IFC-2018-CET01

IntelliFlux Research & Development Group

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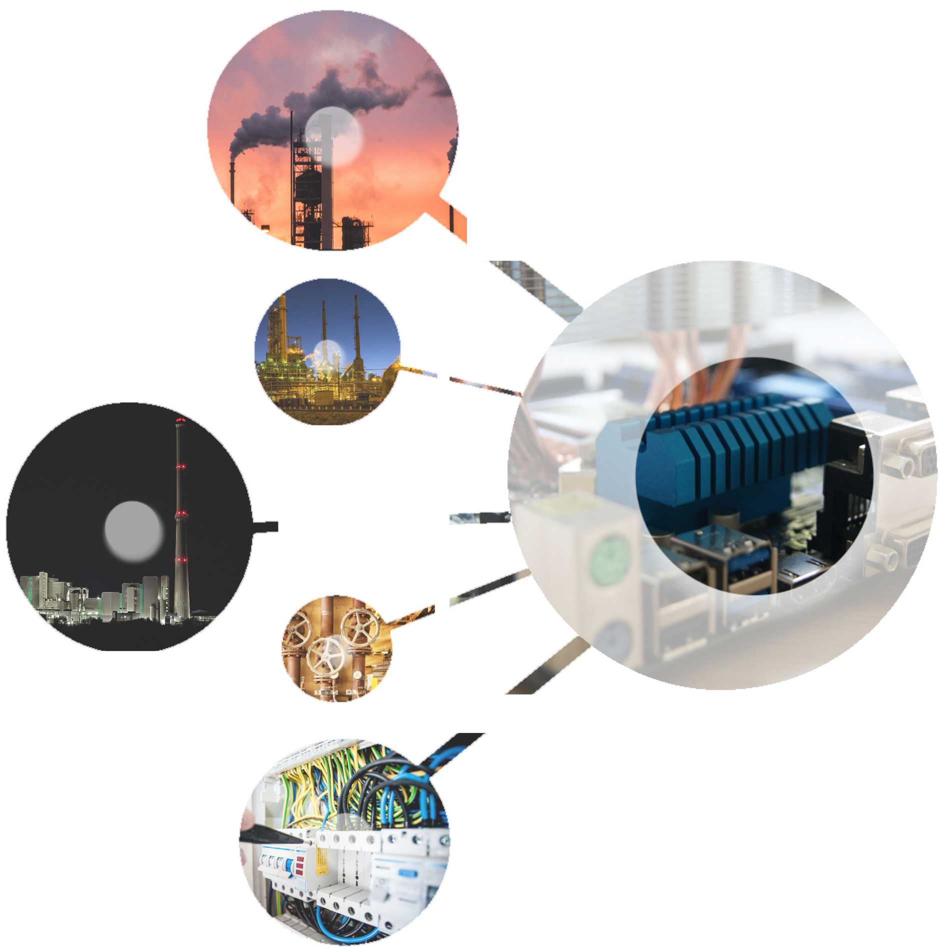
IntelliFlux®

Optimization of a Membrane Bioreactor

APRICOT, Version 0.0.1

March 2018
Revised May 2019



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Optimization of a Membrane Bioreactor

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IntelliFlux Controls, Inc.
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Final Report

This is additional info.

Prepared for LG Hitachi CONFIDENTIAL

Abstract: IntelliFlux Controls, Inc. conducted a six-month field test of its first generation Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT) on a membrane bioreactor (MBR) located at an industrial wastewater treatment facility in South Korea. The system was retrofitted with the software which monitored and controlled only the membrane filtration component of the MBR. The tasks included optimization of membrane cleaning and filtrate throughput in response to influent water quality variations. The six-month study demonstrated the benefits of IntelliFlux, which included its ability to respond to influent quality variations and adaptively modulate the cleaning intensity, ability to detect faults in the plant hardware, and improve the operations of the plant. The system experienced a 34% savings in operating energy per unit volume of filtrate produced, a 2.1% increase in net yield of the plant, and a 40% reduction in the rate of irreversible fouling of the membranes.

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1 Executive Summary

IntelliFlux® membrane fouling management and flux optimization system was installed on Client's R&D membrane bioreactor (MBR) in South Korea for a three-month performance demonstration. This report summarizes the findings of the demonstration, highlighting the following key observations.

1.1 Objectives:

The objectives of the demonstration were to:

- Compare the performance of IntelliFlux adaptive cleaning of UF membranes against conventional membrane cleaning performed at the plant,
- Assess how IntelliFlux benefits membrane plant operation, including lowering chemical and energy consumption, increasing production, and improving membrane residual life, and,
- Demonstrate how IntelliFlux autonomously protects the membrane from high intensity fouling due to sudden changes in influent quality or operating conditions.

1.2 Key Observations

- During isolated high intensity fouling events, IntelliFlux autonomously increased the frequency and intensity of backwash to prevent extensive membrane fouling and maintain system performance.
- During normal operation, IntelliFlux reduced backwash intensity and increased backwash interval leading to the following savings compared to conventional operation calculated from historical data
  1. 34% energy savings per cubic meter net water produced
  2. 2.1% increase in the net volume of water produced
  3. 40% reduction in the irreversible fouling
- IntelliFlux demonstrated several other benefits, including,
  1. Alerting operator to pump malfunction

2. Automatic startup after power failure at plant site
3. Continuous remote monitoring and altering operator on critical event triggers

2 Introduction

A demonstration of the IntelliFlux® membrane fouling management and flux optimization system was conducted on Client 's 50 m^3/ day (2 m^3/hr) membrane bioreactor (MBR) system located in South Korea. The MBR system treats regional sewage water on a 24-hour operation cycle for chemical oxygen demand (COD), nitrogen, phosphorous, and suspended solids removal. The MBR is equipped with outside-in PVDF hollow fiber membranes. The MBR operates using a suction (driven by a vacuum pump) in the filtrate line, while the feed is maintained at atmospheric pressure. The system is controlled with a programmable logic controller (PLC). The membranes were conventionally cleaned using a timed filtrate backwash of 30-second duration in conjunction with air scouring. The backwash interval was 14.5 minutes. Once the permeability of the membranes decreased below 50 lmh/bar, or the transmembrane pressure (TMP) exceeded 0.4 bar (kg/cm^2), the system would be taken off production cycle and a manual Clean in Place (CIP) was conducted. Prior to installation of IntelliFlux , remote monitoring was achieved using a remote desktop connection software, which was connected directly onto the PLC-networked computer.

