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Case Study : Sustaining Water Treatment and Distribution Automation System Through Whole-system Energy and Water Management at JEA

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Introduction

Sustainability, including environmental, economic and technical sustainability, is a goal that should be high on the list of objectives for water or wastewater treatment system managers. This paper reports on interim results of an on-going study directed at finding a good way to drive sustainable performance in a water treatment utility.

Porter[1] proposed the use of value-chain analysis as a basic tool for examining all the activities of an organization and to understand the sources of value created by the organization[†]. The value chain approach for a water utility disaggregates the activities of the organization into individual processes that can be understood, measured and managed. The processes include both the engineered treatment unit processes and the management activities that ultimately get expressed as the set-points and schedules for those treatment processes. Without the broader perspective provided by a value chain analysis it's difficult to make good sustainability decisions because people-processes and technology-processes interact creating a complex characterization of objectives that must be understood in order to optimize the whole system.

This paper supports the thesis that improved water treatment and distribution system sustainability is achieved when designers and implementers of automation systems take a value-chain or whole-system perspective. Important aspects of value-chain analysis are the data and decisions that characterize the people and technology processes that drive energy and water use up or down. Managed properly, these data and decisions must reflect value to the utility, the community and the environment by including terms for items such as direct monetary costs (e. g., for energy), the value of water and the value of customer satisfaction. Measurement of value in this way may be a better indicator of automation system benefit and penalty. A whole-system metric enables management to drive performance in a desired direction. Interestingly, managers operate their systems towards lowest total cost based on this type of metric and not always towards lower real dollar cost to the utility. This suggests that a "triple bottom line"[3] approach to value measurement is appropriate for use in water and wastewater utilities.

Keywords : sustainability, automatic control, water distribution, energy, optimization, water use, value chain
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Background

JEA is the electric, water and wastewater utility for the City of Jacksonville Florida and parts of three adjacent counties. The JEA water system is a ground water source system. The ground water supply is from the Floridan Aquifer and is delivered using well fields, reservoirs for storage and high service pumps for delivery. There are a total of 36 plants and 139 wells within the total system which deliver approximately 121 million gallons daily. There are 3,400 miles of distribution mains in the JEA water delivery system.

The JEA water system is physically separated by the St. Johns River into a north grid distribution system and a south grid distribution system with various other satellite facilities in St. Johns and Nassau Counties. The North Grid system consists of 9 water treatment plants and 49 wells. The South Grid System consists of 13 water treatment plants and 67 wells[‡]. Water is pumped from the Floridan Aquifer through aerators at each reservoir for hydrogen sulfide stripping.

[†] A previous paper in this journal[2] proposed the more widespread use of a value-chain reference model for the water and wastewater industry.

[‡] Additional plants and wells are not assigned to either the North or South grid.

Water is then chlorinated as it leaves the plant and pumped into the distribution system. Currently, 72 reservoirs located at water treatment plants have a combined capacity of 71 million gallons of water. Pressure is normally maintained at each water treatment plant between 70 and 80 psi via high service pumping. There are no elevated storage tanks in the distribution system. Distribution system pressure is maintained by the high service pumps at the plants. The water treatment and distribution system is monitored and controlled at a System Control Center by operators and managers with a distributed SCADA system. Manual control adjustments are made through a human machine interface on the SCADA system. Automatic control logic is programmed into supervisory software and programmable logic controllers at remote sites.

In 2003 JEA completed a prototype well-field optimization project that demonstrated the effectiveness of a system for improving the automation of JEA well fields. In 2003-04, this work was extended to include optimization of the JEA water distribution system within the South Grid. This Water Operations Optimization (WOO) system effort was completed in 2005 and published in a report for the Water Research Foundation[3]. In 2007 WOO was extended to cover the JEA north grid distribution network, a new grid feedback mechanism was added to improve control, default demand profiles per plant were added to allow the well field optimization to operate independently of the water distribution optimization and studies were conducted to determine if the grid model used in optimization could be improved. The system is fully automated with failover to manual or semi-automated systems when optimization constraints cannot be met.

