Property based management and optimization of water usage and discharge in industrial facilities

Arwa Rabie and Mahmoud El-Halwagi

Department of Chemical Engineering,

Texas A&M University

Outline

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- Problem Scope
- Literature Survey
- Problem Statement &Representation
- Novel Approach
- Case Study
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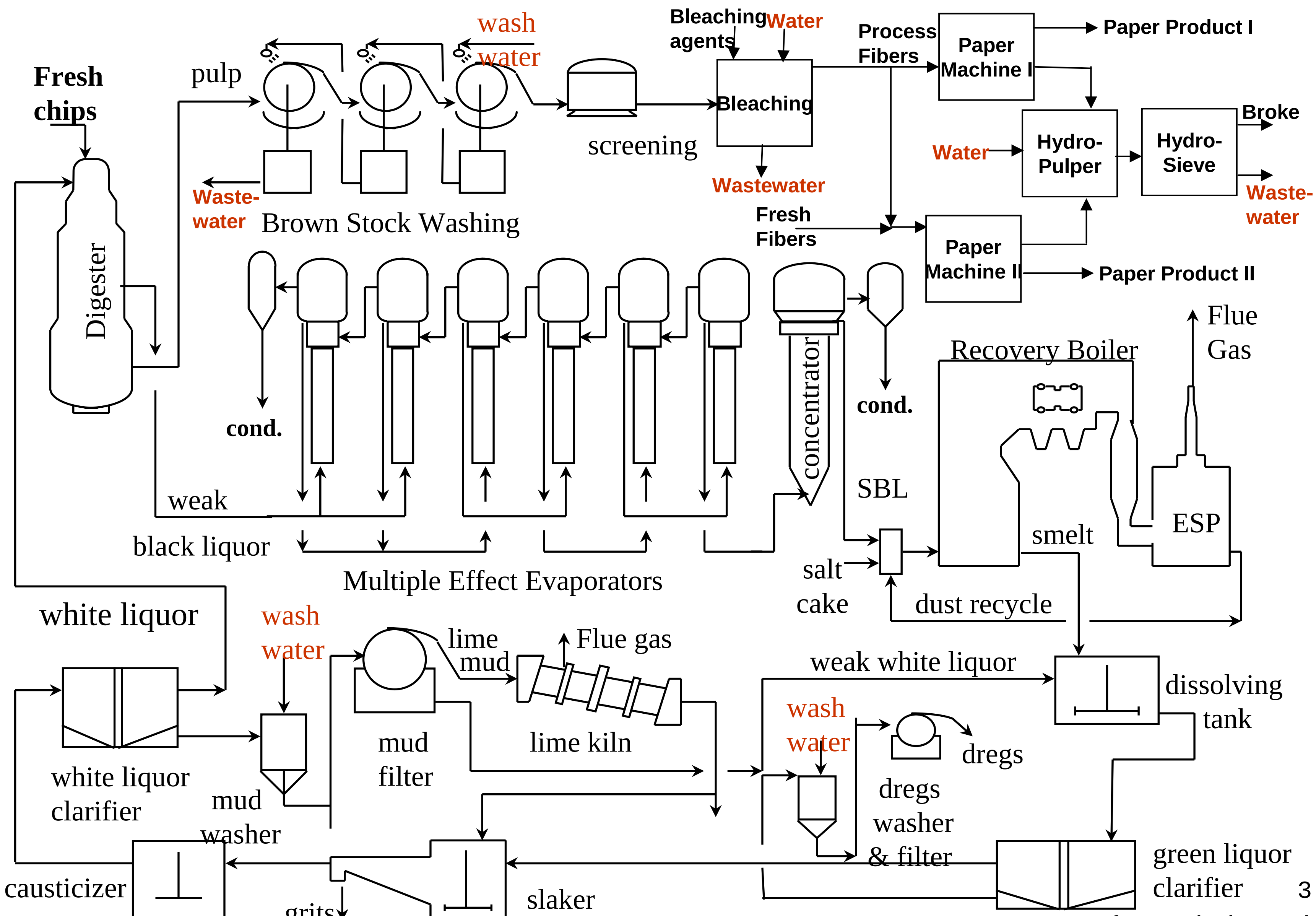
Motivating Example



