Journal of Cleaner Production 17 (2009) 1465–1479

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Synthesis of batch water network for a brewery plant

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ARTICLE INFO

Article history:
Received 31 March 2009
Received in revised form
25 June 2009
Accepted 30 June 2009
Available online 7 July 2009

Keywords:
Water minimisation
Wastewater
Batch-continuous processes
Industrial application

ABSTRACT

This paper presents an industrial application of mixed-integer nonlinear programming (MINLP) models for the optimisation of a water network, which was initiated by an integral need for cleaner production within a brewery. Several mathematical models were developed in order to reduce the use of freshwater, whilst considering the specific requirements of each particular production section. These models are based on the design method developed by Kim and Smith [1]. The original formulation is modified to enable efficient integration of discontinuous and semi-continuous water-using processes in the packaging area. Semi-continuous processes are treated as water sources of limited capacity. The option of installing storage tanks for semi-continuous water streams is included in the model, in order to re-use these streams during the shutdown periods of semi-continuous operations. The original model is additionally extended with the option of installing local (on-site) wastewater treatment units operating either in batch or semi-continuous modes. This enables the analysing of opportunities for regeneration re-use within the production area, i.e. the brewhouse with a cellar, because of high contaminant concentrations at these sites. The scheduling of batch wastewater treatment units is performed simultaneously in order to adjust the treatment schedule to a fixed schedule of batch processes.

1. Introduction

Water is one of the most important natural resources used in process industries. Minimisation of freshwater usage by means of water consumers' integration could contribute significantly to cleaner production and sustainable development. Numerous companies are thus interested in improving and optimising their water systems. Excluding process changes, there are three approaches for reducing freshwater demand: re-use, regeneration re-use, and regeneration recycling [2,3].

In the literature, studies on the design of water re-use and wastewater treatment networks in industry have mainly been concerned with continuous processes [4,5], while very little attention has been directed towards the development of water conservation strategies for batch operations or combinations of batch-continuous processes which would be suitable for the brewing process. Namely, water-using operations within the packaging area operate mainly in a discontinuous manner, with the exception of rinsers for non-returnable glass bottles and cans. Production in the brewhouse is based on sensible biotransformations operating in a discontinuous manner. The complexities for batch process industries lies in the fact that production processes consist of elementary tasks operating under time varying operating conditions and resource demands.

Two main approaches are generally used to address the issue of freshwater demand minimisation, i.e. the graphical approach and the mathematically-based optimisation approach. Graphical design methods are mostly two-stage procedures, where the time dimension is taken as a primary constraint, and concentration as a secondary one, and/or vice versa [6–10]. Graphical techniques enable the targeting of freshwater and wastewater flows, as well as detailed network design, however, they are focused more on quantitative water targets than economic objectives. These techniques are often applied to processes with a single contaminant and fixed production schedule. Mathematical methods are based on superstructure presentations, and optimised water re-use/recycling by the installation of a central storage tank for wastewater, with acceptable purity [11–16], or by providing a storage tank after each water-using operation [1]. Such storage tanks prevent the mixing of wastewater streams having different contaminant concentrations, which could reduce water re-use options, in some cases. However, mixing could lead to less complex batch water networks, as reported in [16]. One of the advantages of mathematical models is the possibility of incorporating several optimisation subproblems, e.g. the batch scheduling, the water re-use network and the wastewater treatment network, into a single

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doi:10.1016/j.jclepro.2009.06.009

Nomenclature

Sets

c	a set of contaminant
fw	a set of freshwater sources
k	a set of processes divided over time intervals
j	a set of time intervals
n	a set of water-using operation
w	a common set of water sources, $w = fw \cup ww$
ww	a set of semi-continuous water sources

Parameters

$C_{c,n}^{\mathrm{GAIN}}$	mass concentration of water gain in operation n, g/m^3
$C_{c,n}^{\mathrm{LOSS}}$	mass concentration of water loss in operation n, g/m^3
$C_{c,w}^{\mathrm{W}}$	mass concentration of water source w, g/m^3
$C_{c,n}^{\mathrm{IN,\ MAX}}$	maximum inlet mass concentration of operation n, g/m^3
$D_{n,nc}^{\mathrm{PP}}$	distance between operation n and nc, m
$D_{k,\ kc}^{\mathrm{PP,\ E}}$	distance between processes k and kc, m
$D_{n,nc,tr}^{\mathrm{TR}}$	distance between operations n and nc through treatment unit tr, m
$D_{k,kc,tr}^{\mathrm{TR,\ E}}$	distance between processes k and kc through treatment unit tr, m
$D_{ww,n}^{\mathrm{W}}$	distance between water source ww and operation n, m
$D_{ww,k}^{\mathrm{W}}$	distance between water source ww and process k, m
F_{AN}	annualization factor, a^{-1}
J	average filtrate flux, m^3/(m^2 h)
K_{tr}	investment parameter
M	large number
$m_{ww,\ j}^{\mathrm{C}}$	limiting water mass of semi-continuous stream ww in time interval j, t
m_{c}^{E}	equivalent mass load unit of contaminant c, kg
$m_{c,n}^{\mathrm{ML}}$	mass load removed by water in operation n, g
$m_{ww,n}^{\mathrm{W}}$	water mass from water source ww to operation n, t
$m_{nc,n,tr}^{\mathrm{LB,\ TR}}$	lower bound for re-used water mass from operation nc to operation n purified in local treatment unit tr, t
$m_{nc,n,tr}^{\mathrm{UB,\ TR}}$	upper bound for re-used water mass from operation nc to operation n purified in local treatment unit tr, t
n_{tr}^{TR}	capacity exponent of local treatment unit tr
P^{E}	price of wastewater treatment, €/load unit
$P^{\mathrm{E,\ LB}}$	price of wastewater treatment in the local batch treatment unit, €/load unit
$P^{\mathrm{E,\ LC}}$	price of wastewater treatment in semi-continuous local treatment unit, €/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
t_{j}^{E}	ending time of interval j, h
t_{n}^{E}	ending time of operation n, h
t^{LB}	lower bound of time difference, h
t_{j}^{S}	starting time of time interval j, h
t_{n}^{S}	starting time of operation n, h
t^{UB}	upper bound of time difference, h
q	fixed parameter of piping investment cost
$q_{\mathrm{m},\ ww}$	mass flow rate of semi-continuous stream ww, kg/h
λ_{OHY}	annual operating time, h/a
Δt_{n}	processing time of operation n, h
Δt^{ALL}	overall time interval, h
Δt_{k}^{E}	total processing time of process k, h
$\Delta t_{tr}^{\mathrm{TR}}$	treatment time in local treatment unit tr, h

