Multilevel Strategies for the Retrofit of Large-Scale Industrial Water System: A Brewery Case Study

Hella Tokos
State Key Laboratory of Chemical Engineering, Dept of Chemical and Biochemical Engineering, Zhejiang University, Hangzhou, Zhejiang 310027, P.R. China

Zorka Novak Pintarič
University of Maribor, Faculty of Chemistry and Chemical Engineering, Smetanova 17, SI–2000 Maribor, Slovenia

Yongrong Yang
State Key Laboratory of Chemical Engineering, Dept of Chemical and Biochemical Engineering, Zhejiang University, Hangzhou, Zhejiang 310027, P.R. China

Zdravko Kravanja
University of Maribor, Faculty of Chemistry and Chemical Engineering, Smetanova 17, SI–2000 Maribor, Slovenia

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This article presents an approach to designing a large-scale water system, which integrates water-using operations and wastewater treatment units in different production sections within the same network. This approach uses a mixed-integer nonlinear programming (MINLP) model for water reuse and regeneration reuse in batch and semicontinuous processes. The application of this mathematical formulation to large-scale industrial problems with changing daily production schedule leads to huge and complex mathematical models. Two alternative multilevel strategies are proposed to solve such problems by means of temporal decomposition. The approach is illustrated with a brewery case study that integrates water consumers in two production sections. The results obtained show that, despite the high piping cost, integration of both sections yields better result than the separate water network design in each section. *AIChE J*, 58: 884–898, 2012
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Introduction

Fierce competition in the global market and strict environmental regulations motivate the companies to increase their competitiveness and efficiency, and to discover new ways for reducing the environmental impact of their production. Reduction of fresh water consumption is one of the main concerns in process industries, including food and beverage industry where water cost represents considerable part of the total cost. For example, in modern breweries, the freshwater consumption generally ranges from 3.7 to 4.7 m^3 m^{-3} of beer sold.[1] Most breweries discharge over 70% of the supplied water as wastewater in the central treatment unit. Because of the rising freshwater and effluent treatment costs the total cost of water supply and wastewater treatment is about the same as the energy cost for most breweries.

Correspondence concerning this article should be addressed to Y. Yang at yangyr@zju.edu.cn.

Recently, motivation has increased to use integrated approaches for designing total water networks with aim to reduce the freshwater and effluent treatment costs. Design of such network integrates water-using operations and wastewater treatment units in several production sections within the same network. Integrated networks optimize simultaneously the distribution of water resources to satisfy process demands, and treatment of effluent streams to comply with environmental regulations at minimum total cost. The water system may discharge wastewater into the central treatment unit or use the local treatment unit (LT) to purify wastewater in the place of its generation, i.e., at the production site. The latter makes possible to introduce a water regeneration reuse, and reduce the contaminant load of wastewater discharged into the central treatment unit.

Two main approaches are generally used to address the issue of freshwater demand minimization in total water networks, i.e., the graphical approach and the mathematically based optimization approach. The developed graphical methods are mainly based on water-pinch approach[2–7] or water sources diagram.[8,9] The existing design approaches based on mathematical optimization can be classified as sequential or simultaneous. In the case of the sequential procedures, the design of a water network is decomposed into a series of simpler steps and the acceptable solution is obtained gradually.[10–12] The simultaneous methods identify the optimal water network based on interval elimination procedure,[13] deterministic spatial branch, and contract algorithm,[14] stochastic-,[15,16] superstructure-based mathematical programming[17–24] or genetic algorithms.[25–27] Design method for industrial water system, which combines the principles of water-pinch with mathematical programming was developed by Alva-Argaez et al.[28] and Bai et al.[29] Li et al.[30] introduced a state-time-space superstructure for optimization of batch water network in both, time and space dimensions. To solve the resulting mixed integer nonlinear programming (MINLP), model a hybrid optimization strategy were proposed by the authors, where deterministic and stochastic searching techniques are combined.

The total water network design has been successfully applied to certain process industries, such as chemical industry,[31,32] oil refineries,[8,17,19,33,34] pulp and paper mills,[35] the textile industry,[22,36] and food and beverage plants.[37–39]

In this article, an approach is proposed for retrofitting large-scale water network composed of water using operations located in several production sections. This approach is based on the MINLP model developed by Tokos and Novak-Pintarič[37] which enables for water reuse and regeneration reuse between batch and semicontinuous processes. Two solution strategies based on temporal decomposition are proposed for solving large and complex mathematical model. An early version of the first strategy was presented in our previous work (Tokos and Novak Pintarič, submitted), which also provides a detailed formulation of the applied mathematical models. In this article, an alternative strategy to the first one is proposed, and an improved objective function was formulated to prevent from multiple summations of pipeline and storage tanks investment costs of those processes that operate over several time intervals. Higher freshwater price is used as well.

This article is organized as follows. The basic problem statement and short description of the applied mathematical model are given in Chapter 2. Two solution procedures for solving large and complex mathematical model are proposed in Chapter 3. In Chapter 4, the proposed approach is illustrated with an industrial case study that integrates production and packaging sections of the brewery. The result of the integrated water network design is compared with individual water network designs, and the optimal water network is proposed.

Problem Statement

Given is a set of batch and semicontinuous water using operations with defined maximum allowed inlet and outlet contaminant concentrations, and limiting water masses. Water using operations belong to several production sections that are separated by a considerable distance. Water consumers operate either in batch or semicontinuous mode. The production schedule changes daily over the working week, and daily schedules repeat weekly. Water demands can be satisfied by freshwater, wastewater from semicontinuous operations, and wastewater reuse and regeneration reuse between batch processes. Freshwater is regarded as an unlimited water source, whereas wastewater from semicontinuous operations is considered as a water source of limited capacity. Operating schedule of batch operations is known and fixed. The on-site purification of the wastewater can be accomplished by local treatment units operating in batch and/or semicontinuous manner. Water streams treated in the semicontinuous treatment units are available for reuse immediately, whereas those streams purified in batch treatment units are available after certain treatment time. The operating durations of batch treatment units are significantly shorter than the overall batch time interval. Scheduling of batch wastewater treatment units is performed simultaneously to adjust the treatment schedule with the fixed schedule of batch processes.

The main goal is to obtain the optimum water integration scheme with identified reuse and regeneration reuse options between water consumers within the production sections and among them. Because mathematical models of such integrated water systems are usually very large and complex, two-level solution procedures are proposed based on a temporal decomposition of a large mathematical model.

The applied mathematical model is formulated as a mixed-integer nonlinear programming (MINLP) model, which enables the investigation of several integration options: (1) direct water reuse between batch and semicontinuous consumers operating within the same time interval, (2) indirect water reuse between batch and semicontinuous processes operating in different time intervals via storage tank, and (3) regeneration reuse options by designing and scheduling an on-site wastewater treatment system. The objective function includes the annual freshwater cost, annual treatment cost of discharged wastewater, investment costs for the storage tank, piping installation, and local treatment units. The model was presented in Tokos and Pintarič.[37]

In this work, an improved objective function was formulated in the MINLP model for water network synthesis, which prevents from multiple summations of not only the pipeline installed costs[37] but also of the storage tanks installed costs. This is required when the process is integrated with other processes over several time intervals. As different storage capacities could be determined in different intervals, the largest value is considered as a final storage capacity of process k. Note that symbols used for sets, parameters, and

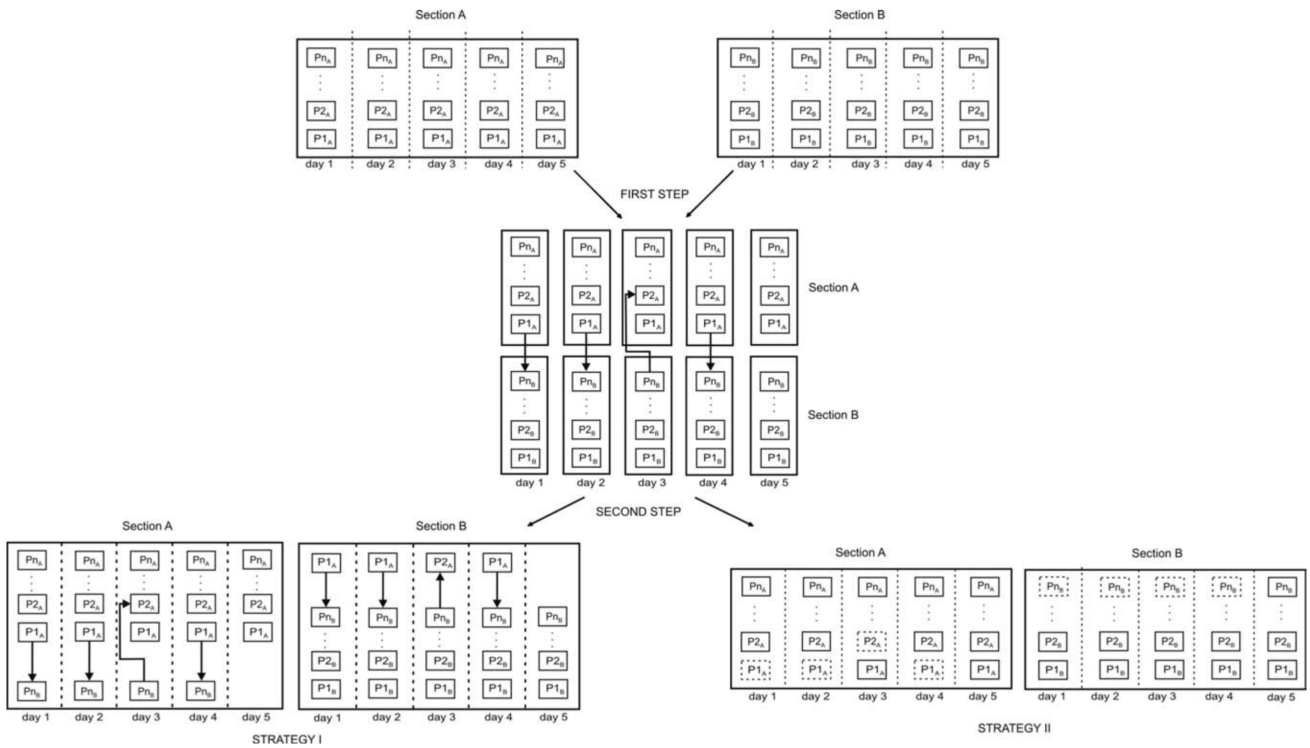

Figure 1. The proposed solution procedures, Strategy I and Strategy II.