Ref. Lovelady et al. 2007

Motivation

- Industrial facilities significantly use fresh water and discharge wastewater
- Growing public concern as well as environmental regulations
- Conservation of resources
- Enhanced market competitiveness

Problem Scope

Given: a batch process with a number of

- water sources whose composition and flow rate vary over time
- sinks whose water demand and maximum admissible composition vary over time

Objectives: Develop a systematic procedure to

- Synthesize an optimal batch water network
- Schedule an operating network of a minimum total annualized cost while meeting all process constraints

Examples of Previous Literature

- Wang and Smith(1995), Majozi (2005)
  - Graphical method limited to mass transfer based utilities
  - Limited to single contaminant systems
  - Used storage tanks
  - Water sources were not recycled to lower concentration utilities or in previous times of the cycle.

- Foo, Manan& Tan(2005)-Water Cascade Analysis
  - Graphical method for non-mass transfer based utilities
  - Limited to single contaminant systems
  - Water sources were not recycled to utilities that required water in previous times of the cycle.
  - Mixing of water sources at different impurities in the same tank was not allowed

Examples of Previous Literature

- Kim and Smith(2004), Majozi(2005a),Majozi(2005b)
  - Mathematical formulation limited to mass transfer based water units
  - Limited to single contaminant systems
  - Used storage tanks
  - Water sources were not recycled to utilities that required water in previous times of the cycle.

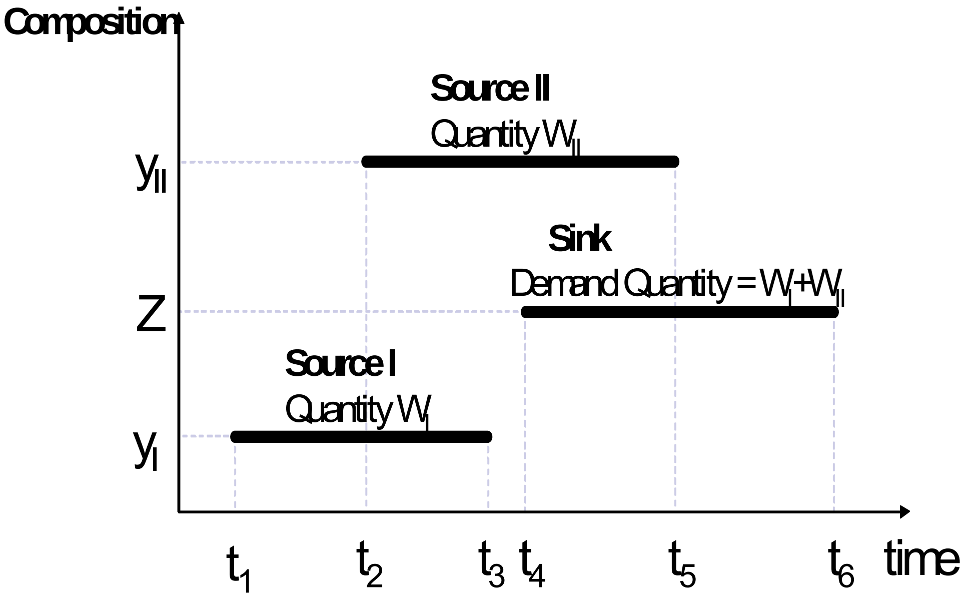
- Chang & Li(2006)
  - Mathematical formulation not limited to mass transfer based water units
  - Used storage tanks
  - Water sources were not recycled to utilities that required water in previous times of the cycle.