Motivations for a Measurement & Verification Program

The WOO application has been in service since 2007, with considerable experience and historical data on its operation. The WOO application has worked as designed ; however, it has been a challenge to maintain the many and changing parameters required by WOO. Also, questions arise as to the costs and benefits associated with WOO and whether it is helping to achieve economic, technical and environmental sustainability objectives. These difficulties present a significant challenge to effective on-going maintenance of WOO.

Meetings held in 2009 focused on the definition of a single WOO performance metric that would encapsulate and express whole-system objectives including the hard cost of energy, the value of water and the importance of achieving customer satisfaction. Earlier studies indicated that reductions in chemical costs, better use of energy, cost avoidance-specifically Consumptive Use Permit (CUP) penalty avoidance and capital infrastructure cost avoidance or deferment-improved water quality and streamlined operations. However, collection of data to support these assertions on an on-going basis has been difficult. Data are available to make isolated performance assessments ; however, work processes for continuous measurement are not standard procedures and data collection with detailed performance analysis is a challenge for busy operations staff. In addition, no agreed-upon metric or method for performance analysis, including description of the data required, assumptions and analytical procedures, has been established to continuously measure WOO performance.

A measurement & verification (M&V) plan was implemented for the WOO system. The purpose of the M&V plan is to directly address performance measurement. The M&V Plan included ;

- A definition of the managed system(s) being measured,
- Rationale for calculation of a performance metric, including assumptions,
- A list of tags comprising the raw measurements,
- A list of instruments used for measurement and a method of up-keep (calibration and maintenance),
- Work processes to collect the data and conduct analyses required to evaluate a performance metric,
- Time interval(s) to be used for the measurements,
- A sample calculation of the performance analysis including format,
- Cost of the M&V plan,
- A sample report including examples of all data elements, calculations and representative results.

Water Operations Optimization-Managed System

Good decisions about managing the JEA water systems have to be based on knowledge of the whole system. The broadest definition would include many people-processes and technical-processes in the environment, the community, JEA plant management and JEA business administration. Each of these can have an impact on decisions in a value-chain sense because they all in some way relate to management of water resources for JEA. Organizationally, the JEA Water & Wastewater System Control director has management authority over the water extraction wells, plants and distribution network, thus the "whole system" or "managed system" definition is restricted to these systems.

The managed system for WOO is shown in **Figure 1**.