variables are consistent with those used in our previous article.[37] The capacity of the storage tank of process k which is divided into operations n over several time intervals is determined by the expressions:

$$m_k^{\mathrm{ST,\,E}} \geq m_n^{\mathrm{ST}} \qquad \forall n \in N \ \wedge \ \forall k \in K \tag{1}$$

$$Y_n^{\mathrm{ST}} - Y_k^{\mathrm{ST,\,E}} \leq 0 \qquad \forall n \in N \ \wedge \ \forall k \in K \tag{2}$$

where m_n^{ST}/t is the storage tank capacity of operation n, $m_k^{\mathrm{ST,E}}$/t represents the largest reuse water mass of process k, Y_n^{ST} is the binary variable for storage tank to operation n, and $Y_k^{\mathrm{ST,E}}$ is the binary variable for installation of a storage tank for process k. If several processes are divided over the time intervals, the modified equations for the storage tank investment cost of process k, CT_k/€, and annual investment cost of storage tanks installation, f_2, are:

$$\mathrm{CT}_k = r \cdot m_k^{\mathrm{ST,E}} + s \cdot Y_k^{\mathrm{ST,E}} \qquad \forall k \in K \tag{3}$$

$$f_2 = \left(\sum_k \mathrm{CT}_k + \sum_{tr} \mathrm{CT}_{tr}^{\mathrm{TR,OUT}} \right) \cdot F_{\mathrm{AN}} \tag{4}$$

where r and s are the variable and fixed parameters, respectively, for the storage tank investment costs, $\mathrm{CT}_{tr}^{\mathrm{TR,OUT}}$/€ is tank cost for purified water after the treatment in the unit tr, and $F_{\mathrm{AN}}/\mathrm{a}^{-1}$ is the annualization factor.

The Solution Procedure

Applying the mathematical formulation for water reuse and regeneration reuse[37] with improved objective function as described above, to a large-scale integrated water network composed of several distant networks produces a huge mathematical model. Two two-level solution strategies are thus proposed to explore the reuse and regeneration reuse options between water consumers within the sections and among them. These strategies are suitable for plants with batch and semicontinuous production where the production schedule changes daily over the working week, and daily patterns repeat over weeks.

Strategy I

In the first ''daily'' level, joint integrations of water networks in all sections are performed for each working day of a week to identify daily connections between the sections. This step determines the matches between water consumers in different sections, which are then fixed in the next level.

In the second ''weekly'' level, weekly integration of each section is performed in the following way: the set of water operations in the section under consideration is extended with those operations from other sections that were identified for integration with this section in the first step. The predetermined matches and their masses are fixed, and the extended model of each section is solved for joint integration over the entire week. The goal of this step is to determine intradaily and interdaily matches between the production sections. Figure 1 presents an example of two water networks in sections A and B. Suppose that daily integrations in the first step determine the matches between processes $\mathrm{P1_A}$ and $\mathrm{Pn_B}$ in the Days 1, 2, and 4, and the match between processes $\mathrm{Pn_B}$ and $\mathrm{P2_A}$ in Day 3, whereas no integration between sections is determined in Day 5. According to the Strategy I, in the second step, weekly optimization model of section A is extended by process $\mathrm{Pn_B}$, and model of section B by processes $\mathrm{P1_A}$ and $\mathrm{P2_A}$.

Some modifications of the second-level mathematical model are needed to consider the information of the first level properly. Two subsets are defined for each section i: ns_i^{I} is the subset of those processes that supply water to section i from other sections, and nu_i^{I} is the subset of those processes that use wastewater from section i.

• The reused water mass between process n from section i and process nc from any other section is fixed to the value obtained in the first level:

• for direct reuse:

$$m_{n,nc}^{\mathrm{LB,PP}} = m_{n,nc}^{\mathrm{UB,PP}} = m_{n,nc}^{\mathrm{PP,1.step}} \qquad \forall ns_i^{\mathrm{I}},\ nu_i^{\mathrm{I}} \in N \tag{5}$$

• for regeneration reuse:

$$m_{n,nc,tr}^{\mathrm{LB,TR}} = m_{n,nc,tr}^{\mathrm{UB,TR}} = m_{n,nc,tr}^{\mathrm{TR,1.step}} \quad \forall ns_i^{\mathrm{I}},\ nu_i^{\mathrm{I}} \in N \wedge \forall tr \in TR \tag{6}$$

where $m_{n,nc}^{\mathrm{PP,1.step}}$/t represents reused water mass between operation n and nc determined in the first step, and $m_{n,nc,tr}^{\mathrm{TR,1.step}}$/t regenerated and reused water mass between operation n and nc determined in the first step.

• The binary variables of identified reuse and regeneration reuse connections between the sections are fixed to 1:

$$Y_{nc,n}^{\mathrm{PP,1.step}} = 1 \qquad \forall ns_i^{\mathrm{I}},\ nu_i^{\mathrm{I}} \in N \tag{7}$$

$$Y_{nc,n,tr}^{\mathrm{TR,1.step}} = 1 \qquad \forall ns_i^{\mathrm{I}},\ nu_i^{\mathrm{I}} \in N \wedge \forall tr \in TR \tag{8}$$

where, $Y_{nc,n}^{\mathrm{PP,1.step}}$ is the binary variable for water reuse between operation n and nc determined in the first step, and $Y_{nc,n,tr}^{\mathrm{TR,1.step}}$ is the binary variable for regeneration reuse match between operation n and nc via local treatment unit tr obtained in the first step.

• The expression for annual freshwater cost is modified to exclude freshwater cost of those processes from other sections that supply water to section i, because freshwater cost of these processes is considered during the optimization of their home sections.

$$f_1 = \left(\sum_{fw} \sum_{n \notin ns_i^{\mathrm{I}}} m_{fw,n}^{\mathrm{W}} + \sum_{ww} \sum_{j} m_{ww,j}^{\mathrm{C}} \right) \cdot \frac{P^{\mathrm{W}} \cdot \lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}} \tag{9}$$

The expression for annual wastewater treatment cost is modified to exclude the treatment cost of those processes from other sections that use wastewater of section i, because the reused water of these processes is discharged and accounted during the optimization of their home sections.

$$f_4 = \left(\begin{array}{l} \sum\limits_{n \notin nu_i^{\mathrm{I}}} \sum\limits_{c} \frac{0.001 \cdot m_n^{\mathrm{OUT}} \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} + \sum\limits_{ww} \sum\limits_{c} \frac{0.001 \cdot m_{ww}^{\mathrm{C,FOUT}} \cdot C_{c,ww}^{\mathrm{W}}}{m_c^{\mathrm{E}}} + \\ \sum\limits_{nu_i^{\mathrm{I}}} \sum\limits_{c} \frac{0.001 \cdot \left(m_n^{\mathrm{OUT}} - m_{n,nc}^{\mathrm{PP,1.step}} - m_{n,nc,tr}^{\mathrm{TR,1.step}} \right) \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \end{array} \right) \cdot P^{\mathrm{E}} \cdot \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}}$$
$$+ \left(\sum_{c} \sum_{n} \sum_{nc} \sum_{tr \in batch} \frac{0.001 \cdot m_{n,nc,tr}^{\mathrm{TR}} \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \right) \cdot P^{\mathrm{E,LB}} \cdot \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}}$$
$$+ \left(\sum_{c} \sum_{n} \sum_{nc} \sum_{tr \in continuous} \frac{0.001 \cdot m_{n,nc,tr}^{\mathrm{TR}} \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \right) \cdot P^{\mathrm{E,LC}} \cdot \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}} \tag{10}$$

In this way, the overestimation of freshwater and wastewater treatment costs is avoided.

• The total investment cost of joint integration is corrected to avoid the overestimation of investment, because the investment costs of identified daily intersectional matches are included in the objective functions of all sections that contain these matches. For example, in Figure 1, an intersectional match between processes $\mathrm{P1_A}$ and $\mathrm{Pn_B}$ is identified in Days 1, 2, and 4. In the second level, the connection between these processes is accounted for in both sections, A and B. The total investment cost therefore needs to be corrected to account for the cost of this match only once.