Limitations of Previous Work

One of more of the following limitations:

- Recycle within the same cycle: water recycle is limited to units that require water later in the same cycle
- Lumped usage of water over a cycle: this assumption accounts for a total quantity and quality of water supply
- The objective of minimizing fresh water usage: it is important to consider an objective dealing with fixed cost in addition of operating cost.
- Lack of global solution procedure

Lumped usage of water



$$Gj = W_I + W_{II}$$

$$Z^{max} = \frac{W_I y_I + W_{II} y_{II}}{W_I + W_{II}}$$

Problem Statement

During a batch cycle (τ) of a given batch process there is a number of:

-Sources; process streams

- impurity concentration of $y_{v,u}(t)$
- flow of $w_v(t)$
- $0 \leq t \leq \tau$

-Sinks; process units that are in need of water

- maximum inlet impurity composition $z_{s,u}(t)$
- flow rate requirement $g_s(t)$
- $0 \leq t \leq \tau$

Available for service are:

-Tanks; used for water storage and dispatch

-Fresh water streams

- Impurity composition x_r
- cost of C_r

Optimization Formulation

- Dynamic variation of sources and sinks
- Synthesis:
  - Numerous source and sink constraints
  - Tanks selection and assignment
- Scheduling:
  - When to store sources and when to dispatch them to sinks

Mathematical programming approach

Characteristics and Features:

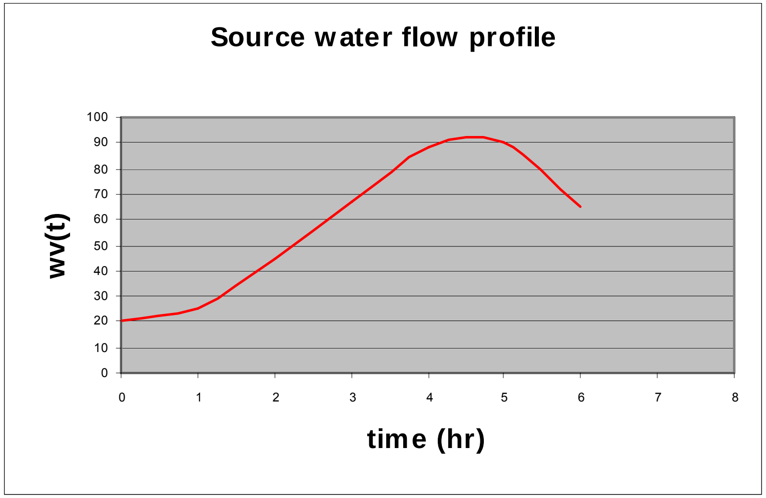
- Mathematical programs can tackle complex systems
- Need to handle multiple sources
- Need to handle multiple sink requirements
- Need to incorporate storage and dispatch tanks

Novel Approach

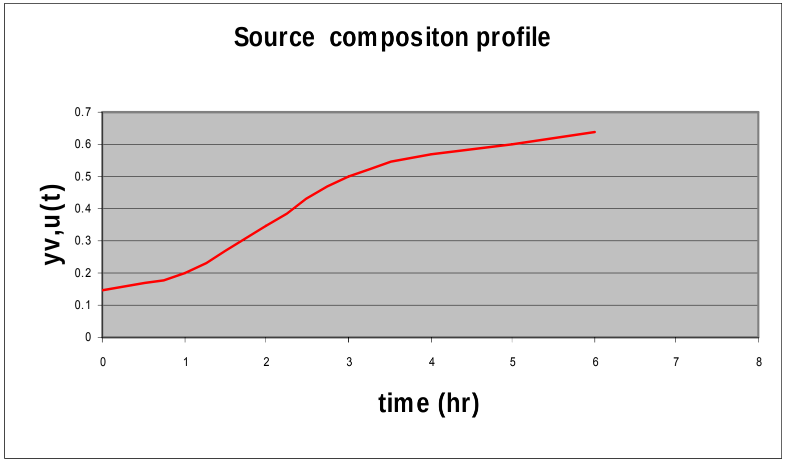
- Reformulate sources and sinks into discrete events
- Determine target for minimum usage of fresh water and minimum waste water discharge
- Synthesize a direct-recycle water network using storage and dispatch tanks to achieve the water target
- Schedule an optimum operating scheme to achieve the target
- Use insight to further simplify network design
- Tradeoff water usage, discharge, fixed and operating costs to obtain minimum TAC

Source Reformulation

During a batch cycle τ, the profile for both $w_v(t)$ and $y_{v,u}(t)$ are known ($0 \le t \le \tau$).



