. In the autumn/winter of 2000 we wrote the book '*Get More Out of Your Wastewater Treatment Plant*' together. I did most of the writing and every Tuesday evening, I travelled from Copenhagen to Malmö to discuss the writing in the home of Gustaf and Kirsti.

By 2002 the PhD programme came to its end. I am not a lot into national symbols, but still I was moved when I realised that Gustaf had organised a Danish flag for the flagpole at the institution at the day of my defence.

Later we co-wrote the book '*Smart Water Utilities*' and he was a tremendous support during the difficult writing of the Water Stewardship book – always encouraging the work and convincing me of its importance when I doubted. Still today we often have complex discussions of how to understand and work with water from sustainable systems view.

Currently, we are working on a project called Leap. The purpose is to develop leadership skills for a successful transition to a sustainable world. Until now, we only have pieces of the puzzle, but working with Gustaf, I hardly feel any doubt, that we will find a good way sooner or later.

But also, when it comes to difficult times in my life, he has been steadfast. He has been part of my life for more than half of it. Not a single time has he given me reason to regrets – except perhaps the one time where he could not stop laughing at my hysteria when a leech attacked my leg. It was my first leech and yes, I panicked. Even years … decades later, he lets me hear about it. But that small thing is easily forgiven. The place where our lives intersect has always been wonderful and I am immensely thankful for all that he has been: a friend, a counsellor, a philosopher, a sparring partner, a cheerleader, a role model and a second father.

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Professor Gustaf Olsson has devoted countless hours over many years to *Water Science and Technology*, *Water Supply* and *Water Practice and Technology* as an author, reviewer, editor and Editor in Chief until finally stepping down from all functions in 2021. In order to honour Prof. Olsson's devotion and contribution to the journals, IWA Publishing has compiled a *Festschrift*: that is, a book made up of contributions from Prof. Olsson's former students, his colleagues (past and present), and of course his friends.

As the contributions testify, Gustaf's devotion and influence by far exceeds his work at *Water Science and Technology*. It has been a joy to read through the testimonies about Gustaf and how he has shaped and influenced lives and academic careers. They express an overwhelming gratitude for the way he has influenced and, in some cases, significantly formed both the professional and personal attitude of those he has touched. It also testifies to great scientific contributions, contributions that are strongly embedded in the water sector industry and with great impact at the time of publishing and clearly also well into the future. His leadership example is a source of inspiration to everybody in the water sector whether in academia or industry.

We urge you to read this *Festschrift* to celebrate Gustaf and get inspired about how to work in service for the greater good of water.

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