Strategy II

The first level of the second strategy is the same as in Strategy I (Figure 1). The second level of Strategy II is based on the modifications of freshwater and wastewater upper and lower bounds. Integration is performed within each section considering its original set of processes, but with modified bounds of those processes that were determined for the integration with other sections in the first level. Processes with modified bounds are denoted by dashed lines in Figure 1. It should be noted that in the original model tight upper bounds of water masses are applied which are equal to water consumptions in nonintegrated processes. Decreasing the upper bounds thus affects the optimal water consumptions and water mass available for integration in the home section. The processes of section i that are integrated with other sections are divided into two subsets: the subset of those processes that supply wastewater to other sections via reuse or regeneration reuse matches, ns_i^{II}, and the subset of those processes that reuse wastewater from other sections, nu_i^{II}. The modifications of mathematical model are as follows:

• The freshwater upper bounds of those processes that use wastewater from other sections are reduced for the amount of reused water determined in the first step:

$$m_{w,n}^{\mathrm{UB,W,2.step}} = m_{w,n}^{\mathrm{UB,W}} - m_{nc,n}^{\mathrm{PP,1.step}} \qquad \forall nu_i^{\mathrm{II}} \in N \tag{11}$$

where, $m_{w,n}^{\mathrm{UB,W,2.step}}$/t is the upper bound of water mass from water source w to operation n in the second step.

• The wastewater lower bounds of those processes that supply wastewater to other sections are increased by the amount determined in the first step. In this way, the sufficient wastewater mass for other sections is guaranteed:

$$m_n^{\mathrm{LB,OUT,2.step}} = m_n^{\mathrm{LB,OUT}} + m_{nc,n}^{\mathrm{PP,1.step}} \qquad \forall ns_i^{\mathrm{II}} \in N \tag{12}$$

where $m_n^{\mathrm{LB,OUT,2.step}}$/t is the lower bound of wastewater mass from operation n to discharge in the second step.

• The annual wastewater treatment cost is increased by the amount of wastewater that processes of section i receive from other sections, and reduced by the amount of wastewater that processes of section i supply to other sections:

Table 1. Limiting Water Data for the Production and Packaging Area

No.	Process	Limiting Concentration (g m^{-3})		G_n^{MAX}/t	Δt_n/h
		$C_{c,n}^{\mathrm{IN,MAX}}$	$C_{c,n}^{\mathrm{OUTMAX}}$		
1	Wort boiling	24.25	425	41	4
2	Water used to pour the batch material in the Brewhouse	100	980	47.2	4
3	Water used to pour the batch material in the Cellar	100	330	46.2	4
4	Filtration	34	56	46.9	4
5	Central CIP system	100	299	261	4
6	Local CIP system	24.25	55.24	5	4
7	Bottle washer for returnable bottles-filling line A	72	228	2.5	4
8	Crate washer-filling line A	600	1000	1.5	4
9	Bottle washer for returnable bottles-filling line B	72	376	2.5	4
10	Crate washer-filling line B	600	1000	1.5	4
11	Pasteurizer-filling line C	29	72	13.5	4
12	Pasteurizer-filling line D	29	62	35	4

$$
\begin{aligned}
f_4 = {} & \left(\begin{aligned} & \sum_{n \notin ns_i^{\mathrm{II}}, nu_i^{\mathrm{II}}} \sum_c \frac{0.001 \cdot m_n^{\mathrm{OUT}} \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} + \sum_{ww} \sum_c \frac{0.001 \cdot m_{ww}^{\mathrm{C,FOUT}} \cdot C_{c,ww}^{\mathrm{W}}}{m_c^{\mathrm{E}}} \\ & + \sum_{ns_i^{\mathrm{II}}} \sum_c \frac{0.001 \cdot \left(m_n^{\mathrm{OUT}} - m_{n,nc}^{\mathrm{PP,1.step}} \right) \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \\ & + \sum_{nu_i^{\mathrm{II}}} \sum_c \frac{0.001 \cdot \left(m_n^{\mathrm{OUT}} + m_{n,nc}^{\mathrm{PP,1.step}} \right) \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \end{aligned} \right) \\
& \cdot P^{\mathrm{E}} \cdot \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}} \\
& + \left(\sum_c \sum_n \sum_{nc} \sum_{tr \in batch} \frac{0.001 \cdot m_{n,nc,tr}^{\mathrm{TR}} \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \right) \cdot P^{\mathrm{E,LB}} \cdot \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}} \\
& + \left(\sum_c \sum_n \sum_{nc} \sum_{tr \in continuous} \frac{0.001 \cdot m_{n,nc,tr}^{\mathrm{TR}} \cdot C_{c,n}^{\mathrm{OUT}}}{m_c^{\mathrm{E}}} \right) \cdot P^{\mathrm{E,LC}} \cdot \frac{\lambda_{\mathrm{OHY}}}{\Delta t^{\mathrm{ALL}}}
\end{aligned} \tag{13}
$$

- The required investment cost of joint integration between the sections is increased by the pipeline and storage tank investment costs of identified connections between the production sections.

The above strategies simplify the original large-scale formulation. It could not be guaranteed that decomposed models are equivalent to original problem because a simultaneity level is decreased. Anyway, it could be expected that modified formulations are fair approximations that could produce good water network solutions with relatively low computational effort. This is illustrated with industrial application of the described strategies in the next section.

Industrial Case Study

The strategies for large-scale water network design described in previous section are illustrated by a brewery case study. The brewery consists of two sections: production and packaging areas. The production area includes two subsections, the brewhouse and the cellar. Processes in the brewhouse involve several sensible biotransformations with precisely defined processing times. The packaging area includes processes operating in batch (e.g., bottle washers) and semicontinuous modes (e.g., rinser for nonreturnable glass bottles). The production area is separated from the packaging area by the railway, which is a part of transportation infrastructure.

Brewery produces annually 114,200 m^3 of beer, and consumes 653,300 m^3 a^{-1} of freshwater. The volume ratio of water consumption to beer sold is determined to be 6.04 m^3 m^{-3}, which indicates that the freshwater consumption exceeds the upper limit specified in BREF,[1] by 144,900 m^{-3}. The intention of a brewery is thus to reduce the freshwater consumption and the contaminant load of wastewater discharged into the central wastewater treatment system by retrofitting the total water network. The water reuse and regeneration reuse opportunities were analyzed within the production and packaging area separately and jointly according to the described multilevel strategies.

Separated Design of Water Networks

The design of water networks was first performed within the production and packaging areas separately without integrating water consumers between them. The limiting water data of batch processes in production and packaging areas are given in Table 1. The first 5 processes operate in the production area, whereas the next 7 processes belong to the packaging area. Two semicontinuous processes also operate in the packaging area: (1) the rinser for nonreturnable glass bottles (K1) in the filling line C, and (2) the can rinser (K2) in the filling line D. The water flow rates through these processes are 12.5 and 1.87 t h^{-1}, and the outlet concentrations are 34 and 23 g m^{-3}.

The shortest distances between the processes defined by the existing pipeline system are given in Table 2, whereas Table 3 represents the estimated distances between processes and potentially installed local treatment units. The shaded cells in Tables 2 and 3 represent the distances between processes within the production area (1–5) and within the packaging area (6–12). The model parameters and the economic data are listed in Table 4. The current weekly consumption of fresh water for both sections is 4725.2 t, from which 2592.2 t is used in the production area, and 2133 t in the packaging area.

Table 2. Distance Data Between Processes in Production and Packaging Area

Process	$D^{PP}_{k,kc}$/m												$D^{W}_{ww,k}$/m	
	1	2	3	4	5	6	7	8	9	10	11	12	$K1$	$K2$
1	0	60	140	150	200	490	500	508	592	580	579	598	659	609
2	60	0	130	180	195	498	508	500	600	688	691	705	671	621
3	140	130	0	50	65	508	518	510	610	698	701	715	781	731
4	150	180	50	0	30	538	548	540	640	728	731	740	811	761
5	200	195	65	30	0	–	598	555	–	–	–	755	–	861
6	490	498	508	538	–	0	5	13	85	82	57	90	150	100
7	500	508	518	548	598	5	0	8	92	80	79	98	140	90
8	508	500	510	540	555	13	8	0	100	88	72	91	120	70
9	592	600	610	640	–	85	92	100	0	10	63	82	100	50
10	580	688	698	728	–	82	80	88	10	0	53	72	90	40
11	579	691	701	731	–	57	79	72	63	53	0	35	60	10
12	598	705	715	740	755	90	98	91	82	72	35	0	20	40

Design of Water Network in the Packaging Area

In the packaging area, the water reuse opportunities were analyzed between the semicontinuous wastewater streams with moderate contaminant concentrations and batch processes with lower purity requirements. The freshwater consumption in this section is 2133 t per week.