Historical plant performance data, the process flow diagram (PFD), the process and information diagram (P&ID), as well as the PLC control program and input/output (I/O) list were reviewed and analyzed by the technical team of IntelliFlux Controls to ensure that retrofitting the plant with IntelliFlux automation system should provide a measurable performance improvement compared to the baseline operation. Historical performance data during the previous year's operation was reviewed. Key observations were:

1. The permeability of the membrane in June 2016 was nearly 180 lmh/bar (temperature normalized permeability $\sim$ 170 lmh/bar).
2. The UF train was down for long duration (about a month) during September-October 2016, January-February 2017, and May 2017, most likely immediately after a clean-in-place (CIP).
3. The permeability of the membrane before a recovery clean and long shutdown was around 50 lmh/bar.

The IntelliFlux retrofit consisted of installing an Industrial PC (IPC) to the PLC of the MBR system. The installation and commissioning were conducted between September 18 to September 23, and the full time IF operations began thereafter. Full-time IF operations have been monitored since September 20th to present date including a brief phase of static cleaning to collect data for a base case of performance with the previous non-adaptive cleaning protocol. After the static testing period, a second phase of IntelliFlux operation was initiated between November 3 to the end of the project. During this second phase of IntelliFlux operation, the backwash pump often cavitated, which resulted in incomplete cleans. This limited the benefits of the IntelliFlux cleans. This report analyzes the IntelliFlux performance information gathered during the trial, and compares this against the baseline performance of conventional membrane cleaning. Attention is given to the performance metrics that can be observed instantaneously, daily, and over prolonged usage.

3 Objectives

The objectives of the demonstration were to:

- Compare the performance of IntelliFlux adaptive cleaning of the MBR Ultrafiltration (UF) membranes against conventional membrane cleaning performed at the plant,
- Assess how IntelliFlux benefits membrane plant operation, including lowering chemical and energy consumption, increasing production, and improving membrane residual life, and,
- Demonstrate how IntelliFlux autonomously protects the membrane from high intensity fouling due to sudden changes in influent quality or operating conditions.

The key performance indicators agreed during the commissioning of the demonstration were:

- KPI 1: Average energy savings: 5-20 % over the baseline plant
- KPI 2: Average operating expense (OPEX) savings of 5-20% over the baseline plant.

The goal of the project was to test the cost savings of the IntelliFlux control system on a membrane bioreactor (MBR) against previously established baseline costs. For this study, the duration of that testing has been assessed as three months. Analysis of the plant performance has been achieved by monitoring temperature- normalized permeability (normalized to 20 °C), transmembrane pressure, water production, and hydraulic specific energy consumption. Water production was characterized as the gross water production, *i.e.*, filtrate flow rate, as well as the net water production, which is the net water produced after accounting for the amount of water consumed during membrane cleaning. Hydraulic specific energy consumption is the theoretical energy consumed normalized by the volume of net water produced. Energy consumption was calculated as the amount of energy required by the vacuum pump during normal filtration as well as the energy consumed by cleaning. It was calculated using the measured pressures and flows around the filtrate vacuum pump as well as the expected power consumption during each clean. Environmental conditions were also monitored, especially by calculating a filtration metric known as the "fouling time constant." The fouling time constant is descriptive of the fouling rate and is calculated by modeling the rate of decline of the membrane permeability. For example, a high fouling time constant, such as 500 minutes, represents low fouling conditions and a low fouling time constant, such as 50 minutes, represents severe fouling conditions.

4 Project Timeline

The overall demonstration project timeline and milestones are shown in Figure 1.

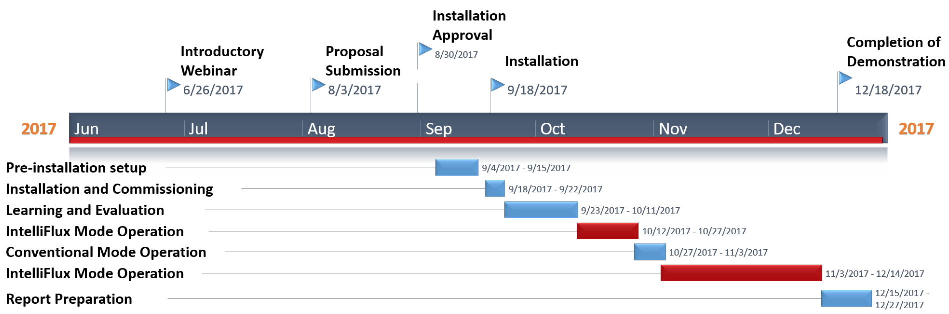

Figure 1. Project timeline for the demonstration of IntelliFlux operation on Client's MBR.

The original, proposed test plan included an initial installation and commissioning stage followed by the three-month demonstration stage. The IntelliFlux IPC hardware was successfully installed and commissioned within the allotted two-week window, leading to the official demonstration start date of October 13, 2017 (October 12, in Pacific Standard Time, PST). This start date was chosen so that IntelliFlux operation could begin with the membrane in a clean state after the scheduled clean-in-place (CIP) on October 12, 2017. The original test schedule suggested by IntelliFlux Controls included two separate weeks devoted to conventional operation to directly measure the system performance under baseline conditions. Due to unforeseen issues (cavitation) with the filtrate/backwash pump, the schedule was slightly amended to maximize operation in the IntelliFlux mode and minimize the impact of the faulty pump. The final schedule was as shown in Table 1.

Table 1. Updated IntelliFlux testing schedule.

Week	Mode	Parameters	Observations
$1-2$	IntelliFlux	Table 2	Phase 1. October 12 - 27.
3	Conventional	Backwash with air scour for 30 seconds at 14.5 minutes interval	October 27 - November 3. Site blackout on November 2 and 3. Sporadic pump cavitation observed.
$4-9$	IntelliFlux	Table 2	Phase 2. November 3 – December 14. Cavitation observed between Nov 11 – 14 and Nov 17 – 30. Cavitation repaired on Dec 1 and maintenance clean performed on December 5. Normal operation resumed on December 6.

5 Historical Performance

The historical performance data (Figure 2) over more than one year of operation was analyzed to identify the key performance features of the MBR system. The MBR operated at a constant flux mode, and the pressure was increased over time as the membrane fouled to maintain the desired throughput. The membrane was operated at different flux values, namely, ~23, 20, and 18 lmh, and it was evident that the fouling rate was the least when the flux was in the 18 – 21 lmh range. At higher TMP (> 0.3 kg/cm^2), the membrane fouling rate increased dramatically irrespective of the flux. This indicates that a different mechanism can cause aggressive flow reduction as the TMP increases beyond a threshold value. The temperature of the MBR system varies quite significantly over the winter days, and it was observed that the temperature recorded was between $10 - 15$ °C between January and March 2017. Under such low temperatures, the efficiency of the MBR's bio-processes are significantly lowered, and this could have adverse effect on the membrane performance.