- $$Wi = \int_{t_{q-1}}^{t_q} w_v(t)\,dt$$

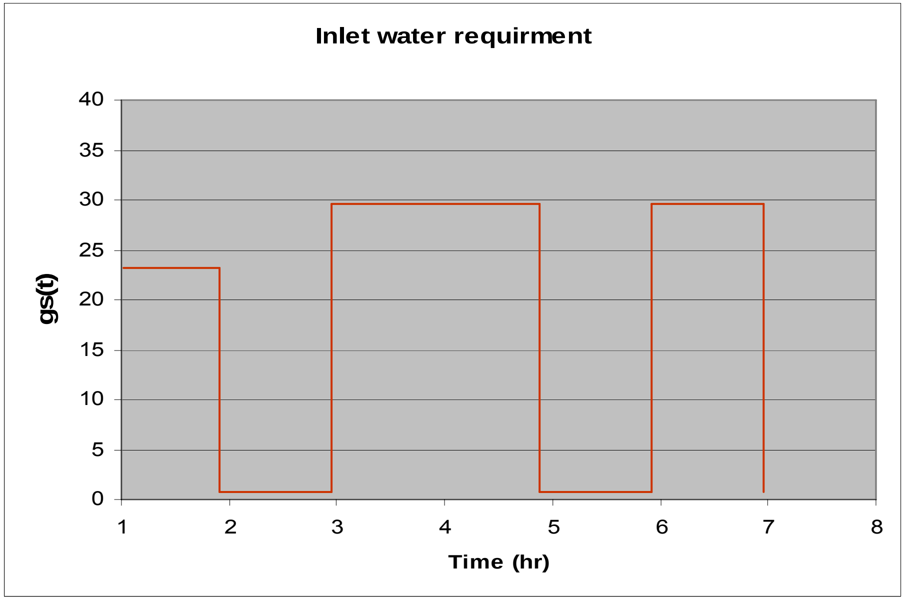


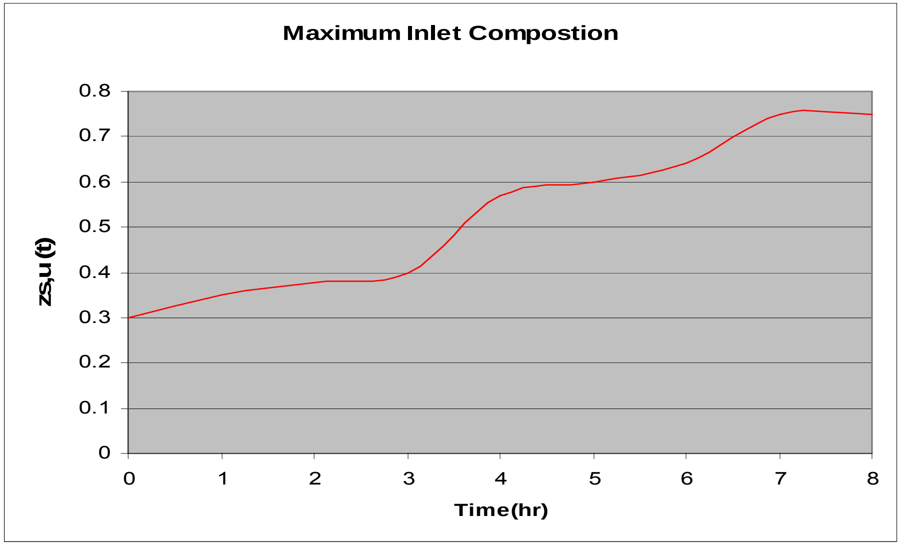
- $$Y_{i,u} = \frac{\int_{t_{q-1}}^{t_q} w_v(t)\,y_{v,u}(t)\,dt}{W_i}$$