The optimal water network is shown in Figure 2. It should be noticed, that processes operating in the packaging area (processes 6–12 in Table 1), are divided into several parts in terms of time intervals within the weekly production schedule. For example, process 7, which corresponds to the bottle washer in filling line A, is divided into five operations P2–P6 over five time intervals, whereas process 11 (the pasteurizer in filling line C) is divided into four operations P24–P27 over four time intervals. The wastewater from the semicontinuous process, K2, can be reused in the pasteurization operations P24–P27, P29, and P32. Based on the chemical oxygen demand (COD) values, the outlet stream of the rinser K1 for nonreturnable glass bottles could be connected to the tunnel pasteurizer. However, this is not allowed as the outlet stream of K1 contains chemicals which must not enter the pasteurization process. The outlet stream of the rinser for nonreturnable glass bottles, K1, is reused in washer for returnable glass bottles along filling line B, (P16–P18). The wastewater from the local CIP (Clean-in-Place) system, P1, can be reused in the washer for returnable glass bottles in filling line A, P5.

The freshwater consumption is reduced from 2133 t to 1531.1 t per week with the proposed water network. No storage tank installation is needed. The total savings of freshwater and wastewater treatment costs is 130,956 € a^{-1}, and the piping investment cost for new reuse connections amounts to 25,857 € (Table 5). Low outlet concentrations from semicontinuous processes and pasteurizers (P24–P32) induce significantly lower wastewater treatment cost than freshwater cost. The net present value of water network reconstruction is 584,108 € and payback period around 0.26 year.

The size of the applied MINLP model was ~4800 constraints, 2500 continuous variables and 1100 binary variables. The number of nonlinear constraints was 46, and the nonlinearity degree was estimated to be 0.262. The nonlinearity degree was calculated as a ratio of nonlinear nonzero terms and the total number of nonzero terms in the mathematical model. The model was solved by the GAMS/DICOPT solver[40] using 6 s of CPU time on the PC (P4, 2.6 GHz and 512 MB RAM).

Key drivers of computational cost were bilinear products of two continuous variables, i.e., mass flow and outlet concentration, in mass load balance of each operation. The initialization of these variables was thus important for optimization. The maximum levels of outlet concentrations were used as the initial values, $C^{OUT}_{c,n} = C^{OUT,MAX}_{c,n}$, because the contaminant(s) levels of the exit water streams have strong tendency to reach maximum values in the water network design with

Table 3. Distance Data Between Processes and Treatment Units in Production and Packaging Area

Process	$D^{TR}_{k,kc,tr}$/m																							
	Continuous Local Treatment Unit												Batch local Treatment Unit											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	0	70	150	160	210	500	510	518	602	590	589	608	0	80	160	170	220	510	520	528	612	600	599	618
2	70	0	140	190	205	508	518	510	610	698	701	715	80	0	150	200	215	518	528	520	620	708	711	725
3	150	140	0	60	75	518	528	520	620	708	711	725	160	150	0	70	85	528	538	530	630	718	721	735
4	160	190	60	0	40	548	558	550	650	738	741	750	170	200	70	0	50	558	568	560	660	748	751	760
5	210	205	75	40	0	–	608	565	–	–	–	765	220	215	85	50	0	–	618	575	–	–	–	775
6	500	508	518	548	–	0	15	23	95	92	67	100	510	518	528	558	–	0	25	33	105	102	77	110
7	510	518	528	558	608	15	0	18	102	90	89	108	520	528	538	568	618	25	0	28	112	100	99	118
8	518	510	520	550	565	23	18	0	110	98	82	101	528	520	530	560	575	33	28	0	120	108	92	111
9	602	610	620	650	–	95	102	110	0	20	73	92	612	620	630	660	–	105	112	120	0	30	83	102
10	590	698	708	738	–	92	90	98	20	0	63	82	600	708	718	748	–	102	100	108	30	0	73	92
11	589	701	711	741	–	67	89	82	73	63	0	45	599	711	721	751	–	77	99	92	83	73	0	55
12	608	715	725	750	765	100	108	101	92	82	45	0	618	725	735	760	775	110	118	111	102	92	55	0

Table 4. Data for the Industrial Case Study

Model Parameters	
Water density (t m^{-3})	$\rho = 1$
Water velocity (m s^{-1})	$v = 1$
The average filtrate rate [m^3/(m^2 h)]	$J_F = 0.525$
The capacity exponent of batch local treatment unit	$n_{tr}^{TR} = 0.59$
The capacity exponent of semicontinuous local treatment unit	$n_{tr}^{TR} = 0.6$
Removal ratio of contaminant *c* in local batch treatment unit	$r_{c,tr}^{TR} = 0.9$
Removal ratio of contaminant *c* in local semicontinuous treatment unit	$r_{c,tr}^{TR} = 0.85$
Treatment time in local batch treatment unit (h)	$\Delta t_{tr}^{TR} = 2$
Economic Data	
Freshwater price (€ t^{-1})	$P^W = 3.03$
Price of wastewater treatment in the central unit (€ per load unit)*	$P^E = 29$
Price of wastewater treatment in the local batch treatment unit (€ per load unit)	$P^{E,LB} = 15$
Price of wastewater treatment in the local semi-continuous treatment unit (€ per load unit)	$P^{E,LC} = 7.5$
Variable parameter of piping investment cost	$p = 3603.4$
Fixed parameter of piping investment cost	$q = 124.6$
Variable parameter of storage tank investment cost	$r = 116.95$
Fixed parameter of storage tank investment cost	$s = 10{,}142.16$
Investment parameter of local batch treatment unit	$K_{tr} = 850$
Investment parameter of local semicontinuous treatment unit	$K_{tr} = 950$
Annualization factor (a^{-1})	$F_{AN} = 0.437977$
Annual operating time (h a^{-1})	$\lambda_{OHY} = 8000$

*The equivalent mass load unit of contaminant *c*, $m_c^E = 50$ kg.

minimum cost. The investment costs of local treatment units were estimated by power functions, which also contributed to the nonlinearity of the model.

Design of Water Network in the Production Area

The production area consumes 2592.2 t of freshwater per week. In this section, only wastewater from filtration could be reused without treatment, whereas the outlet chemical oxygen demands (COD) of other processes are too high. For example, the average COD value of the condensate from wort boiling is 425 g m^{-3}, and the value of CIP rinsing water varies from 299 to 329 g m^{-3}. The regeneration reuse opportunities were thus evaluated in this section including the installation of on-site treatment units (LT).

Processes operating in the production area (1–5 in Table 1) are also divided into several parts in terms of time intervals within the weekly production schedule. For example, process 1 which represents wort boiling is divided into nine operations P1–P9 over nine time intervals. In the optimum design, the wastewater purification is carried out in a semi-continuous treatment unit based on nanofiltration (Figure 3). The water used for pouring the batch material (P25–P38) is clarified and reused in CIP (Clean-in-Place) system (P10). Wastewater from filtration (P39–P42) is reused without treatment as water for pouring the batch material.

The weekly freshwater consumption is reduced from 2592.2 t to 1896.36 t, i.e., by 26.8%. The total saving of freshwater cost and wastewater treatment cost amounts to 153,856 € a^{-1} (Table 5). The size of the required membrane is 28 m^2. Investment cost of semicontinuous treatment unit with storage tank is 77,477 €, and the investment cost of new piping connections is 10,891 €. The net present value of the proposed water network reconstruction is 642,756 € and payback period around 0.74 year.

The size of MINLP model was ~21,500 constraints, 10,500 continuous variables and 4600 binary variables. The

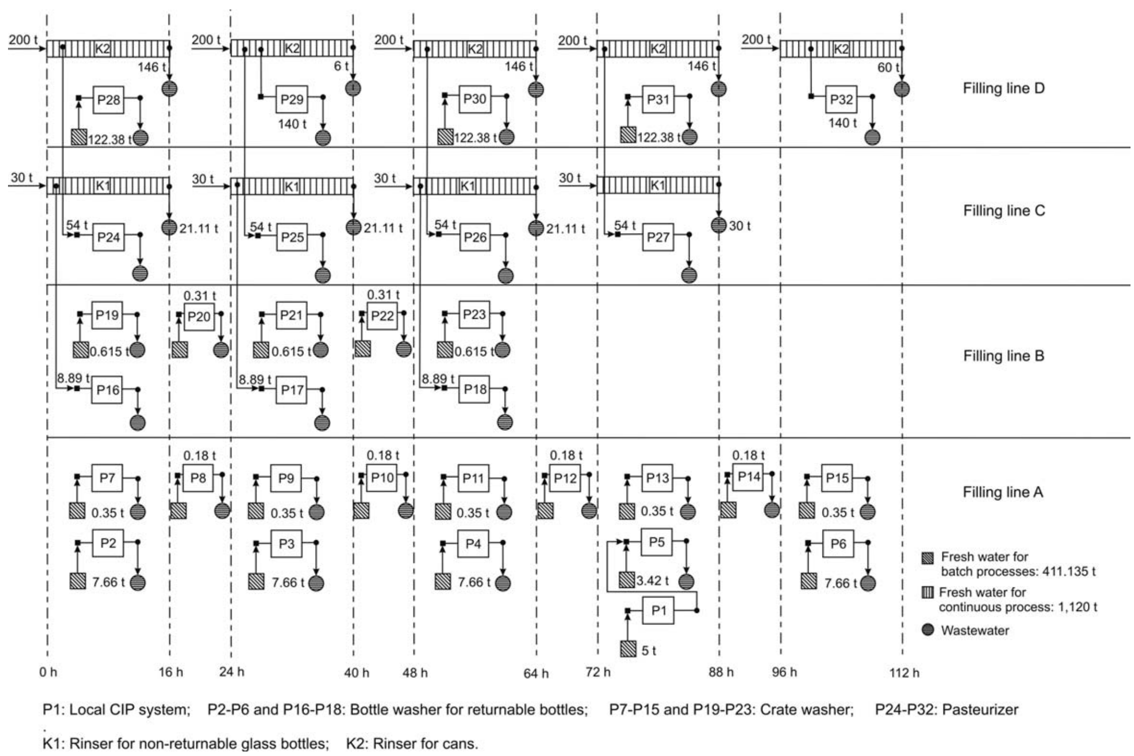

Figure 2. Optimal water network in the packaging area.