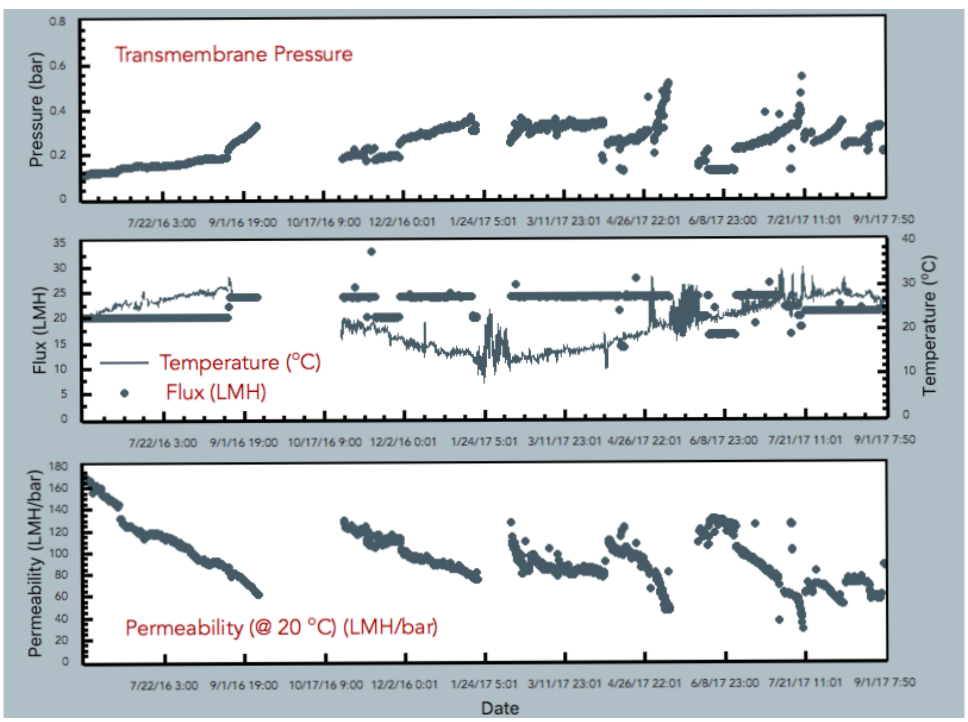

Figure 2. Historical performance data for the pilot MBR system spanning a period from June 2016 to September 2017.

6 IntelliFlux Installation and Programming

The IntelliFlux control software provides an artificial intelligence-guided control philosophy that optimizes membrane maintenance and cleaning in response to influent water quality fluctuations and fouling – the technology deploys only what is necessary to clean the membrane under the environmental conditions at the time. The IntelliFlux hardware includes an industrial PC (IPC) that connects to the existing PLC running a standard operational and cleaning program. The IPC contains the SCADA-level IntelliFlux software, which assumes control of the PLC cleaning set-points.

Without changing the existing PLC program or adding any new equipment other than the IPC, a matrix of 8 different cleaning types was created by the IntelliFlux Controls engineers and made available to the IPC hardware/software solution through an Ethernet connection to the PLC. Table 2 lists the different cleaning regimens created for IntelliFlux optimization.

Filtrate relaxation involved stopping the filtration (vacuum) pump, whereas backwash involved reversing the flow direction of the filtrate pump, resulting in a back flow of the filtrate through the membrane. The air scour involved separately blowing air bubbles on the feed side of the membrane. The energy consumption of each backwash involves the energy of operating the feed pump, whereas air scouring involves the additional energy of blowing compressed air. Relaxation does not involve any energy consumption.

Table 2. IntelliFlux cleaning intensity levels.

Cleaning Intensity	Cleaning Method/Type
0	30 – Second Filtrate Relaxation.
1	30 – Second Filtrate Relaxation with Air Scour
2	60 – Second Filtrate Relaxation with Air Scour
3	15 – Second Filtrate Backwash
4	30 – Second Filtrate Backwash
5	60 – Second Filtrate Backwash
6	30 – Second Filtrate Backwash with Air Scour (Pre- IntelliFlux Conventional Cleaning)
7	90 – Second Filtrate Backwash with Air Scour
8	Recovery Clean (CIP) [alarm triggered – cleaning performed manually]. Duration: 10800 seconds

7 Results

7.1 Instantaneous Response to Fouling Events

The core value proposition of IntelliFlux is its responsive membrane cleaning and flux maintenance when facing sudden changes in conditions (influent water quality fluctuations, or sudden fouling events triggered by a variety of causes). In these situations, the total filtrate flow, pressure, and permeability decline are too subtle for an operator to quickly assess the rate of fouling and take preventive action in a timely manner. This is where IntelliFlux excels. It uses a judicious combination of signal enhancing parameters that can identify subtle changes in permeability that is not discernible to visual observation. Figure 3 showcases a single fouling event that occurred between October 20 and October 21. Prior to the fouling event, stable operation was maintained with permeability around 96.5 LMH/bar. Under these conditions, IntelliFlux was maintaining stable operation with a 15-second backwash every 30 minutes. However, environmental conditions abruptly changed at approximately 2AM PST on October 21. Figure 3a shows that the fouling event is not evident from the time variations of the membrane permeability (blue line) measured from the filtrate flow rate and pressure. However, on the same figure, we have superimposed one of our high sensitivity enhanced signal — the fouling time constant (red line), which shows a distinct change in fouling trend. IntelliFlux learns to respond to these enhanced signals with increasing accuracy over time (by filtering out noise), and immediately alters the membrane cleaning procedure. Figure 3b shows how the cleaning intensity (red) as well as the backwash interval (blue) is altered in response to the enhanced fouling signal. More intense backwash at a rapid interval maintains the permeability of the membrane through these fouling spikes. Once the fouling event passed approximately 10 hours later, permeability was immediately recovered and IntelliFlux eased the cleaning requirement back to optimum, pre-event settings.

During the trial, several events prompted IntelliFlux to execute more intense cleans at a faster frequency. Aside from the response to equipment malfunction, as previously described, IntelliFlux was also seen to respond to natural variability in water quality. For example, environmental factors causing more severe fouling was observed from October 19 to 24. These fouling

