Synthesis of Cost Effective and Sustainable Pathways to Wastewater Treatment

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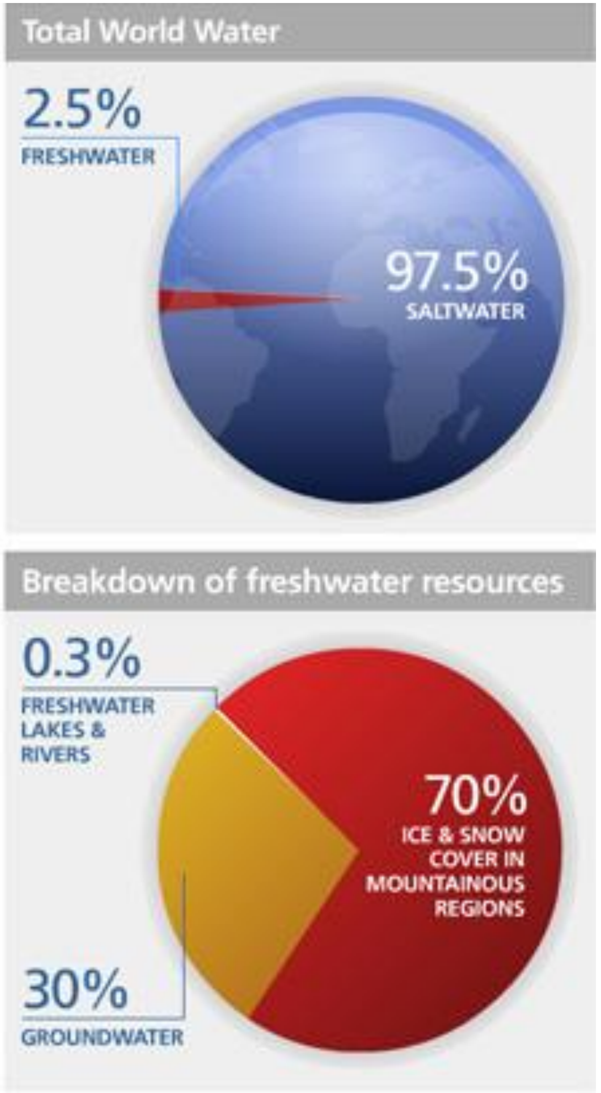
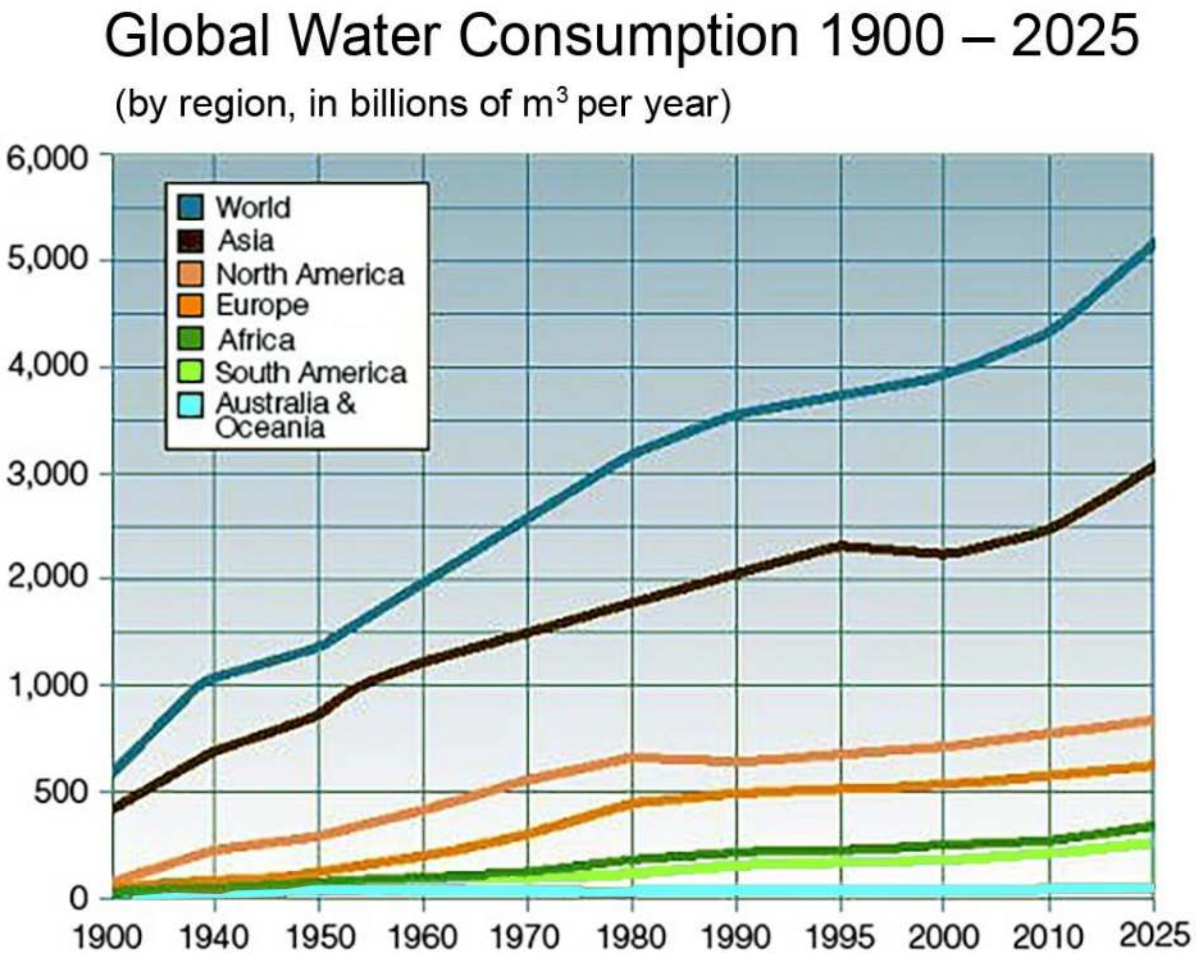
Global Water Resources & Consumption