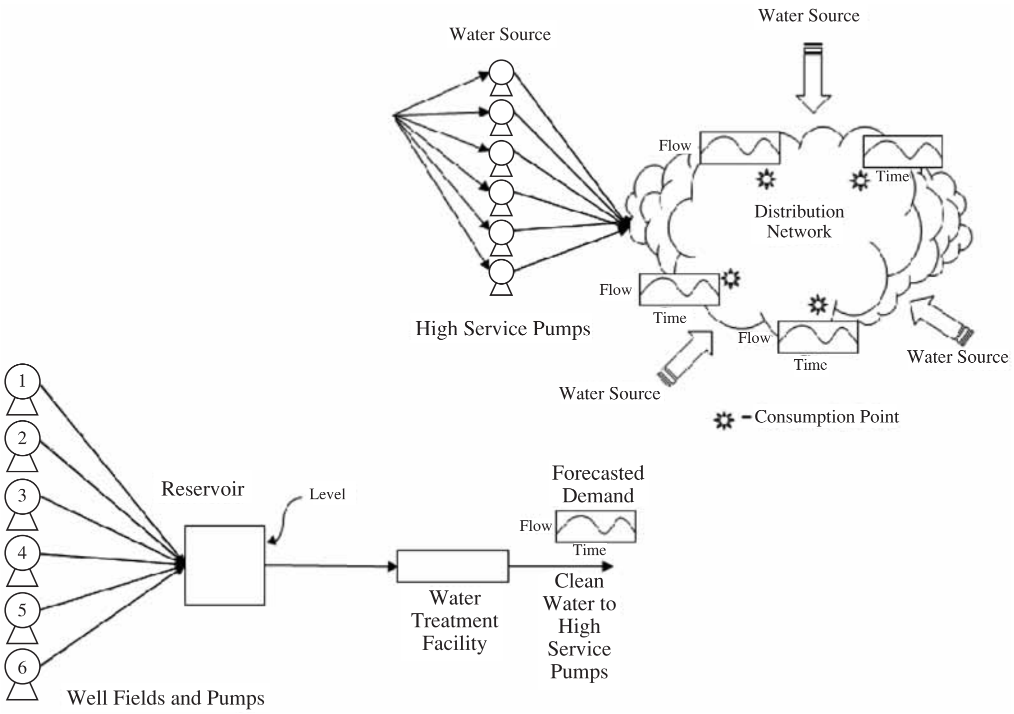

Figure 1　Definition of the WOO managed system

Each water source, comprising well-pumps, treatment and reservoir (s), feeds the pressurized distribution network, which includes both the North and South grids. Water supply and distribution are viewed as separate sub-systems that can be controlled independently. The sources of supply are linked to the distribution network through demand profiles ; the total demand for water within the distribution network is met by water supply delivered by each source of supply as shown in **Figure 1**.

The managed system includes all of the north grid, south grid and satellite water treatment plants, wells and the water distribution network. The managed system includes all the well pumps, high service pumps, and reservoirs in each water treatment plant, and the pipe network, valves and other apparatus in the distribution system up to the point of water discharge. The managed system does not include ;

- water treatment (hypochlorite addition) apparatus in each treatment plant,
- booster pumps internal to the water distribution network, and,
- high service pump bank sequencing controls (only set-points are managed for banks of pumps).

The north and south grids are connected via a transfer pipe between these grids. The transfer pipe is viewed as a sink from the north side and an additional, though constrained by volume and flow rate, water source from the south side.

The WOO system controls the managed system in real time (minute-by-minute) to reduce pumping costs, based on an hourly cost profile obtained from the energy utility each day and pump starts/stops while increasing water quality based on conductivity measurements from the wells and maintaining water levels in the reservoirs at or above a specified limit. See reference[3] for details on the WOO system design and operation.

Whole-System Performance Metric

This section contains a definition of the metric that has been proposed for use by JEA to assess performance of the WOO system. It includes the assumptions or stipulations that are made in development of the metric.

Assumption : Energy minimization and water conservation are the primary reasons for implementing an automation system such as WOO. Other reasons for implementing automation include improvements in ;

- customer service & trust
- safety & security
- environmental protection
- regulatory compliance
- sustainability
- flexibility

These other factors are related in complex ways, both positive and negative, to energy minimization and water conservation measures. For example, environmental protection and sustainability should be enhanced with improved water conservation ; water conservation should result in better water quality and fewer customer complaints provided that sufficient quantity is supplied. More efficient use of energy may improve sustainability and flexibility. However, improvements in each of these other areas are not guaranteed by a sole focus on energy minimization. For example, energy minimization may limit the amount of higher quality water that can be pumped long distances to areas where water quality is low, resulting in more customer complaints in those areas.

Definition : Benefit or Penalty of operating WOO during a selected time period is defined as the difference between the sum of the energy used and water supplied when WOO is turned off (also called Baseline), less the sum of the energy used and water supplied when WOO is turned on :

$$\textit{Benefit or Penalty} = \textit{Baseline Energy} - \textit{WOO Energy} + \text{Baseline Water Use} - \text{WOO Water Use} \quad (1)$$

Where, for a selected time period (t),

Baseline Energy = the energy used by the Managed System when WOO is turned off, $

WOO Energy = the energy used by the Managed System when WOO is turned on, $

Baseline Water Use = the water supplied to the Managed System when WOO is turned off, $

WOO Water Use = the water supplied to the Managed System when WOO is turned on, $

Qualitatively, Energy and Water Use term sums will be a positive number if energy or water is conserved by using WOO. Equation (1) is the whole-system performance metric defined for WOO. To make use of this metric, monetary values for each of the four terms of the equation must be determined. The sections below describe the calculations used to evaluate each term and the assumptions made in these calculations.