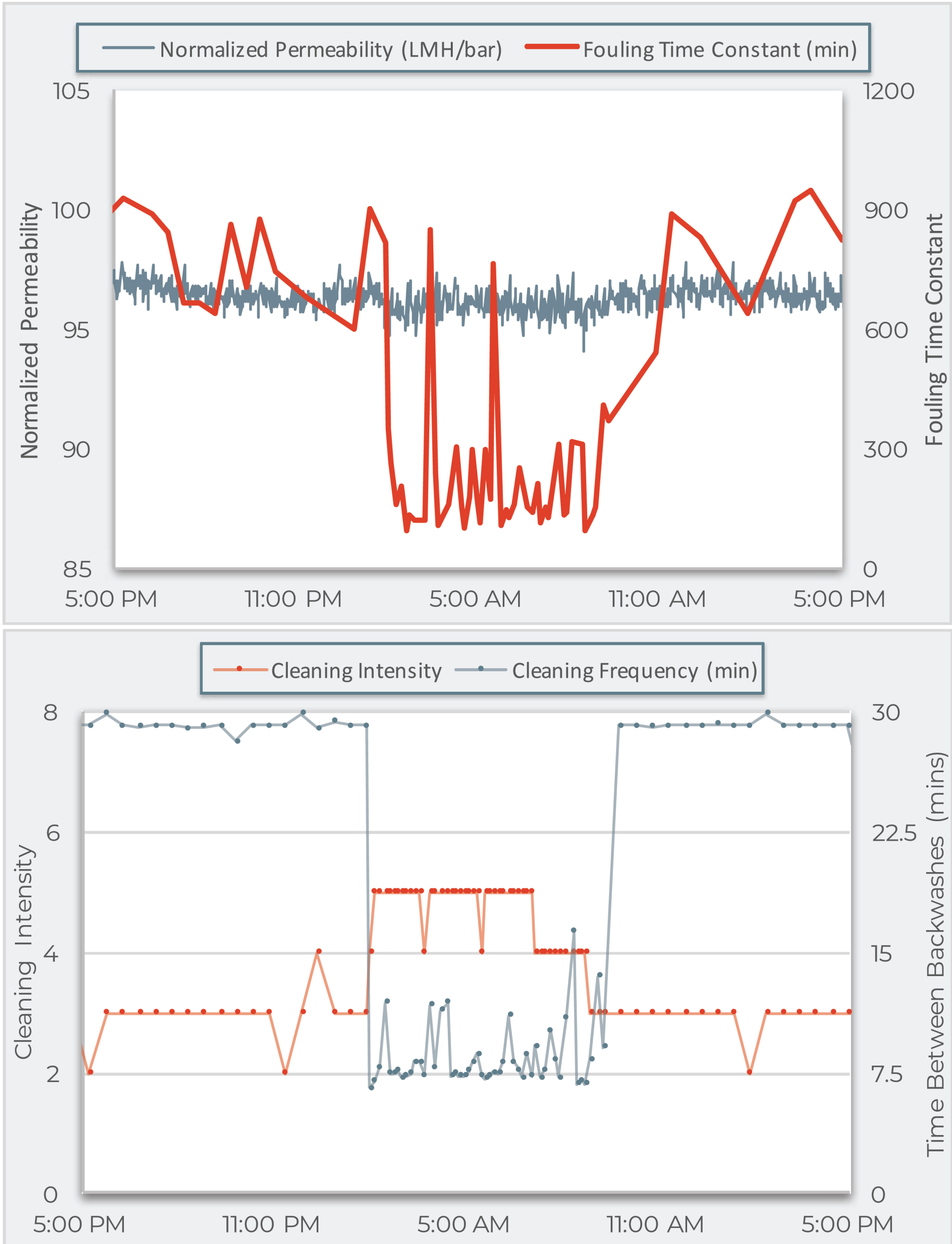

Figure 3. (a) Permeability and fouling time constant and (b) IntelliFlux response by altering cleaning intensity and interval during a fouling event.

events were addressed in real-time by the IntelliFlux software to minimize irreversible fouling and maximize membrane permeability.

7.2 Representative Daily Performance

A simple approach to assess the benefit of IntelliFlux for a brownfield membrane plant is to compare the actual daily performance based on IntelliFlux against a projected daily operation with a regular timed backwash schedule (conventional operation). In this pilot operation, it was fairly straightforward to set up the comparison, as the conventional operation involved a 30 second backwash with air scouring at intervals of 14.5 minutes. This implies that over a 24-hour period, there will be 100 back-washes with 50 minutes of total downtime (due to backwash). Also, the total energy and filtrate consumption for these back-washes are known. Daily performance of IntelliFlux operation can be bench-marked against this baseline. Two representative statistics for October 14, 2017 and October 25 are discussed below.

7.2.1 October 14, 2017

Figure 4 shows the actual performance of IntelliFlux for October 14 bench-marked against the projected performance of conventional mode cleaning over the same 24 hour period.

Clearly, the lower intensity of cleaning, as well as the longer interval between consecutive cleans will lead to energy savings, higher production of filtrate (as less filtrate will be consumed for back-washing), possibility of less down-time due to back-washing, and fewer number of cycling between filtration and back-washing mode.

Figure 5 shows the performance improvement achieved on October 14 against the benchmark of conventional operation. We do not observe any change in downtime for this date in the IntelliFlux mode of operation (in other words, IntelliFlux also spends about 50 minutes on this day to conduct back-washes). However, as most of the cleans using IntelliFlux were relaxation cleans, the filtrate volume consumption was significantly reduced. Energy consumption was also reduced, as the number of air scours were reduced, which significantly reduce power consumption. Finally, only 71 back-washes were conducted using IntelliFlux on this date, which represents a 29% reduction in number of back-washes.

7.2.2 October 25, 2017

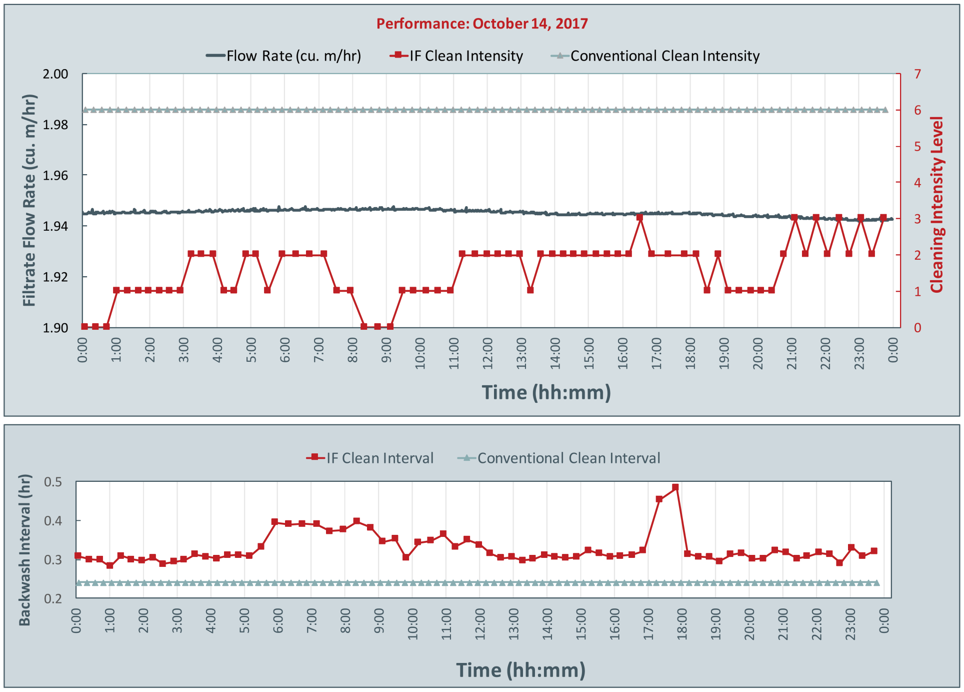

Figure 4. a) Filtrate Flow rate, IntelliFlux (IF) based backwash intensity level, and conventional mode backwash intensity level (Top). b) Variation of cleaning interval (in hours) over the day with IntelliFlux , against the projected backwash interval of 14.5 minutes (0.24 hours) of the conventional cleaning (Bottom).