Sink Reformulation

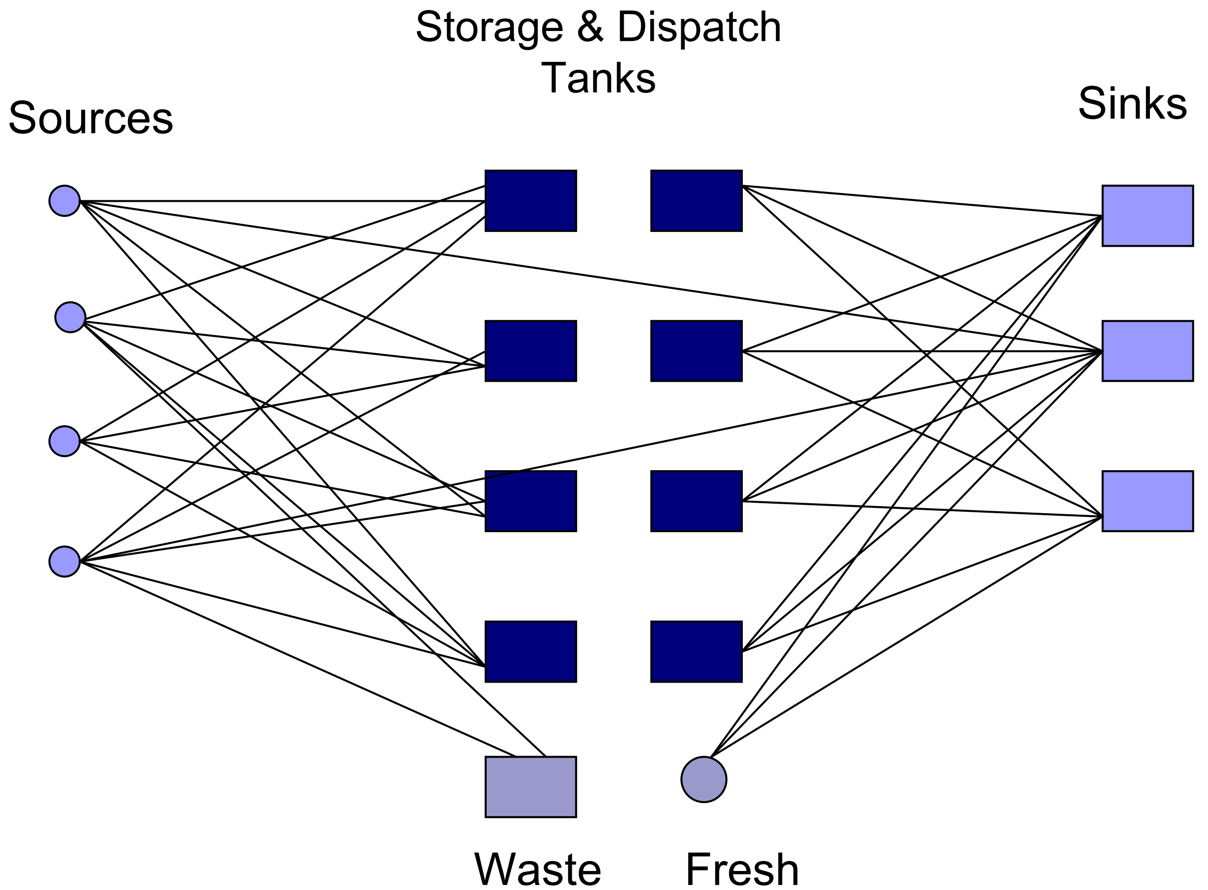
During a batch cycle τ, the profile for both $g_s(t)$ and $z_{s,u}(t)$ are known ($0 \le t \le \tau$).

- $$G_j = \int_{t_{p-1}}^{t_p} g_s(t)dt$$
- $$z_{j,u}^{\max} = \frac{\int_{t_{p-1}}^{t_p} g_s(t) z_{s,u}^{\max}(t)dt}{G_j}$$





Water Recycle Network Representation



- Availability and demand are not concurrent.
- Assumption: two sets of tanks will be used one for storage and one for dispatch

Targeting Mathematical Formulation

- **Minimize** $\sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} C_r \, f_{r,j}$

Subject to:

- **Splitting of Sources**

$$W_i = \sum_{j=1}^{N_{Sinks}} w_{i,j} + w_{i,waste}$$

i=1, 2,…,NSources

- **Waste flow**

$$Waste = \sum_{i=1}^{N_{Sources}} w_{i,waste}$$

- **Sink Balances**

$$G_j = \sum_{i=1}^{N_{Sources}} w_{i,j} + \sum_{r=1}^{N_{Fresh}} f_{r,j}$$

j=1, 2,…,NSinks

$$G_j Z_{j,u} = \sum_{i=1}^{N_{Sources}} w_{i,j} Y_{i,u} + \sum_{r=1}^{N_{Fresh}} f_{r,j} x_{r,u}$$

j=1,2,…,NSinks and u=1,2,…,NComponents

$$Z_{j,u} \le Z_{j,u}^{\max}$$

j=1,2,…,NSinks and u=1,2,…,NComponents

Synthesis & Scheduling Mathematical Formulation

- **Minimize** $2N_k$

Subject to:

$$N_k = \sum_{k=1}^{N_{Tanks}} I_k$$

$$I_k \in \{0,1\}$$

$$T_k \leq U_k I_k$$

- **Splitting of Sources**

$$W_i = \sum_{k=1}^{N_{Tanks}} w_{i,k} + w_{i,waste}$$

i=1,2,…,NSources

- **Storage Tank Balances**

$$T_k = \sum_{i=1}^{N_{Sources}} w_{i,k}$$

k=1,2,…,NTanks

$$T_k y_{k,u}^{Tank} = \sum_{i=1}^{N_{Sources}} w_{i,k} Y_{i,u}$$

k=1,2,…,NTanks and u=1,2,…,NComponents

$$T_k = \sum_{j=1}^{N_{\sin ks}} t_{k,j}$$

k=1,2,…,NTanks

Synthesis & Scheduling Formulation Continued

- **Waste Flow**

$$Waste = \sum_{i=1}^{Nsources} w_{i,waste}$$

- **Sink Balances**

$$G_j = \sum_{k=1}^{N_{Tanks}} t_{k,j} + \sum_{r=1}^{N_{Fresh}} f_{r,j}$$

j=1,2,…,NSinks

$$G_j Z_{j,u} = \sum_{k=1}^{N_{Tanks}} t_{k,j} y_{k,u}^{Tank} + \sum_{r=1}^{N_{Fresh}} f_{r,j} x_{r,u}$$