Energy Use and Cost

The cost of energy is available as a daily profile and for each plant from JEA's energy supplier.

Assumption : The energy used by WOO at a JEA water treatment plant is proportional to the total energy used at that plant, expressed as a $/MG of water supplied. It is not possible to isolate only those systems (primarily the high-service water distribution pumps, but also valves, chemical delivery systems, etc.) managed by the WOO application. However the total plant energy use largely reflects increases and decreases due to WOO operation because the high service pumps are the largest energy users in a plant. Impacts on energy use for a plant due to other programs or processes are not monitored.

The use of plant total energy cost means that other "hidden" factors causing a change in energy use at a plant may impact the calculation of equation (1). Hidden factors may include energy conservation programs, the occurrence of planned or unanticipated maintenance resulting in different numbers or types of pumps in use, use of energy consuming equipment not related to WOO, or environmental changes (rain, drought, etc.) that impact energy use profiles.

Definition : Energy use during a specified reporting period for a selected plant is calculated as the product of the plant's energy cost and the energy usage :

$$\textit{Energy Use} = (\textit{Plant Energy Cost} \times \textit{Plant Energy Usage}) \quad (2)$$

Where,

Energy Use = value of energy used during the selected period, $

Energy Cost = JEA's energy cost for the plant, $/kW-h

Plant Energy Usage = energy use by the plant, kW-h

This calculation was used for both Baseline Energy (WOO off) and WOO Energy (WOO on) terms in equation (1). The period was the reporting period defined in the measurement plan.

Water Use and Cost

Because of the practical limits on available water supplies, which is described in JEA's regional water management plans[5, 6] and regulatory controls on quality, the management of water consumption and quality is an important goal for JEA and operational objective for the WOO system. The cost of water can be assigned to water use in two ways as depicted in **Figure 2**. The CUP (top left in **Figure 2**) method was selected.

Assumption : Water quality is managed by managing to the CUP as set by the St. Johns River Water Management District. As a result, the value of water can be determined relative to the CUP without need for an additional cost calculation related to water quality.

Assumption : The value of water is equal to the cost of producing water above the current capacity of JEA, where the current capacity is defined as the CUP limit. For example if, within a monthly reporting period, the quantity of water supplied to meet demand is less than the CUP limit for