- Very small percentage of the total water available is freshwater
- Yet, we depend on freshwater for our municipal, agricultural and industrial processes



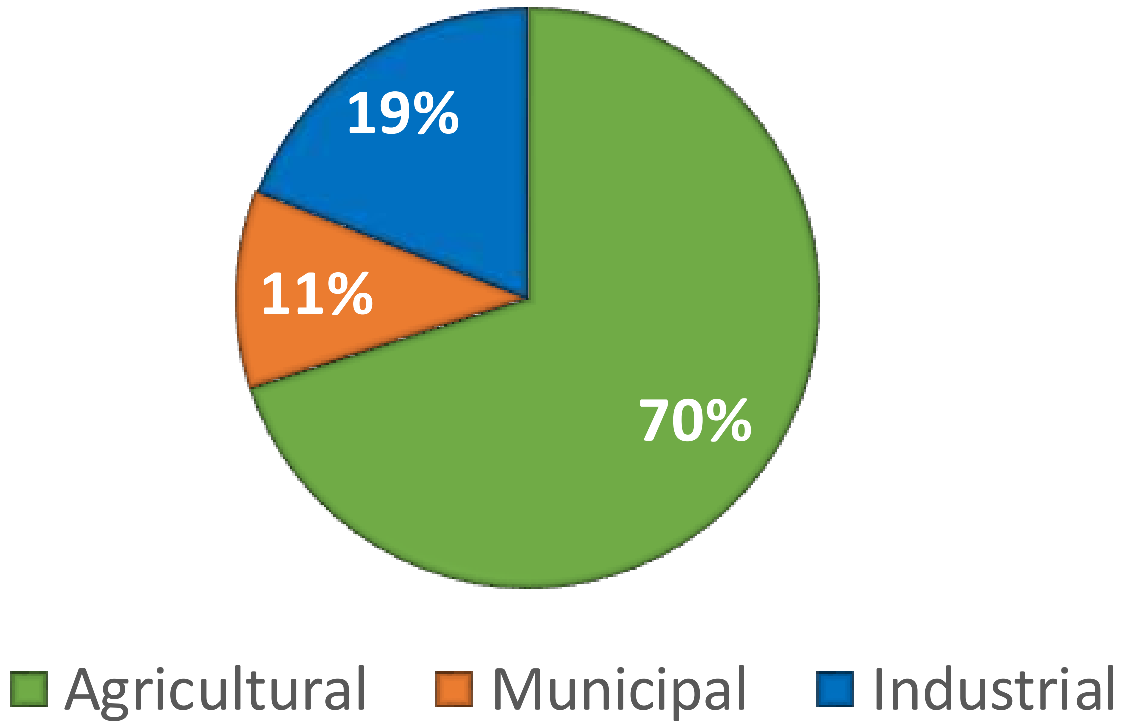
Source: Legacy Water Foundation, 2018