j=1,2,…,NSinks and u=1,2,…,NComponents

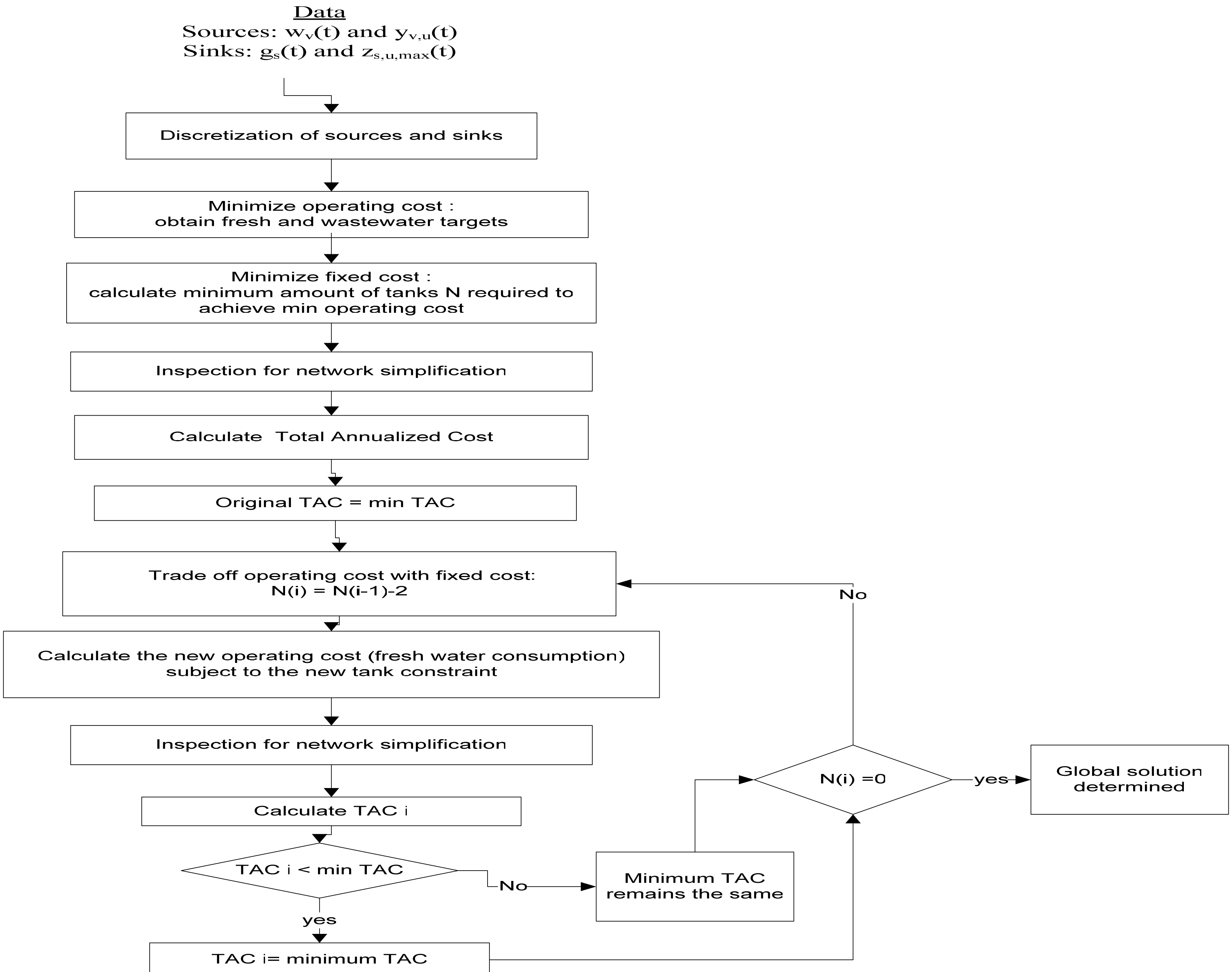
$$Z_{j,u} \leq Z_{j,u}^{\max}$$

j=1,2,…,NSinks and u=1,2,…,NComponents

- **Operating Cost Constraint**

$$\sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} C_r f_{r,j} = \text{Cost}$$

Approach


Data
Sources: $w_v(t)$ and $y_{v,u}(t)$
Sinks: $g_s(t)$ and $z_{s,u,max}(t)$
Discretization of sources and sinks
Minimize operating cost : obtain fresh and wastewater targets
Minimize fixed cost : calculate minimum amount of tanks N required to achieve min operating cost
Inspection for network simplification
Calculate Total Annualized Cost
Original TAC = min TAC
Trade off operating cost with fixed cost: N(i) = N(i-1)-2
Calculate the new operating cost (fresh water consumption) subject to the new tank constraint
Inspection for network simplification
Calculate TAC i
TAC i < min TAC
No
Minimum TAC remains the same
yes
TAC i= minimum TAC
N(i) =0
No
yes
Global solution determined