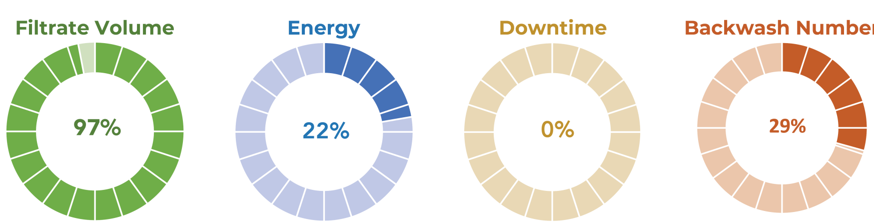

Figure 5. Projected reduction in filtrate volume wasted for back-washing, lower energy consumption, variation in downtime owing to back-washing, and reduction in backwash number (owing to larger intervals between back-washes in IntelliFlux).

It is imperative that these statistics will vary from day to day, as the influent water quality and operating conditions will change the cleaning parameters deployed by IntelliFlux . For instance, Figure 6 shows the performance bench-marking for October 25. During the early hours of this date, the system performance is quite normal, with backwash intensity being at level 3 and 4, and fairly long backwash intervals (> 30 minutes). However, as the day progresses, the backwash intensity increases, reaching levels of 5 toward the late hours, and a dramatically lower backwash interval ensuing during the latter half of the day.

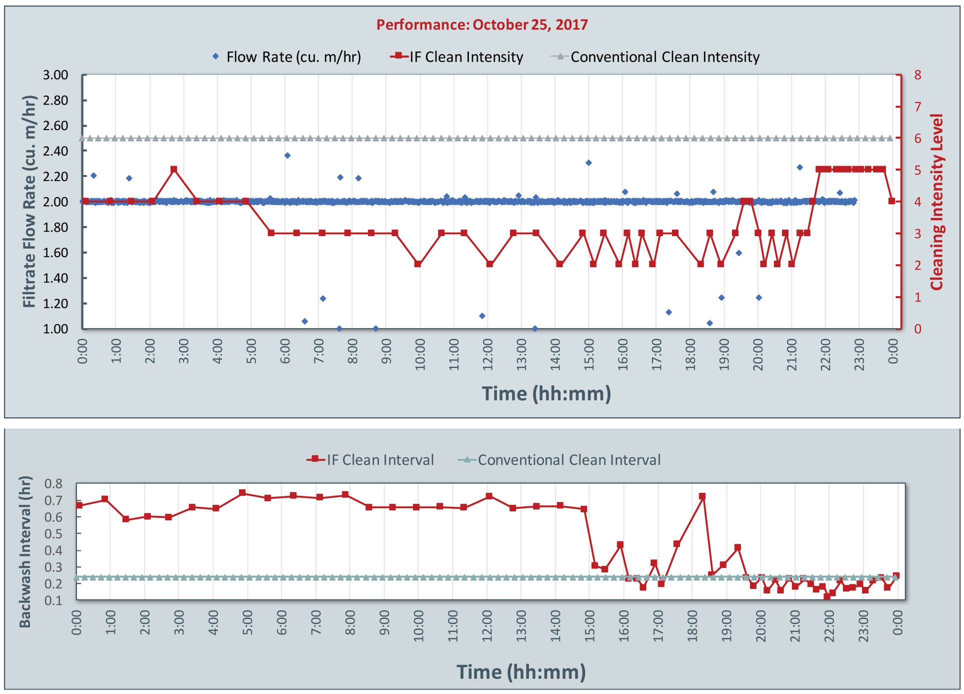

Figure 6. a) Filtrate Flow rate, IntelliFlux (IF) based backwash intensity level, and conventional mode backwash intensity level (Top). b) Variation of cleaning interval (in hours) over the day with IntelliFlux , against the projected backwash interval of 14.5 minutes (0.24 hours) of the conventional cleaning (Bottom).

The corresponding statistics are quite different from those of October 14 (Figure 7). The filtrate volume savings over conventional mode is now 50%, whereas the energy savings is 74%. The downtime is also improved as IntelliFlux spends about 30% less time back-washing the membranes compared to conventional mode, with 42% fewer back-washes performed on this date.

7.3 Aggregated IntellFlux Cleaning Statistics

IntelliFlux mode operation was conducted in two phases (Table 1). During the first phase (Spanning October 12 ˘ 27), the membrane performance was maintained at an optimal level with the permeability remaining at a high level (about 100 lmh/bar). The aggregated backwash statistics from this

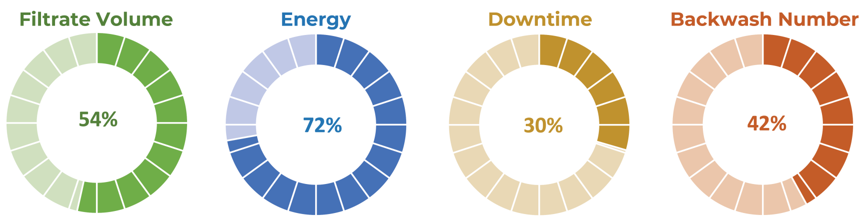

Figure 7. Projected reduction in filtrate volume wasted for back-washing, lower energy consumption, variation in downtime owing to back-washing, and reduction in backwash number (owing to larger intervals between back-washes in IntelliFlux).