Source: https://en.wikipedia.org/wiki/Water_scarcity

Freshwater Usage Data

Current freshwater usage statistics (2018)

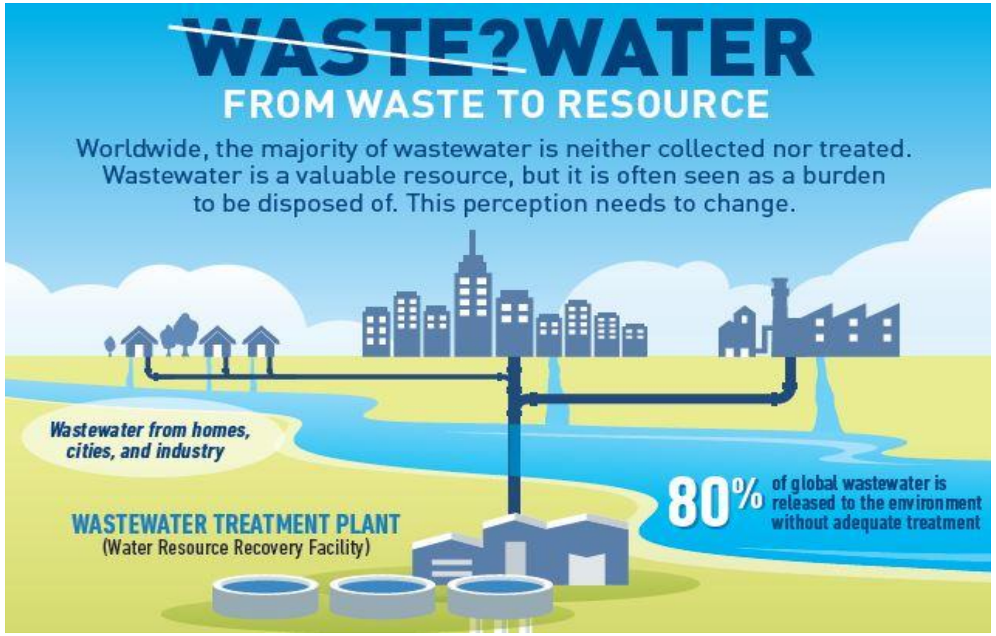


Projected freshwater usage in 2030

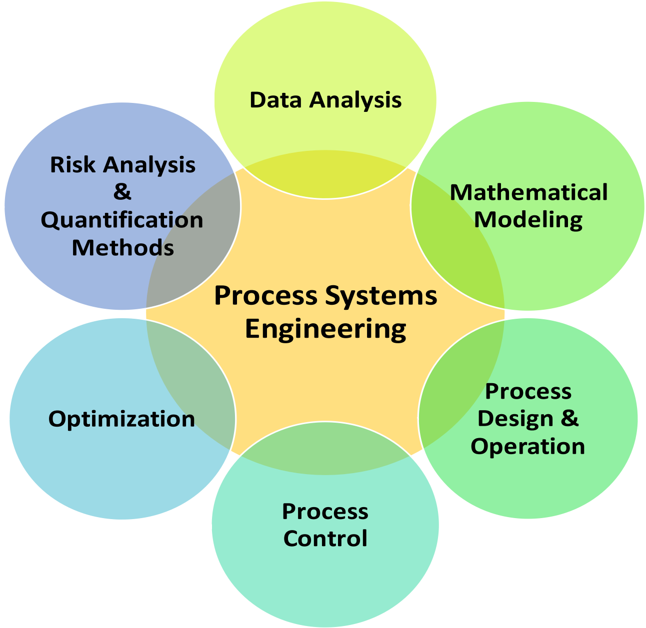
Where will this additional 20% come from?