Table 5. Results of Packaging and Production Area (Separated Integration)

Water Network	Freshwater Cost (€ a^{-1})	Wastewater Treatment Cost (€ a^{-1})	Storage tank Cost (€ a^{-1})	Piping Cost (€ a^{-1})	LT Investment (€ a^{-1})	Total Cost (€ a^{-1})
Packaging Area						
Current state	461,760	5039	0	0	–	466,799
Integrated	331,461	4382	0	11,325	–	347,168
Production Area						
Current state	561,165	56,722	0	0	0	617,887
Integrated	410,527	53,504	20,997	4770	12,936	502,734

model contained 84 nonlinear constraints, whereas degree of nonlinearity was estimated to 0.289. The model was solved by the GAMS/DICOPT solver[40] using 178 s of CPU time at the PC (P4, 2.6 GHz and 512 MB RAM).

The total net present value of optimal designs obtained by separate integrations of two sections amounts to 584,108 € + 642,756 € = 1,226,864 €. In the next section, this result will be compared with the result of joint integration of both sections.

Joint Integration of Water Networks in Packaging and Production Area

According to the proposed two-step strategies the integration within and between both water networks was performed for daily and weekly production schedules. The first step, daily integration of the packaging and production sections, is common for both strategies. The packing area operates at maximum capacity during the first 3 days. Filling line for returnable bottles is stopped on Wednesday, and filling line for nonreturnable bottles on Thursday. The local CIP starts on Thursday.

Daily Integrations

The optimum daily integration scheme was first determined for the first 3 days of the week, when the production and packaging sections operates at maximum capacity.

Day 1

The optimal water network obtained for Monday schedule is shown in Figure 4. In the packaging area, the wastewater from the semicontinuous operation K1 is reused in the bottle washer for returnable glass bottles (P12–P14 and P20–P23). Operations P12–P14 actually represent parts of the same process, which are carried out in the same equipment. The wastewater from semicontinuous process K2 is reused in pasteurization (operations P28, P30, P32, and P34). Reuse connections between batch operations are not selected in the optimal water network of packaging area. In the production area, the wastewater from filtration (P11) can be directly reused for pouring the batch material (P10) within the same section.

Two connections are determined between the production and packaging area: (1) reuse of wastewater from pasteurization in the packaging area (P32–P34) for pouring the batch material in the production area (P4–P6), and (2) regeneration reuse of the condensate from wort boiling (P1) in the production section for washing returnable glass bottles (P15) in the packaging area via semicontinuous nanofiltration. Storage tank with the capacity of 35 t (T1 in Figure 4) is required for wastewater reuse between the packaging and production area. Equations 1–4 ensure that the investment cost of storage tank installation is considered only once, as it connects the same two equipments in three different time intervals. The daily freshwater consumption is reduced from 949.7 t to 626.5 t, and the overall annual cost is correspondingly lower (Table 6).

Days 2 and 3

The optimal network for Days 2 and 3 is slightly different, although both sections operate at the same (maximum) capacity as on Monday. The filtration process, P11, operates in the third time interval, whereas on Monday it operates in the last, i.e., fourth interval (Figure 4). Only the first connection is thus identified between the packaging and production area, i.e., between pasteurization and pouring. The wastewater from wort boiling is not used in the packaging area as in Figure 4, but rather within the same (production) section for pouring batch material after clarification in the semicontinuous local treatment

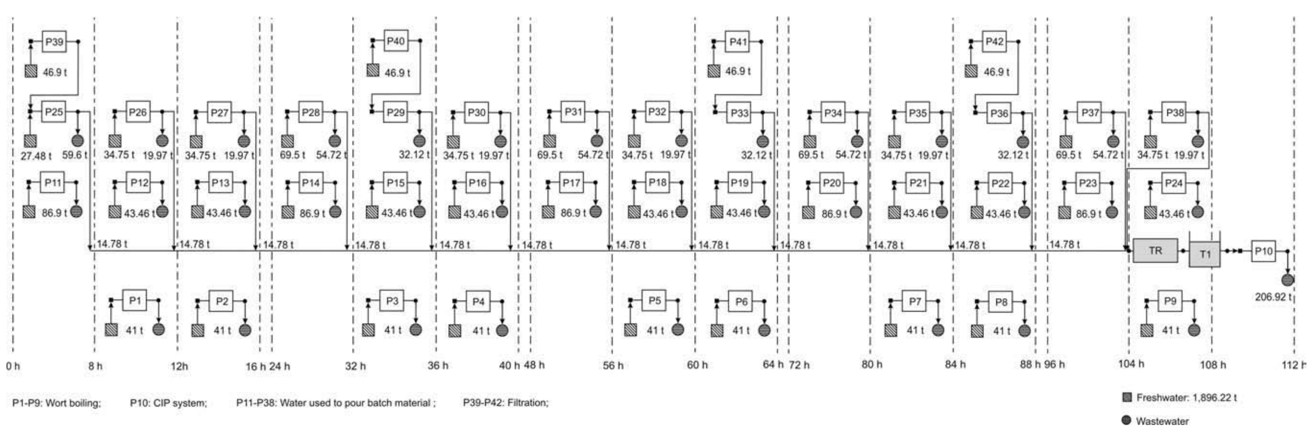

Figure 3. Optimal water network in the production area.

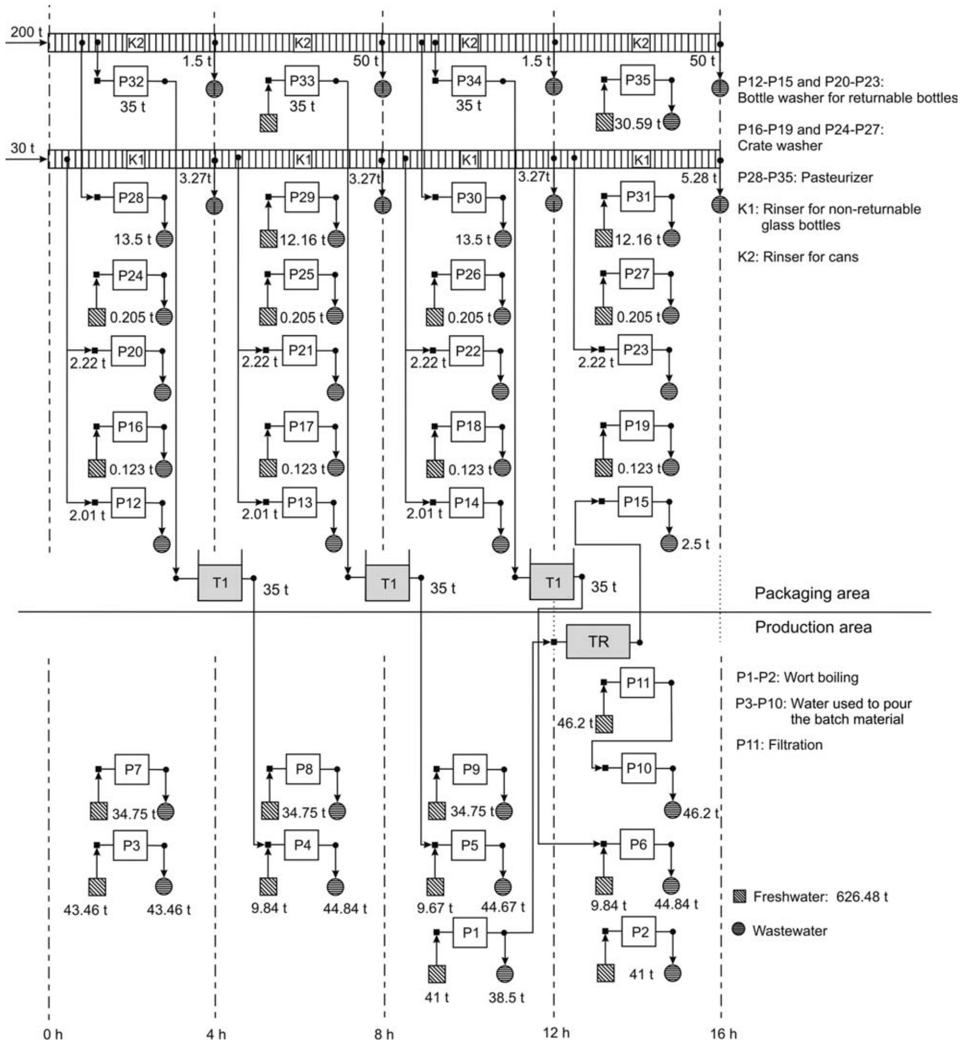

Figure 4. Water network in production and packaging area (Monday).

unit. The amount of wastewater from semicontinuous operation K1 reused in washer for returnable glass bottles (P12–P15) decreases from 2.01 t on Monday (Figure 5) to 1.53 t on Tuesday and Wednesday. The daily freshwater consumption is reduced from 949.7 t to 593.6 t. The economic results of daily water network optimization are given in Table 6.