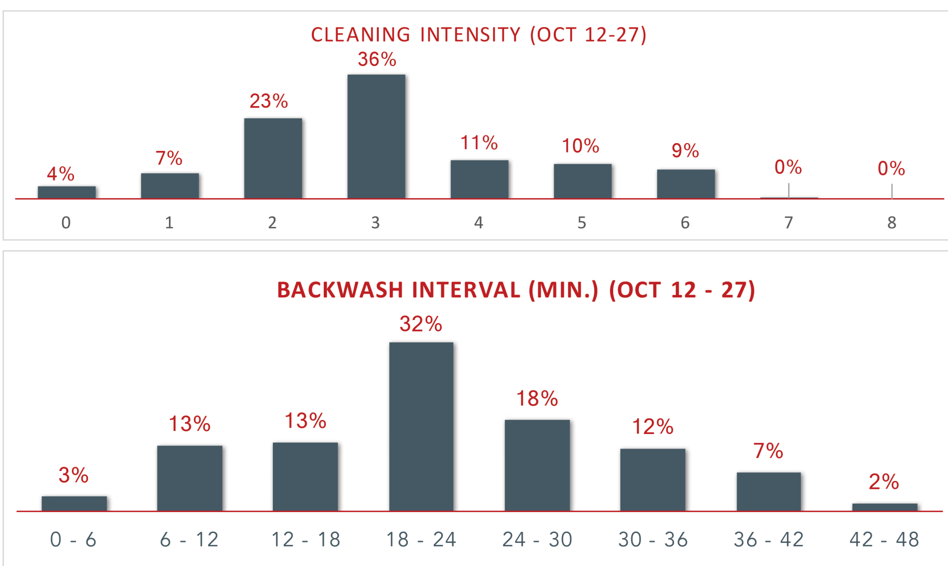

Figure 8. a) Backwash intensity, and b) backwash interval distribution during Phase 1 of the IntelliFlux mode operation.).

phase is shown in Figure 8. We notice from the histogram in Figure 8a that the over 90% of the back-washes performed in this phase were less intense than the cleaning intensity of the conventional mode operation (Level 6). The histogram of Figure 8b depicts the distribution of the backwash intervals. Over 71% of the backwash intervals during this phase are longer than 18 minutes.

The corresponding statistics from Phase 2 of the IntelliFlux mode of operation is shown in Figure 9. We already reported in Table 1 that considerable cavitation of the backwash pump was noticed in this phase of operation. The basic problem was that as the membrane fouled and required cleaning, IntelliFlux would trigger a backwash of a high intensity (Cleaning intensity of 3 or above); however, the backwash pump would fail to operate. This would effectively render the clean as relaxation with no air scouring (similar to clean intensity 0) for clean intensity levels 3, 4, and 5, whereas a relaxation with air scouring (similar to clean intensity of 1 or 2) when the actual clean intensity is 6 or 7 (See Table 2). Such a compromised cleaning will clearly reduce the efficacy of the back-washes. As a consequence, IntelliFlux continued to indicate a consistently high intensity of back-washing and dramatically reduced the time interval between back-washes during this phase. It is evident from the histograms of Figure 9, that despite the failure of a hardware (cavitating pump), IntelliFlux was able to predict the requirement of aggressive cleaning and tune the cleaning intensity and time interval. In fact, during the trial, IntelliFlux has provided multiple early alarms related to equipment faults (mainly the cavitating pump).

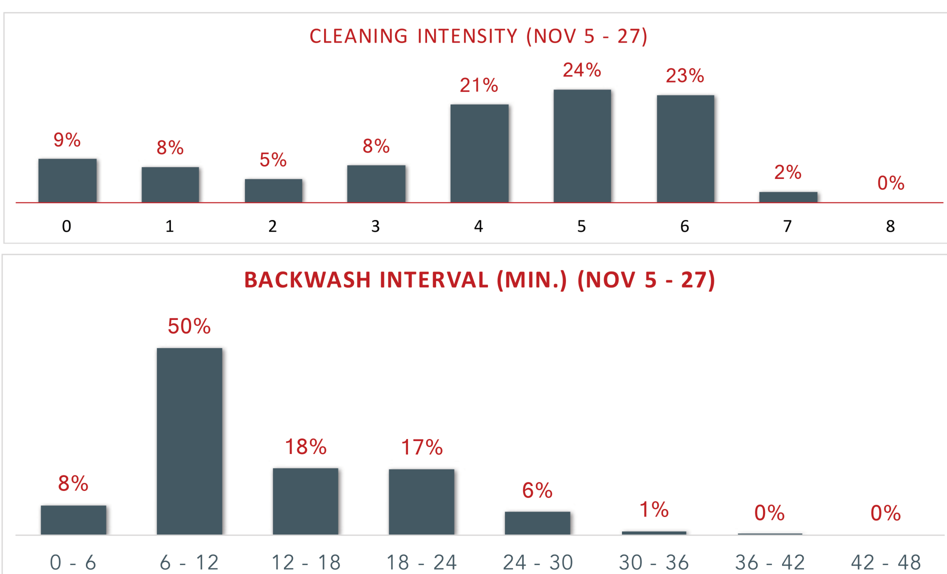

Figure 9. a) Backwash intensity, and b) backwash interval distribution during Phase 2 of the IntelliFlux mode operation.

7.4 Optimized Cleaning and Response to Fouling Events

Aside from a single week in which IntelliFlux operated under "conventional" settings to record baseline system performance, the MBR was continuously operated and optimized by the IntelliFlux software over the full trial period. IntelliFlux sought to optimize membrane cleaning type and frequency to maximize permeability recovery while minimizing the impact on water and energy resources. Overall, a 30-second backwash executed every 18 minutes was deemed the most efficient cleaning sequence by the IntelliFlux algorithms, which resulted in significant water and energy savings as compared to the conventional 30-second air-scoured backwash every 14.5 minutes (Table 3).

Table 3. Optimum cleaning type and frequency for MBR operation under IntelliFlux control, projected conventional operation, and historical conventional operation.

	Most Common Clean Type	Average Cleaning Interval (min.)	Average Cleaning Efficiency (% Permeability Recovery)
IntelliFlux	30-sec Backwash without Air Scour (4)	18.0	98.3 ± 1.5 %.
Conventional	30-sec Backwash with Air Scour (6)	14.5	N/A

7.5 Energy and Water Savings

Immediate improvements in both water production and energy consumption were observed once IntelliFlux assumed control over the MBR cleaning philosophy. Tables 4 and 5 depict the comparison of the entire operation of IntelliFlux (combining Phase 1 and 2) against the historical performance data. IntelliFlux determined that the conventional cleaning regimen was unnecessary for the majority of the time and, therefore, allowed for less costly cleaning when appropriate – only executing more intense cleaning on an as-needed basis. On average, IntelliFlux -controlled MBR treatment devoted 77% of the total hydraulic energy to membrane cleaning and consumed approximately 0.044 kWh of hydraulic energy for every cubic meter of net water produced. In contrast, the conventional MBR required 0.067 kWh/m3 with as much as 85% of the total hydraulic energy consumed by membrane cleaning. Similarly, averaging a less frequent and shorter backwash resulted in an overall increase in the net amount of water produced. The IntelliFlux -operated MBR produced 2.1% more water at a net recovery of 96.4% compared to the 94.3% recovery of the conventional MBR.

In summary, operation by the IntelliFlux software saved 34% of the membrane-specific energy consumption while producing 2.1% more treated water.