Solution……….?

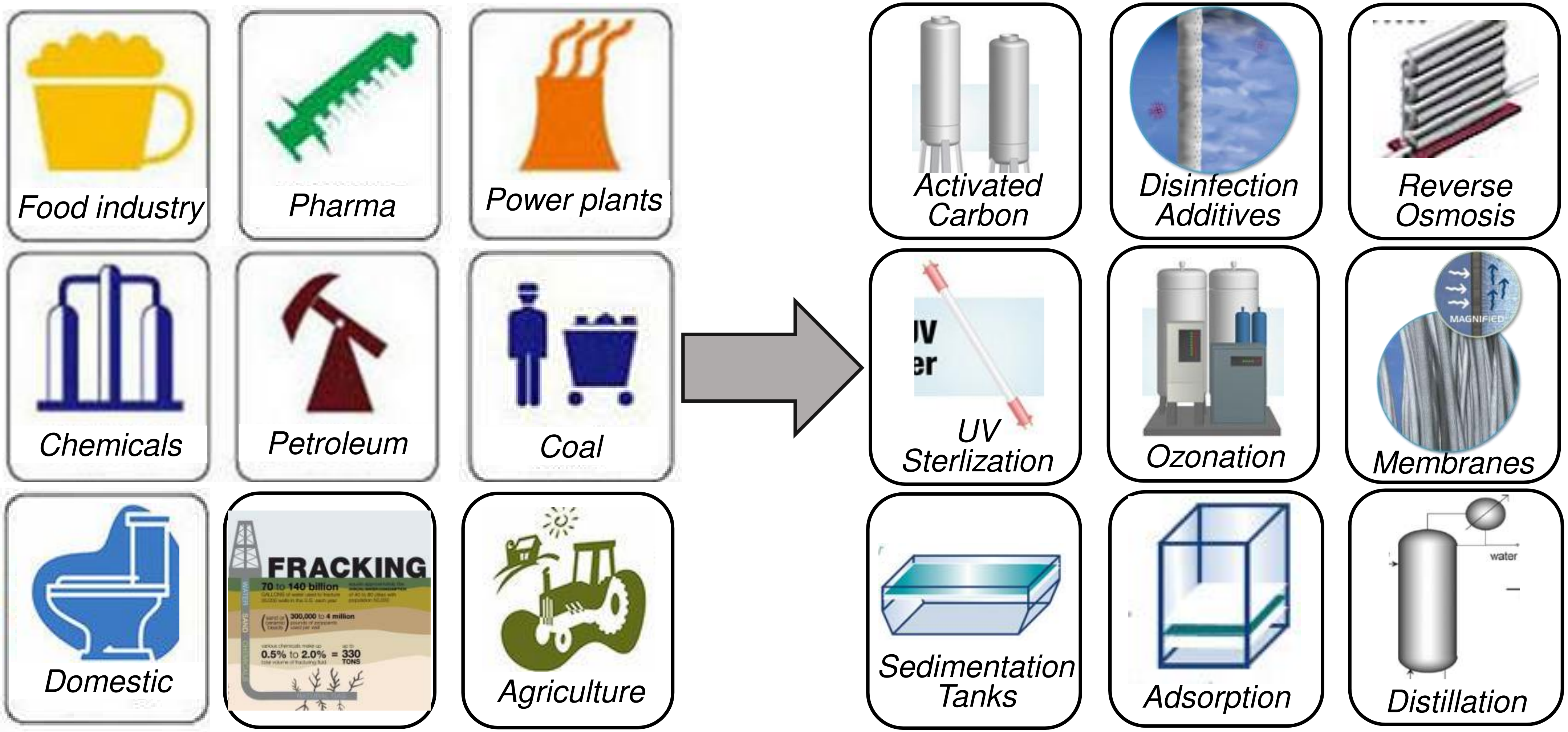
- To meet the demand we have to rely on **treated and recycled** water
- Thus, we need **efficient wastewater treatment methods** today to satisfy demands for sustainable existence tomorrow
- **Systems Engineering** can help in providing sustainable and cost effective insights



https://blogs.worldbank.org/water/wastewater-treatment-critical-component-circular-economy