ρ	density, t/m^3
$v_{n.nc}^{\mathrm{PP}}$	velocity of re-use water flow from operation n to operation nc, m/s
$v_{k,kc}^{\mathrm{PP,\ E}}$	velocity of re-use water flow from process k to process kc, m/s
$v_{n,nc,tr}^{\mathrm{TR}}$	velocity of re-use water flow from operation n to operation nc purified in treatment unit tr, m/s
$v_{k,kc,tr}^{\mathrm{TR,\ E}}$	velocity of re-use water flow from process k to process kc through treatment unit tr, m/s
$v_{ww,k}^{\mathrm{W,\ E}}$	velocity of water flow from water source ww to process k, m/s

Variables

$C_{c,n}^{\mathrm{OUT}}$	outlet water mass concentration of operation n, g/m^3
$C_{c,nc,tr}^{\mathrm{TR}}$	mass concentration of water purified in local treatment unit tr from operation nc, g/m^3
CT_{n}	storage tank investment cost of operation n, €
CT_{ww}^{C}	storage tank investment cost of semi-continuous operation ww, €
$CT_{tr}^{\mathrm{TR,\ IN}}$	storage tank investment cost of wastewater before treatment unit tr, €
$CT_{tr}^{\mathrm{TR,\ OUT}}$	storage tank investment cost of purified water after treatment unit tr, €
F_{Obj}	objective function, €/a
f_1	freshwater cost, €/a
f_2	annual investment cost of storage tank installation, €/a
f_3	annual investment cost of piping, €/a
f_4	wastewater treatment cost, €/a
f_5	annual investment costs of the local treatment units, €/a
m_{n}^{GAIN}	mass of water gain in operation n, t
m_{n}^{LOSS}	water mass loss in operation n, t
m_{n}^{OP}	water mass inside operation n, t
m_{n}^{OUT}	wastewater mass from operation n to discharge, t
$m_{nc,n}^{\mathrm{PP}}$	re-use water mass from operation nc to operation n, t
$m_{kc,k}^{\mathrm{PP,\ E}}$	re-use water mass from process kc to process k, t
m_{tr}^{TRC}	capacity of local treatment unit tr, t
$m_{w,n}^{\mathrm{W}}$	water mass from water source w to operation n, t
$m_{ww,k}^{\mathrm{W,\ E}}$	water mass from water source ww to process k, t
$m_{nc,n,tr}^{\mathrm{TR}}$	re-use water mass from operation nc to operation n purified in local treatment unit tr, t
$m_{kc,k,tr}^{\mathrm{TR,\ E}}$	re-use water mass from process kc to process k purified in local treatment unit tr, t
$m_{ww}^{\mathrm{C,\ FOUT}}$	mass of wastewater from semi-continuous operation ww to discharge, t
$m_{ww,j}^{\mathrm{C,\ OUT}}$	water mass from semi-continuous unit to discharge in the interval j, t
$m_{ww}^{\mathrm{C,ST}}$	capacity of storage tank for semi-continuous water stream ww, t
$m_{tr}^{\mathrm{ST,\ TR,\ IN}}$	capacity of storage tank placed before treatment unit tr, t
$m_{tr}^{\mathrm{ST,\ TR,\ OUT}}$	capacity of storage tank placed after treatment unit tr, t
$t_{n,nc,tr}^{\mathrm{A,\ TR}}$	waiting time after treatment unit tr, h
$t_{n,nc,tr}^{\mathrm{B,\ TR}}$	waiting time before treatment unit tr, h
$t_{nc,tr}^{\mathrm{E,TR}}$	ending time of wastewater treatment from operation nc in treatment unit tr, h
$t_{nc,tr}^{\mathrm{S,\ TR}}$	starting time of wastewater treatment from operation nc in treatment unit tr, h

Binary variables

$Y_{nc,n,tr}^{\mathrm{TR}}$	binary variable for re-used water mass from operation nc to operation n purified in local treatment unit tr