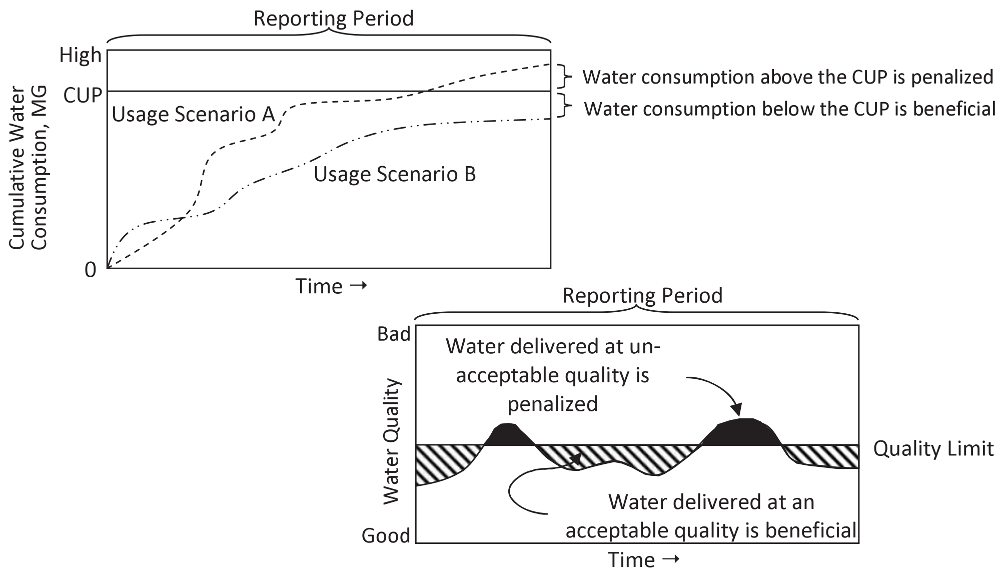

Figure 2　Assigning cost based on water consumption and quality

that period, then a net cost benefit (negative $ value) is obtained with the benefit equal to the cost of providing additional water capacity above the CUP. If on the other hand, within a monthly reporting period, the quantity of water supplied to meet demand is greater than the CUP limit for the period, then a net cost penalty (positive $ value) is obtained with the penalty equal to the cost of providing additional water capacity above the CUP. References 5) and 6) were used to define the cost of providing additional capacity.

Definition : Water use during a specified reporting period for a selected plant is calculated as the product of the value of a quantity of water and the difference between the plant's CUP limit and the actual plant water consumption.

$$\textit{Water Use} = (\textit{Plant Water Consumption} - \textit{Plant CUP}) \times \textit{Water Value} \qquad (3)$$

Where,

Plant CUP＝consumptive use permit limit for the plant and selected reporting period, MG

Plant Water Consumption＝the quantity of water supplied by the plant during the reporting period, MG

Water Value＝the value of water above the CUP limit, $/MG

This calculation was used for both Baseline Water Use (WOO off) and WOO Water Use (WOO on) terms in equation (1). The value used for Water Value is subjective and can significantly influence results. References 5) and 6) suggest that the value of water differs widely depending upon the method used to obtain water (e. g., traditional treatment of groundwater versus desalination). A value on the low end of this range was used in this study though in the future, and if demand cannot be met by groundwater sources, higher values would be used. Qualitatively, water use will be a positive number when the CUP is exceeded and negative when the CUP is not exceeded to reflect that there is a cost penalty for water use over the CUP limit and a cost benefit for water use below the CUP limit.

Data Collection

Equations (1), (2) and (3) enable calculation of the cost benefit or penalty associated with operation of WOO. To obtain data for these calculations both representative plants and representative reporting period were selected.

A "concurrent" measurement approach was used. In this approach, during the reporting period WOO was turned on or off for intervals of time equal to a pre-defined sampling period (2–3 days). For example, a 60 day (2 month) reporting period contains 30 sampling periods of 2 days duration. WOO was turned on for 15 2-day periods and off for 15 2-day periods. The time of initiating on and off periods was chosen at random to equalize the impact of disturbance variables (e. g., time of day, weather conditions, etc.). The frequency of WOO on/off periods was selected to increase the likelihood of measuring both on and off performance spanning periods when hidden factors or disturbances occur. For example, if rain events impact WOO operation then it is more likely that WOO on and off performance will span the period of a rain event if WOO is randomly turned on and off during the same or similar rain events occurring in a month.

Results

In **Table 1** it can be seen that all plants showed a net energy benefit but only one of the three plants showed a net water use benefit. All plants had a water use baseline that was negative indicating that all plants did not exceed CUP limits for the period of study. For the three plants studied the net benefit was about $75/day or $25/day/plant. JEA has 36 plants so the net benefit of WOO for JEA is approximately $330,000 per year or about a 5% reduction in cost. Most benefit is derived from energy reduction ; however, the results for water use are influenced by the conservative (low) value used for water value. For example, if the only practical source of water needed to fulfill regional demand was a desalinization plant, then the values for water cost would be multiplied by a factor of 10 (or larger), the benefit from water conservation would be most significant and the net benefit much larger.