Case Study

Batch water network

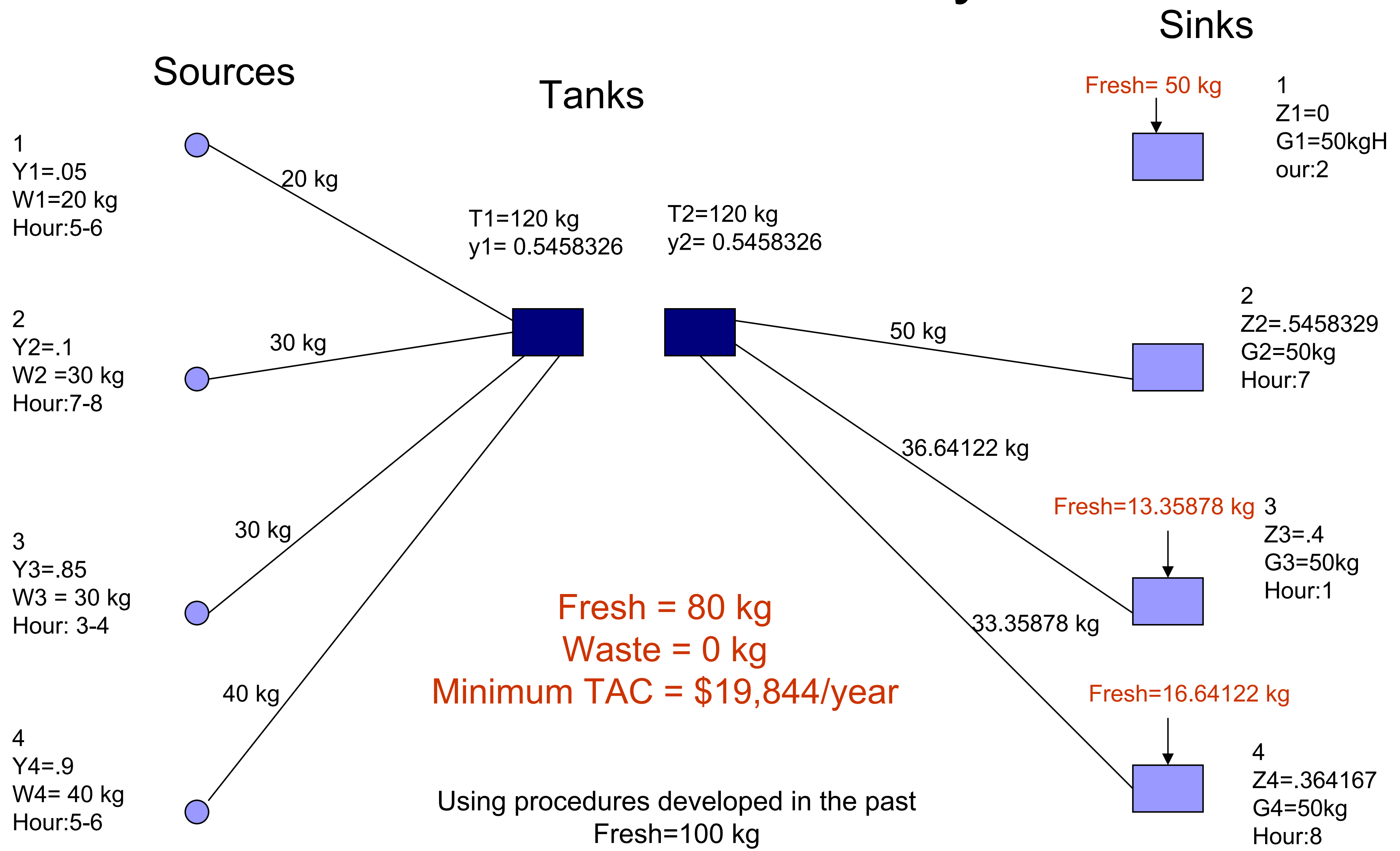
- 2 process sources
- 2 sinks
- 1 contaminant present in water from sources
- 1 fresh water stream
  -x_r=0
  -cost: $0.21/kg
- Available tanks
  -cost: $1000/m^3
  -instillation cost: $1,000 per tank
  -yearly maintenance: $500 per tank
- Batch cycle = 8 hours

Case Study

Source	Hour	Yi	Wi (kg)
1	1-2	0.0	0
	3-4	0.0	0
	5-6	0.05	20
	7-8	0.10	30
2	1-2	0.0	0
	3-4	0.85	30
	5-6	0.90	40
	7-8	0.0	0

Sink	Hour	Zjmax	Gj (kg)
1	2	.5	50
	7	.6	50
2	1	.4	50
	8	.7	50

Solution to Case Study



Fresh = 80 kg
Waste = 0 kg
Minimum TAC = $19,844/year

Using procedures developed in the past
Fresh=100 kg
Waste = 20 kg
TAC = $24,443

Conclusion

- Developed a systematic procedure to synthesize and schedule a batch water network
- Properly discretized batch cycle into meaningful events
- Targeting of water usage and discharge ahead of synthesis and scheduling
- Devised an iterative scheme to achieve total minimum annualized cost