Day 4

Thursday's water network contains eight operations less than previous networks due to the shutdown of the filling line B for returnable bottles (P20–P27 in Figure 4). One new process starts to operate, i.e., the local CIP system in the keg filling line. A match is identified between the production and packaging area: wastewater from the pasteurization in the packaging section can be directly reused for pouring the batch material in the production section.

In the packaging area, the wastewater from semicontinuous operation K1 is reused in washer for returnable glass bottles along filling line A (P12–P15 in Figure 4), whereas the wastewater from semicontinuous operation K2 is reused in the pasteurization processes (P28, P29, P32, and P34 in Figure 4). In the production area, the wastewater from filtration is directly reused for pouring the batch material. The condensate from wort boiling is purified by nanofiltration and reused for pouring the batch material.

The daily freshwater consumption is reduced from 942.7 t to 596 t. The annual reduction in freshwater and wastewater purification cost, and the required investment costs in pipeline, storage tank, and local treatment unit are given in Table 6.

Day 5

Two filling lines stop on Friday. The optimal water network is shown in Figure 5. Process P9 represents the central CIP system of production area, which is used for cleaning the production vessels at the end of the week. The packaging and the production areas are again connected by water reuse between pasteurization (P18 and P19) and batch material pouring (P3 and P4).

In the packaging area, the wastewater from can rinser (K2) is reused directly in the pasteurization operations (P18 and P19) and in washer for returnable glass bottles along

Table 6. Results of Daily Integrations in Production and Packaging Areas

Day	Water Network	Freshwater Cost (€ a^{-1})	Wastewater Treatment Cost (€ a^{-1})	Storage Tank Cost (€ a^{-1})	Piping Cost (€ a^{-1})	LT Investment (€ a^{-1})	Total Cost (€ a^{-1})
1	Current state	1,439,152	88,140	0	0	0	1,527,292
	Integrated	949,371	85,396	9165	84,891	2188	1,131,011
2–3	Current state	1,439,152	88,140	0	0	0	1,527,292
	Integrated	899,491	80,888	9165	85,687	35,889	1,111,120
4	Current state	1,428,544	86,925	0	0	0	1,515,469
	Integrated	903,041	79,745	9165	81,579	35,889	1,109,419
5	Current state	1,485,522	83,559	0	0	0	1,569,081
	Integrated	781,370	48,035	29,761	81,875	81,756	1,022,797

filling line A (P10–P13). In the production area, the wastewater from filtration (P8) can be reused for pouring the batch material (P7). The wastewater from batch pouring is purified (P2, P3, and P5–P7) and reused as CIP rinsing water (P9). Installation of storage tank is needed after the semicontinuous treatment unit with capacity of 186.8 t. The daily freshwater consumption is reduced from 980.3 t to 515.6 t, and the overall annual cost is correspondingly lower (Table 6).

The sizes of the applied MINLP models for daily integrations of production and packaging sections were up to 16,900 constraints, 8300 continuous variables and 3800 binary variables. The number of nonlinear constraints varied between 42 (Day 5) and 70 (Days 1, 2, and 3), whereas the degree of nonlinearity was estimated to be between 0.348 and 0.356. The models were solved by the GAMS/DICOPT solver[40] using up to 146 s of CPU time on the PC (P4, 2.6 GHz and 512 MB RAM).

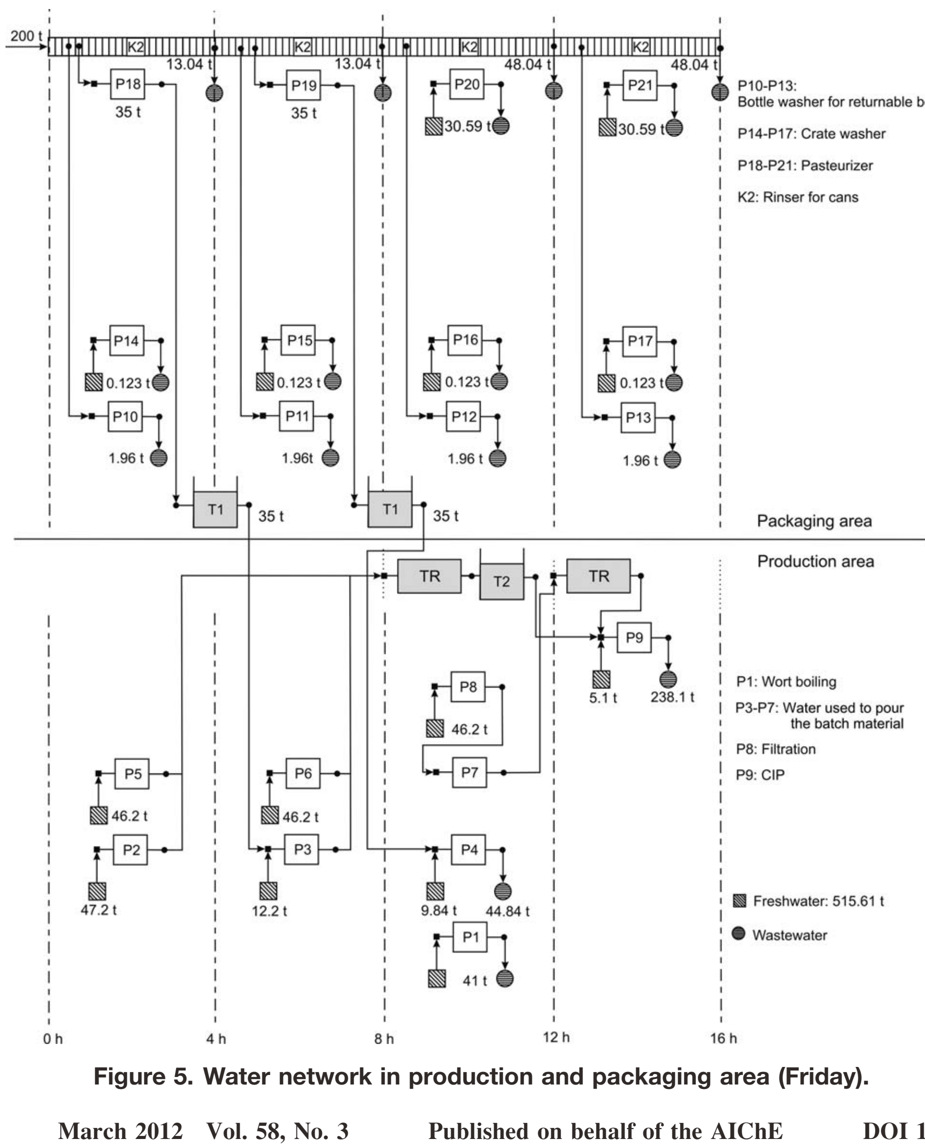

Figure 5. Water network in production and packaging area (Friday).

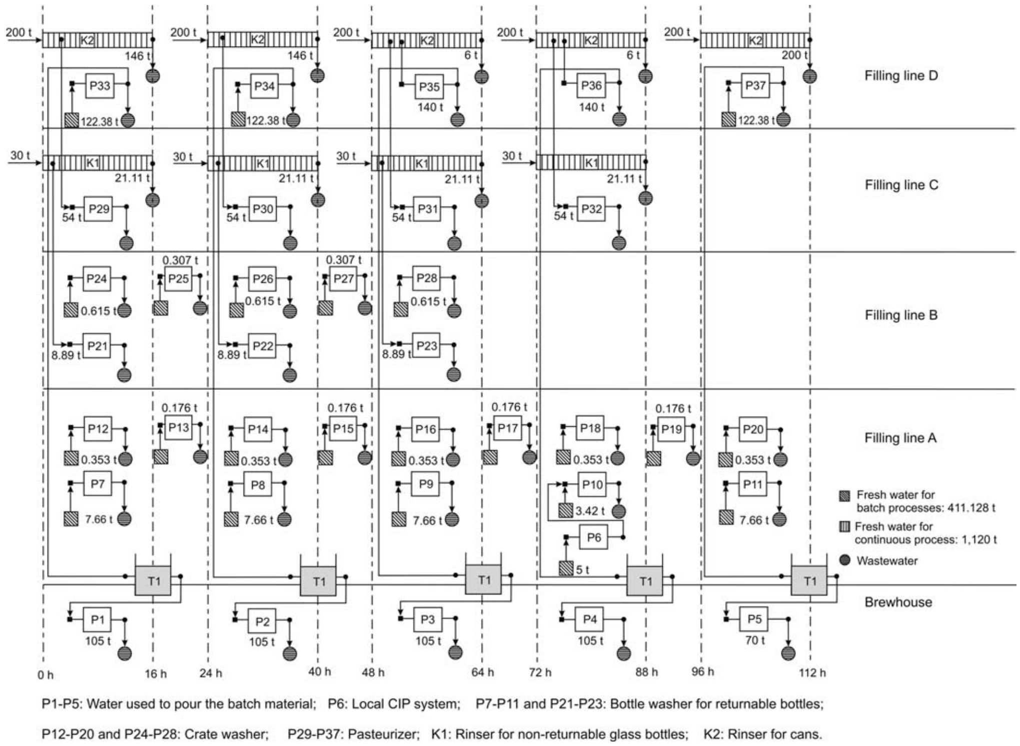

Figure 6. Optimal water network in the packaging area—Strategy I.