Only one of the plants studied had statistically significant results (t-test, $p < 0.05$) so these results cannot be considered conclusive. Qualitatively, the results indicate a consistent trend towards greater benefit when WOO is operational. Evidence of this trend includes the consistently improved stability of operations when WOO is turned on as seen in power usage (**Figure 3**), which reflects pump starts and stops.

Table 1 Cost of WOO based on whole-system performance metric for three plants in the study

Cost, $/day							
	Energy			Water			
Plant	Baseline	WOO	Diff.	Baseline	WOO	Diff.	Total
Southwest	$679	$642	$37	−$142	−$156	$14	$51
Marietta	$484	$461	$23	−$275	−$256	−$18	$5
Arlington	$319	$295	$24	−$15	−$12	−$3	$21

NET : $77

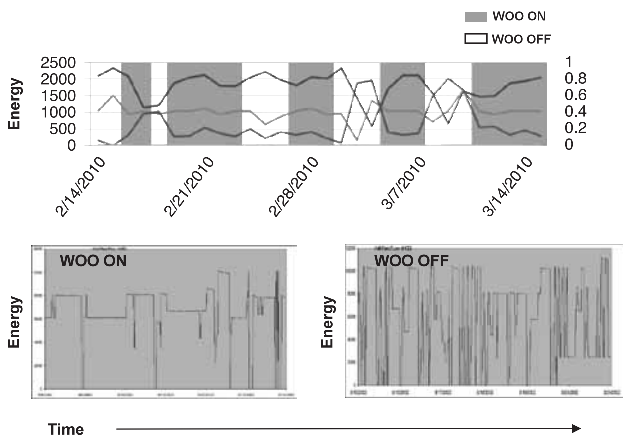

Figure 3 Stability improvement with WOO on as reflected in pump starts and stops

Discussion

Frequently in real-time operation of this water treatment and distribution system economic decisions, as measured by energy consumption only, are not always of greatest importance. For example, managers may set constraints in WOO that result in pumping of large quantities of water across a distance to move higher quality water to regions that have local (well) sources of lower-quality water. Clearly in this case value is being provided to the residents of areas where water quality is lower. Better water quality results, customer complaints are reduced and in this way service to the community is improved. However, measurement of WOO performance based only on energy cost would not show a benefit. There is more "value" that is not reflected by measuring only operating costs in the conventional way.

Consumptive Use Permit (CUP) restrictions capture the value of water quality and, to a degree, customer satisfaction. CUP limits by well-field or (in the future) well pumps are set by the St. Johns River Water Management District based on environmental and water conservation concerns including protection of lakes and wetlands, mining of groundwater sources and maintenance of quality. When the CUP is exceeded in a month or for a specific well or well field, then it is necessary to move water within the distribution system at an energy cost penalty but a water cost benefit. In fact it can be argued that the value to the community is far greater if, through this action, the multiple objectives of environmental sustainability are achieved.

Becuase both energy value and water value are represented in the whole-system metric of equation (1) the metric can be used to make operational decisions that better reflect management objectives for energy efficiency and service to community. The whole system must meet strict CUP limits, operate at all times and maximize asset utilization. As shown in **Figure 4**, JEA's cost for energy and water rises and