Table 4. Hydraulic energy consumption analysis for the MBR. Energy consumption was measured directly during IntelliFlux operation and calculated from conventional performance data recorded during the trial and provided for the prior 16 months of conventional operation between June 2016 and October 2017.

	Total Energy Consumed by Cleaning	Specific Hydraulic Energy Consumption (kWh/m^3 net water produced)
IntelliFlux operation	77%	0.044
Conventional operation	85 ± 3%	0.067 ± 0.005
IntelliFlux savings	−8 %	−34 %

Table 5. Water production analysis for the MBR. Water production was measured directly during IntelliFlux operation and calculated from conventional performance data recorded during the trial and provided for the prior 16 months of conventional operation between June 2016 and October 2017.

	Gross Water Flow Rate (m^3/h)	Net Water Flow Rate (m^3/h)	Average Water Recovery
IntelliFlux operation	1.97	1.90	96.4 %
Conventional operation	1.98 ± 0.2	1.86 ± 0.2	94.3 ± 0.5 %
IntelliFlux savings			2.1 %

7.6 Membrane Life

The IntelliFlux algorithm has been designed to ensure optimum water and energy savings without sacrificing the long-term health of the membrane. To assess membrane health, irreversible fouling was monitored during both IntelliFlux and conventional modes of operation as well as analyzed during 16 months of historical performance data prior to IntelliFlux installation. Irreversible fouling was quantified as the rate of change of membrane permeability and filtrate vacuum pressure. Results in Table 6 show that IntelliFlux operation may have reduced the overall irreversible fouling by up to 40%.

Historical performance data shows that the system had previously suffered from extreme performance variability, with the weekly loss in permeability ranging between 2 and 11% (Figure 10).

It appears that the fouling rate of the membrane increases when temperature drops, which is most probably owing to the inefficiencies in the bioreactor conversion. This causes aggressive additional fouling, and as other types of flux maintenance techniques are not available in this system, it is recommended to reduce the flux to a sustainable value. The accelerated fouling is probably owing to maintaining the flux at a high value of 21 lmh. Reducing it to 19 or 20 lmh could see dramatic improvement in performance during these high fouling phases. However, optimization of sustainable flux was not in the scope of our study during this trial.

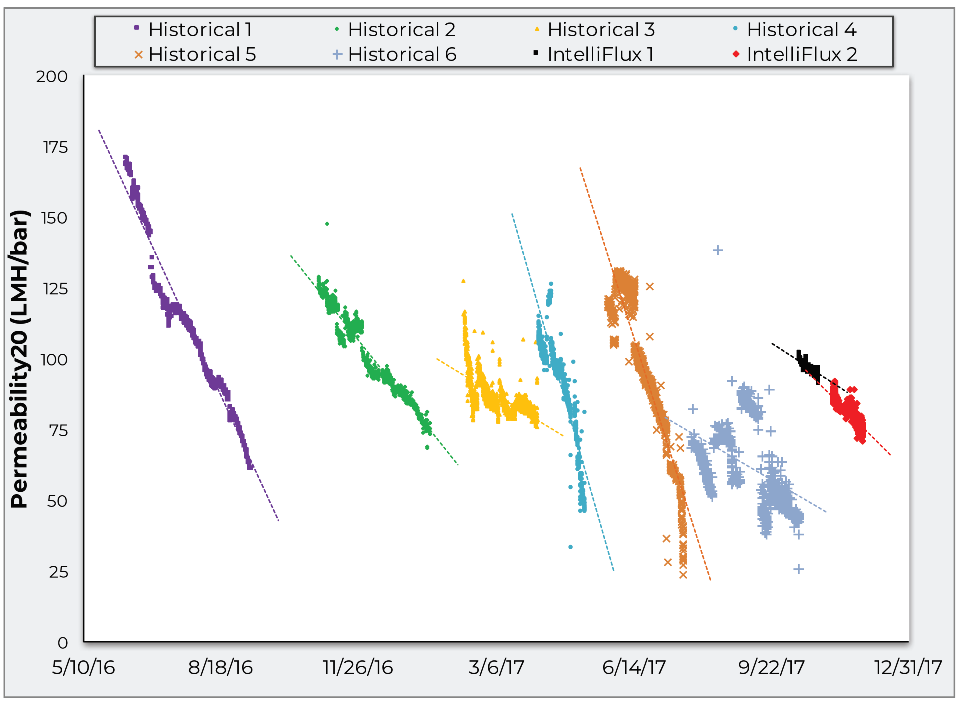

Figure 10. Rate of decline in temperature-normalized permeability for all available MBR performance data. Historical data provided by Coway EnTech for the 16 months before IntelliFlux installation were separated into 6 runs with each run separated by CIPs. The IntelliFlux performance data was separated into two runs with the second run including operation with faulty backwash equipment.

These results further corroborate the conclusion that filters are conventionally over-cleaned when operated under worst-case scenario, fixed cleaning regimens, and that allowing adaptive cleaning based on real-time requirements can save operating costs without sacrificing filter lifetime. If IntelliFlux were to have control over executing and optimizing low-frequency chemical cleaning, such as chemically-enhanced backwash and clean-in-place (CIP) methods, then we project the 40% lower irreversible fouling would be

Table 6. Irreversible fouling analysis for the MBR. Rates of decline for temperature-normalized membrane permeability and filtrate vacuum pressure were measured directly during IntelliFlux operation and calculated from performance data recorded during the trial and provided for the prior 16 months of conventional operation between June 2016 and October 2017.

	Permeability Decline	Filtrate Pressure Change
IntelliFlux operation	2.8 lmh/bar per week ($\sim$ 3% per week)	0.014 kg/cm^2 per week ($\sim$ 5% per week)
Conventional operation	5.4 $\pm$ 4.1 lmh/bar per week ($\sim$ 5% per week)	0.017 $\pm$ 0.013 lmh/bar per week ($\sim$ 8% per week).
IntelliFlux savings	40 %	38 %

observed in reduced chemical costs and downtime, especially in response to seasonal variability.

8 Conclusions

A trial demonstration of the IntelliFlux filtration optimization software was performed on Client's 50 m^3/day MBR system between October and December 2017. Optimization of membrane cleaning via the IntelliFlux algorithms resulted in immediate savings in operating costs despite isolated fouling events and equipment irregularities. In fact, IntelliFlux's cloud-based real-time data management and visualization package provided added insight into system diagnostics and troubleshooting not previously available for plant operators and supervisors. Specifically, the following benefits were directly measured during the trial:

- Overall, IntelliFlux recommended an optimized cleaning schedule of a 30-second backwash every 18 minutes as compared to conventional operation of a 30-second backwash with air scour every 14.5 minutes
  - Extending the time between cleans and avoiding unnecessary air scouring resulted in significant savings in energy consumption and water production
- When needed, such as during isolated fouling events, IntelliFlux executed cleans as intense as a 90-second backwash with air scour every 10 minutes to preserve membrane health and system longevity
- IntelliFlux optimization resulted in the following savings compared to conventional operation measured during the demonstration and calculated from historical data
  - 34 % energy savings per cubic meter net water produced
  - 2.1 % increase in the net volume of water produced
  - 40 % reduction in the irreversible fouling

Appendix A: About IntelliFlux

A.1 Overview of the Product Offering

IntelliFlux is an expert system for process control, helping operators of process and water treatment plant to lower OPEX, and improve plant efficiency through intelligent decision-making. IntelliFlux is based on an expert knowledge-base and engineering fundamentals of the processes it controls, and is driven by machine learning and artificial intelligence engines that enhance the knowledge-base for specific plant adaptations.