Weekly Integration—Strategy I

Based on the results of daily integrations, the connection between pasteurization in the packaging area and batch material pouring in the production area was selected for weekly integration because it was identified in all 5 days of the week. The second connection between wort boiling and returnable glass bottles washer was omitted as it was identified only on Monday. This assumption simplified the problem, and produced more reasonable result, as the water demand of the entire washing process could be satisfied by single connection with the semicontinuous process K1 within the same section. According to the Strategy I, the identified intersectional match between pasteurization and material pouring was fixed and integration was performed for the entire week to determine possible interdaily matches between the consumers within each section.

Packaging area

The final water network design in the packaging area integrated with pouring operations in the production area is shown in Figure 6. Pouring operations (P1–P5) are shown at the bottom of Figure 6. The exchanged water mass is fixed to 105 t for Days 1–4, and to 70 t for Day 5, altogether 490 t as determined in the previous subsection (Figures 4 and 5). The water network includes eight batch and two semicontinuous processes divided over nine time intervals. The size of the applied MINLP model was $\sim$6400 constraints, 3200 continuous variables, and 1500 binary variables. There were 74 nonlinear constraints in the model, and the nonlinearity degree was estimated to be 0.264. The model was solved by the GAMS/DICOPT solver[40] using 9 s of CPU time on the PC (P4, 2.6 GHz and 512 MB RAM).

The wastewater from the semicontinuous operation, K2, can be reused in the pasteurization processes P29–P32 and P35–P36. The outlet stream of the rinser for nonreturnable glass bottles, K1, is reused in washer for returnable glass bottles along filling line B, (P21–P23). The wastewater from the local CIP system, P6, can be reused in the washer for returnable glass bottles in the filling line A, P10. No interdaily connection is selected between water operations in the packaging area, as this would require the installation of additional storage tanks for integrating those processes that operates during different days of a week. The freshwater consumption is 1531 t per week. The piping investment cost of new connections within the production and packaging area, and between the packaging area amounts to 25,858 €.

Production area

The final design in the production area integrated with pasteurization operations in the packaging area is shown in Figure 7. Pasteurization operations (P43–P56) are shown at the top of Figure 7. The water network includes six batch processes divided over 19 time intervals. The exchanged water mass is fixed to 35 t in each operating interval, altogether 490 t. The size of the applied MINLP model was $\sim$39,000 constraints, 18,000 continuous variables and 8400 binary variables. The number of nonlinear constraints was 112, and the nonlinearity degree was estimated to be 0.285. The model was solved by the GAMS/DICOPT solver[40] using 148 s of CPU time at the PC (P4, 2.6 GHz and 512 MB RAM).

In the optimum design, the wastewater purification is carried out in a continuous treatment unit (nanofiltration), whereas batch unit is not selected. Wastewater from filtration (P39–

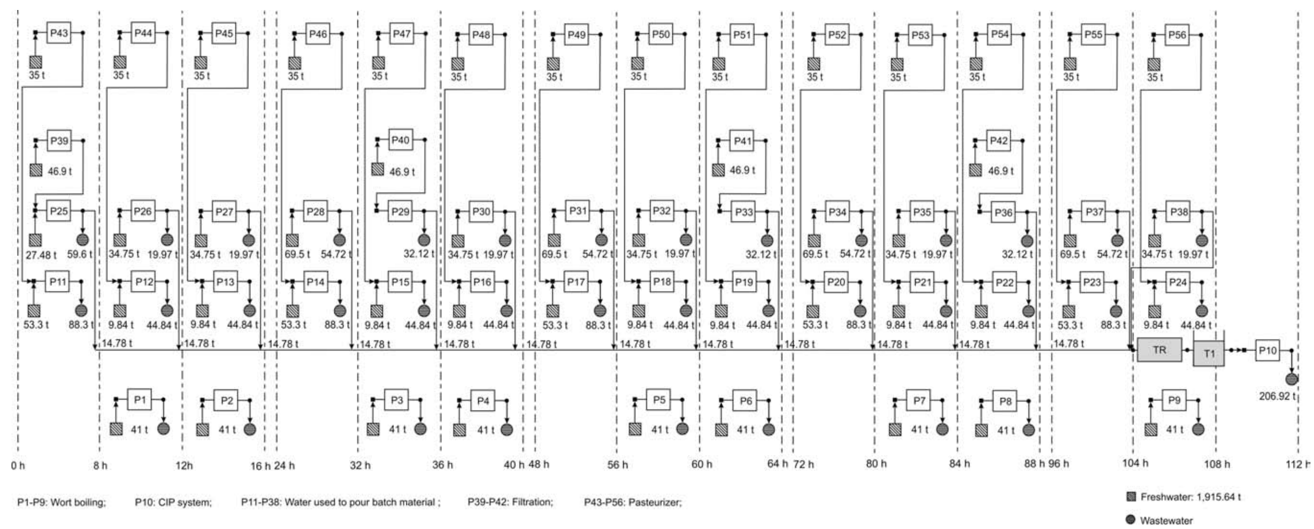

Figure 7. Optimal water network in the production area—Strategy I.

P42) is reused without treatment as water for pouring the batch material. Wastewater from pouring operations (P25–P38) is clarified and reused in CIP system. The freshwater consumption is 1425.7 t per week. The size of the required membrane is 28 m^2. Investment cost for semicontinuous treatment unit with storage tank is 98,403 €, and the investment for new regeneration reuse piping connections is 130,592 €.

The freshwater consumption in the water network obtained by Strategy I is reduced from 4725.2 t to 2956.7 t per week, and the freshwater cost is lower by 382,823 € a^{-1}, or 37.4% (Table 7). The total investment for the new piping connections in both sections, and semicontinuous treatment unit with storage tank is 254,853 €. The net present value of the proposed water network reconstruction is 1,593,302 € and payback period around 0.85 year or 10 months.

Weekly Integration—Strategy II

At this level, according to the proposed Strategy II, the fresh water upper bounds of pouring operations in the production area are lowered by 35 t that are supplied from the pasteurization operations in the packaging area. The wastewater lower bounds of the pasteurization processes are increased by the same amount to assure the required amount of water for intersectional integration.

Packaging area

The packaging water network includes seven batch and two semicontinuous processes divided over nine time intervals. The optimal network and the freshwater consumption are identical to those obtained by Strategy I. Modified lower bounds of wastewater discharge in pasteurization processes do not affect the optimal water network. The size of the applied MINLP model was ~4800 constraints, 2400 continuous variables and 1100 binary variables. There were 64 nonlinear constraints in the model, and the nonlinearity degree was 0.262. The model was solved by the GAMS/DICOPT solver[40] using 6 s of CPU time at the PC (P4, 2.6 GHz and 512 MB RAM).

Production area

The final design for the production area obtained by Strategy II is equal to that of Strategy I (Figure 7). The freshwater consumption is 1445.1 t per week which is 1.3% higher than in the case of Strategy I. The reason is higher freshwater consumption in pouring processes (P12, P13, P15, P16, P18, P19, P21, P22, and P24). The freshwater consumption of these processes is 9.84 t in the case of Strategy I, whereas 11.23 t in the case of Strategy II. The freshwater demand in operations P11–P24 is reduced for the amount of water received from the packaging area, i.e., for 35 t. Also, the annual cost of wastewater treatment in the central treatment unit increases by the amount of water received from the packaging area. The size of the required membrane is 28 m^2. Investment cost of semicontinuous treatment unit with storage tank is 98,403 €, and the investment cost of new regeneration reuse piping connections is 152,014 €.

In total, the freshwater consumption is reduced from 4725.2 t to 2976.3 t per week by the Strategy II, and the freshwater cost is lower by 378,606 € a^{-1} or 37% (Table 6). The total investment for the new piping connections, semicontinuous treatment unit and storage tank is 276,275 €. The investment cost of the piping lines is higher than in the case

Table 7. Results of Total Water Network in a Brewery

Water Network	Freshwater Cost (€ a^{-1})	Wastewater Treatment Cost (€ a^{-1})	Storage Tank Cost (€ a^{-1})	Piping Cost (€ a^{-1})	LT Investment (€ a^{-1})	Total Cost (€ a^{-1})
Current state	1,022,925	61,762	0	0	0	1,084,687
Integrated by strategy I	640,102	57,372	30,162	68,522	12,936	809,094
Integrated by strategy II	644,319	58,232	30,162	77,904	12,936	823,553

Table 8. Results of Separated and Joint Integrations in the Brewery

Water Network	Freshwater Cost (€ a^{-1})	Wastewater Treatment Cost (€ a^{-1})	Storage Tank Cost (€ a^{-1})	Piping Cost (€ a^{-1})	LT Investment Cost (€ a^{-1})	Total Cost (€ a^{-1})
Current state	1,022,925	61,762	0	0	0	1,084,687
Integrated packaging area and nonintegrated production area	892,626	61,104	0	11,325	0	965,055
Integrated production area and nonintegrated packaging area	872,287	58,543	20,997	4770	12,936	969,533
Sum of separated integrations of packaging and production areas	741,988	57,886	20,997	16,095	12,936	849,902
Joint integration of packaging and production areas (Strategy I)	640,102	57,372	30,162	68,522	12,936	809,094

of optimal water network obtained by Strategy I, because of higher water flow in some processes, and consequently wider pipe diameters. The net present value of the proposed water network reconstruction is 1,553,841 € and payback period around 0.93 year or 11 months.