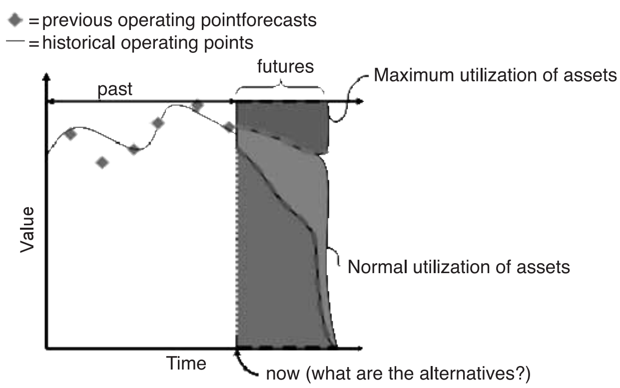

Figure 4 Managing value at JEA

Figure 5　JEA Consumptive User Permit dashboard

falls according to daily pricing of energy and demands of the community. This creates opportunities to maximize total value. At any point in time, JEA is faced with many possible futures including non-optimal operation (lower region), acceptable but sub-optimal operation (middle region) and optimal operation (top region). The regions are in constant flux due to changes in energy pricing, the current condition of assets and water sources, and even the managers and operators on shift. The automation systems driven by the whole-system metric assess possible futures and recommend or directly implement control actions that increase overall value.

The results of this on-going study indicate the need for more continuous and finer granularity of measurements. Planned efforts are directed at creating systems that support more real-time evaluation of equation (1). These efforts include a CUP dashboard (**Figure 5**) to show past, current and projected future usage of water relative to CUP limits, the installation of new power meters for high-service pumps to eliminate possible confounding variables by using data from meters that include other sources of energy usage, processes for validation, estimation and editing of data to improve data quality and improvements to instrument preventive maintenance procedures.

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システム全体のエネルギーと水の管理による持続可能な水処理・配水自動化システムの構築：JEA のケーススタディ

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環境，経済そして技術の持続可能性を確立することは，上水あるいは下水処理システムを管理する者にとって，重要な目的のひとつでなければならない。本論文は，水処理事業体における持続可能性を確立するための手法開発事例の中間報告である。

M.E. Porter は，1985 年に著した「競争優位の戦略」で，組織の活動を調べ，その組織が創出する「価値」の源を理解するツールとして「価値連鎖」を提唱した。水処理事業体にこの「価値連鎖」による解析を適用することによって，組織の複雑な諸々の活動を個々の要素に解きほぐして，それぞれを理解，測定，そして管理することが可能となる。ここに，個々の要素とは，水処理の工学的な個別プロセスや，最終的には，それぞれのプロセスの制御のための設定値と計画として表現されるべき管理作業の両方を指している。全体最適化を達成するためには，極めて複雑な人とプロセスの間，あるいは，技術とプロセスの間の相互関係を理解しなければならないが，価値連鎖解析による幅広い視点なくしては，正しく持続可能な判断を下すことは難しい。

本論文は，自動化システムの設計者とその実装者が，共に価値連鎖，あるいは，システム全体を見渡す視点を持つことによって，システムの改善が可能になることを明らかにしようとするものである。価値連鎖解析の重要な要素は，人とプロセスを特徴づけるデータと意思決定の内容であり，これらがエネルギーや水の消費量の増減を左右する。システムが適切に管理されている場合，これらのデータや決定事項は，エネルギーのように直接的な金銭的価値，水の価値（価格）および顧客の満足度などの，供給事業体，コミュニティおよび環境にとっての「価値」を反映していると考えられる。すなわち，本手法によって評価される「価値」は，自動化システムのメリット・デメリットを表す優れた指標の一つだと考えられると言える。システム全体を対象とする評価指標を採用することによって，システムの挙動を望ましい方向に向けることが可能となるが，興味深いことに，施設管理者は，往々にしてこの「指標」が示すコストを最小にするように管理する傾向があり，必ずしも供給事業体への直接的な金銭的負担だけが少なくなることを目指すわけではない。このことは，水/下水処理における「価値」の評価に，トリプルボトムライン（決算書に，収益，損失の最終結果だけでなく，社会面（人権配慮や社会貢献など），環境面（資源節約や汚染対策など）の評価も述べること）的なアプローチが，有効であることを示唆している。

キーワード：持続可能性，自動制御，配水，エネルギー，最適化，水利用，価値連鎖