The core software platform underlying IntelliFlux product lines are built is referred to as **Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT)**. Engineered with novel machine learning algorithms, the software enables optimization of multiple process components at a plant individually or synergistically. It means that IntelliFlux can optimize any process sequence containing multiple treatment technologies, such as media filtration, coagulation, bio-processes, thermal and reactive systems. With this added capability, IntelliFlux Controls can now provide end-to-end decision automation for water treatment and process plants.

IntelliFlux provides immediate response to process condition variations, as well as thoughtful and learned response based on its machine learning and predictive analytics. The result is a continuously improving smart automation framework that progressively improves it's knowledge of plant operation, enhancing efficiency, adaptability, and reliability of the plant.

IntelliFlux consists of hardware and software components that augment the supervisory control and data acquisition (SCADA) and/or the distributed control system (DCS) framework at a process or water treatment plant to deliver:

- Autonomous optimization of the unit operations or processes at the plant, providing real-time feedback control and adaptive set-point regulation.
- Improved learning from event logs through predictive analytics, statistical correlations, and advanced AI modules, delivering an improved deci-

sion support and automation framework that not only provides operators better insight about the plant, but also circumvents performance loss or plant damage arising from influent quality fluctuations or unexpected perturbations.

The award-winning IntelliFlux filtration software provides an artificial intelligence-guided control philosophy that optimizes flux maintenance and cleaning protocols in filtration operations in response to influent water quality fluctuations and fouling – the technology deploys cleaning only when it is necessary. Furthermore, the intensity and nature of the cleaning deployed is also commensurate with the extent of fouling. This provides unprecedented improvement in system recovery, water use, uptime, cleaning chemical usage, and energy consumption. This product line is mainly applicable to membrane and media filtration processes. Other variations of the software are also-available, and IntelliFlux can be customized for reverse osmosis, biological treatment, mixing, and full plant process control.

A.2 How IntelliFlux Works

Figure A1 depicts the hardware-software architecture of IntelliFlux. IntelliFlux delivers the services as a virtual assistant to the plant operator and engineer using a client-server architecture. The IntelliFlux Client is installed at the customer plant site, where it performs all the real time process control and optimization tasks for the plant. The IntelliFlux server is hosted by IntelliFlux Controls remotely, and provides advanced machine learning, predictive analytics, system identification and optimization tasks to deliver process information to the customer to assist in operational decision-making. This server engine acquires data from the IntelliFlux Client through a secure dedicated connection, processes this information to provide advanced analytics, and delivers decision support to the designated operators and plant personnel. In Ultrafiltration applications with high solids and turbidity influents, difficult to treat waters, as well as highly fluctuating feeds, IntelliFlux has a demonstrated track record of lowering OpEx, energy intensity, chemical consumption, and waste volume, as well as extending membrane useful life, thereby providing tremendous life cycle treatment cost benefits for such plants. Furthermore, the ability to autonomously mitigate water quality excursions and resulting downtime, unscheduled maintenance, and membrane damage improves the reliability and sustainability of the membrane plant.

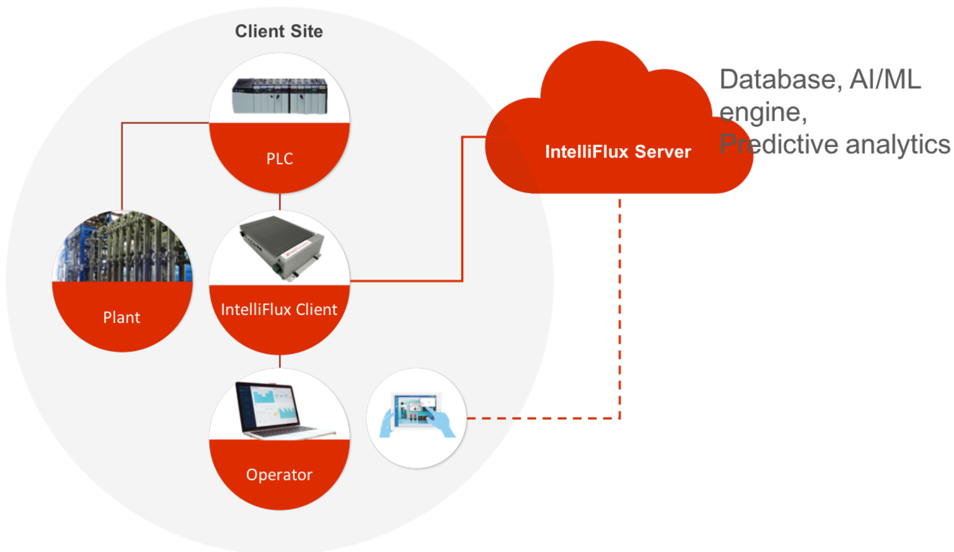

Figure A1. How IntelliFlux works. The system can be easily integrated into any existing plant and starts delivering values immediately after installation and commissioning.

A.3 Applications

IntelliFlux has been deployed on several water treatment plants spanning many types of applications, including

- tertiary treatment of secondary clarifier effluent from municipal sewage plants,
- recycle of cooling tower blow-down water in conjunction with a chemical de-silication process at a power plant,
- wastewater treatment in the food and beverage industry to meet discharge regulations,
- treatment of bioreactor effluent from a mobile sewage treatment plant,
- treatment of oilfield produced water for agricultural reuse, and
- Membrane bioreactors, among other applications.

A.4 Benefits

The key benefits of IntelliFlux include:

- Lower specific energy consumption

- Lower cleaning chemical consumption
- Extended component (cartridges, filter modules, etc.) life
- Increased uptime of plants
- Reduced chances of catastrophic failure or fouling of membranes arising from uncharted excursions of the influent water quality from standard operating range

Depending on the influent water quality and application, the system provides $5-40\%$ savings in system OPEX, $15-70\%$ savings in chemical consumption, between $5-50\%$ energy savings, $20-60\%$ savings in waste volumes, and generally a $2-7\%$ increase in net UF process water recovery.

Application Case Studies

Version: IntelliFlux Ultrafiltration APRICOT™

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