The size of the applied MINLP model was ~21,500 constraints, 10,500 continuous variables and 4600 binary variables. The number of nonlinear constraints was 84, and the nonlinearity degree was estimated to be 0.289. The model was solved by the GAMS/DICOPT solver[40] using 282 s of CPU time at the PC (P4, 2.6 GHz and 512 MB RAM). It is interesting to mention, that the size of the original large-scale problem for weekly integration without applying decomposition strategies would be around 50,200 constraints, 23,300 continuous variables and 10,800 binary variables.

Selection of Optimal Solution

Individual and joint integrations of production and packaging sections produce a series of optimal water network designs. Table 8 summarizes the results to compare these designs and select the final solution: (1) individual integration of each section (either packaging or production), whereas another section is assumed to remain nonintegrated, (2) the sum of separated integrations of both sections, and (3) joint integration of both sections by Strategy I. As expected, separated integrations of both sections result in lower total cost (849,902 € a^{-1}) than single integration of one or another section. According to the results, integration of water network in the packaging area with the total cost of 965,055 € a^{-1} contributes more to reduction of total water network cost than integration of production area with the total cost of 969,533 € a^{-1}. Joint integration leads to the lowest total cost (809,094 € a^{-1}).

The net present value analysis showed that the retrofits of both water systems without any connection between the production and packaging sections produce the total net present value of 1,226,864 €. This value is significantly lower than the net present values of integrated water networks obtained either by Strategy I (1,593,302 €) or Strategy II (1,553,841 €). Obviously, the joint integration of both sections may provide additional decrease in total cost, and this solution was thus proposed to the brewery.

Conclusions

Two multilevel strategies based on temporal decomposition were presented for retrofitting the total water network. The characteristic of the production system under consideration is repeating batch/semicontinuous production, and changing daily production schedule over the working week. In the first level, both strategies perform simultaneous retrofit of integrated water system for each working day identifying daily reuse and regeneration reuse connections among water consumers in all sections. At the second level, in the case of the first Strategy, the design of integrated water system is performed over the entire working week for each section extended with integrated processes of other sections. The identified daily intersectional matches are fixed together with their masses determined in the first level. In the case of the second strategy, integration is performed within each section considering its original set of processes, but with modified bounds of those processes that are integrated with other sections.

Both strategies use mixed-integer nonlinear programming (MINLP) model for water reuse and regeneration reuse in batch and semicontinuous processes (Tokos and Novak-Pintarič[37]). The approach is illustrated with a brewery case study that integrates water consumers in two production sections. The complete analysis of integration options was performed together with the evaluation of economic viability. According to the results, joint integration of production and packaging sections results in considerably higher reduction of freshwater consumption (by 37%), than separated integration of the sections (by 27%). The total cost of joint integration is also lower, despite higher piping and storage investment costs. The optimal water networks obtained by the proposed alternative two-level strategies contain the same reuse and regeneration reuse connections, but the freshwater consumption is slightly higher in water network obtained by Strategy II, due to the modification of freshwater demand upper bounds.

Acknowledgments

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Notation

Sets

C = a set of contaminant
FW = a set of freshwater sources

K = a set of processes divided over time intervals
I = a set of production sections
J = a set of time intervals
N = a set of water-using operation
ns_i^{I} = subset of processes that supply water to section i from other sections
ns_i^{II} = subset of processes in section i that supply wastewater to other sections
nu_i^{I} = subset of processes that use wastewater from section i
nu_i^{II} = subset of processes in section i that use wastewater from other sections
W = a common set of water sources, $W = \mathrm{FW} \cup \mathrm{WW}$
WW = a set of continuous water sources

Parameters

$C_{c,n}^{\mathrm{IN,MAX}}$ = maximum inlet mass concentration of operation n, g m^{-3}
$C_{c,n}^{\mathrm{OUT,MAX}}$ = maximum outlet mass concentration of operation n, g m^{-3}
$C_{c,ww}^{\mathrm{W}}$ = mass concentration of water source ww, g m^{-3}
$D_{k,kc}^{\mathrm{PP}}$ = distance between processes k and kc, m
$D_{k,kc,tr}^{\mathrm{TR,E}}$ = distance between processes k and kc through treatment unit tr, m
$D_{w,k}^{\mathrm{W,E}}$ = distance between water source w and process k, m
F_{AN} = annualization factor, a^{-1}
G_n^{MAX} = limiting water mass for operation n, t
J_F = average filtrate flux, m^3 (m^2 h)$^{-1}$
K_{tr} = investment parameter of local treatment unit tr
$m_{ww,j}^{\mathrm{C}}$ = limiting water mass of the continuous stream ww in time interval j, t
m_c^{E} = equivalent mass load unit of contaminant c, kg
$m_n^{\mathrm{LB,OUT}}$ = lower bound for wastewater mass from operation n to discharge, t
$m_n^{\mathrm{LB,OUT,2.step}}$ = lower bound of wastewater mass from operation n to discharge in the second step, t
$m_{n,nc}^{\mathrm{LB,PP}}$ = lower bound for reused water mass from operation n to operation nc, t
$m_{nc,n,tr}^{\mathrm{LB,TR}}$ = lower bound for reused water mass from operation nc to operation n purified in local treatment unit tr, t
$m_{n,nc}^{\mathrm{PP,1.step}}$ = reused water mass between processes n and nc determined in the first step, t
$m_{n,nc,tr}^{\mathrm{TR,1.step}}$ = regenerated and reused water mass between processes n and nc determined in the first step, t
$m_{n,nc}^{\mathrm{UB,PP}}$ = upper bound for reused water mass from operation n to operation nc, t
$m_{nc,n,tr}^{\mathrm{UB,TR}}$ = upper bound for reused water mass from operation nc to operation n purified in local treatment unit tr, t
$m_{w,n}^{\mathrm{UB,W}}$ = upper bound for water mass from water source w to operation n, t
$m_{w,n}^{\mathrm{UB,W,2.step}}$ = upper bound of water mass from water source w to operation n in the second step, t
n_{tr}^{TR} = capacity exponent of local treatment unit tr
P^{E} = price of wastewater treatment, € per load unit
$P^{\mathrm{E,\ LB}}$ = price of wastewater treatment in the local batch treatment unit, € per load unit
$P^{\mathrm{E,\ LC}}$ = price of wastewater treatment in continuous local treatment unit, € per load unit
P^{W} = freshwater price, € t^{-}
p = variable parameter of piping investment cost
r = variable parameter of storage tank investment cost
$r_{c,tr}^{\mathrm{TR}}$ = removal ratio of contaminant c in treatment unit tr
s = fixed parameter of storage tank investment cost
q = fixed parameter of piping investment cost
λ_{OHY} = annual operating time, h a^{-1}
Δt_n = processing time of operation n, h
Δt^{ALL} = overall time interval, h
$\Delta t_{tr}^{\mathrm{TR}}$ = treatment time in local treatment unit tr, h
ρ = water density, t m^{-3}
v = water velocity, m s^{-1}

Variables

$C_{c,n}^{\mathrm{OUT}}$ = outlet water mass concentration of operation n, g m^{-3}
CT_k = storage tank investment cost of process k, €
$CT_{tr}^{\mathrm{TR,OUT}}$ = storage tank investment cost of purified water after treatment unit tr, €
f_1 = freshwater cost, € a^{-1}
f_2 = annual investment cost of storage tank installation, € a^{-1}
f_4 = wastewater treatment cost, € a^{-1}
m_n^{OUT} = wastewater mass from operation n to discharge, t
m_n^{ST} = storage tank capacity of operation n, t
$m_k^{\mathrm{ST,E}}$ = reuse water mass from process k, t
$m_{w,n}^{\mathrm{W}}$ = water mass from water source w to operation n, t
$m_{nc,n,tr}^{\mathrm{TR}}$ = reuse water mass from operation nc to operation n purified in local treatment unit tr, t
$m_{ww}^{\mathrm{C,FOUT}}$ = mass of wastewater from continuous operation ww to discharge, t

Binary variables

$Y_{nc,n}^{\mathrm{PP,1.step}}$ = binary variable for water reuse between processes n and nc determined in the first step
Y_n^{ST} = binary variable for storage tank to operation n
$Y_k^{\mathrm{ST,E}}$ = binary variable for storage tank to process k
$Y_{nc,n,tr}^{\mathrm{TR,1.step}}$ = binary variable for regeneration reuse match between processes n and nc via local treatment unit tr obtained in the first step

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