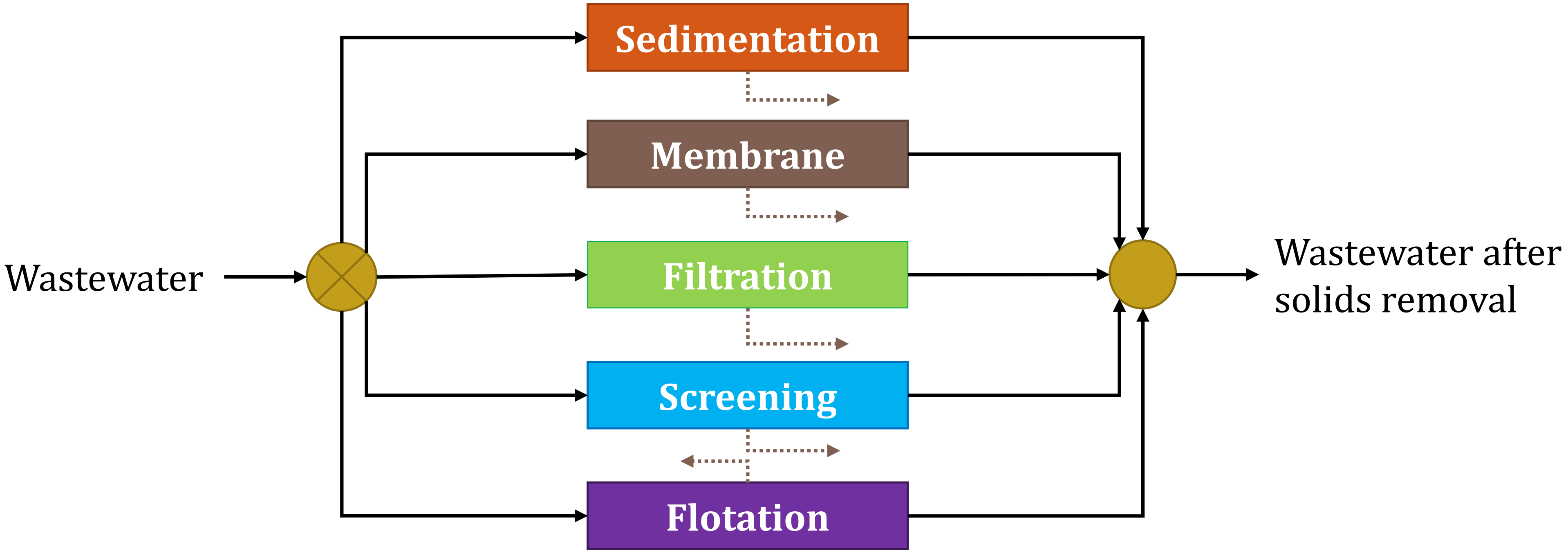
Wastewater Treatment: A Systems Problem



Sources of Wastewater **Treatment Methods**

Designing a Treatment Process

Solids removal is one of the tasks in Wastewater Treatment



Complexity of the design problem

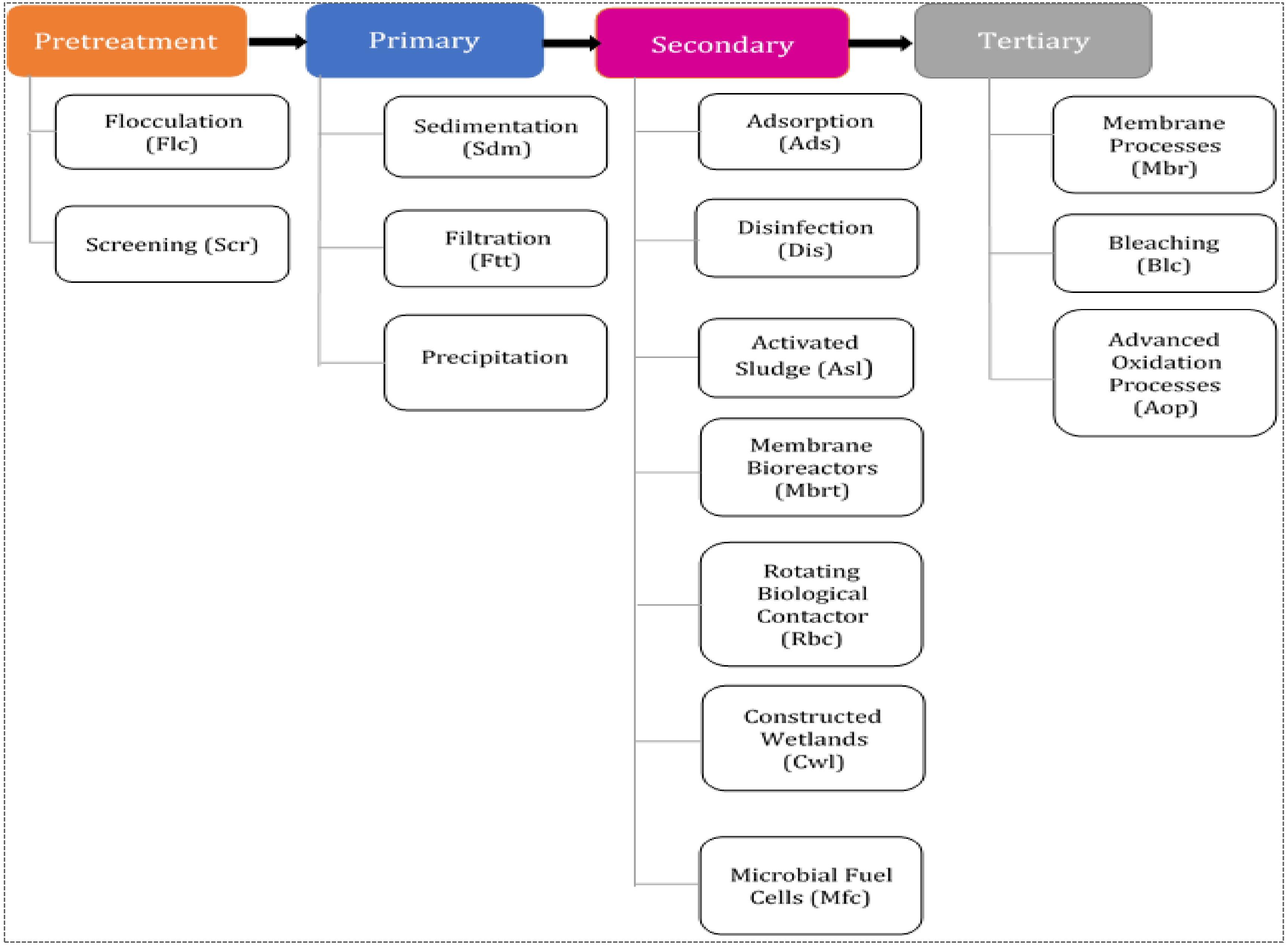
If a wastewater stream has **C** contaminants and **S** technologies for each task, then number of distinct treatment networks (N_f) possible is given by

$$N_f = \frac{[2(C-1)]!\ S^{(C-1)}}{C!\,(C-1)!}$$

If C = 5 and S = 10, then N_f = 1.4x10^5 (close to a million) possible networks

Treatment Stages & Technologies

- Wastewater treatment is most effective using a stage-wise approach
- Technologies are placed is stages based on their contaminant removal capability



Technology Information

Technology	Driving Force	Process conditions
Sedimentation (Sdm) or Decantation (Dct)	Density gradient Particle settling velocity	Size, density of particle Tank depth Residence time
Filtration (Ftt)	Particle size	Average flux, Pressure gradient Filtration rate
Advanced Oxidation Process (Aop)	Oxidation reactions for contaminant degradation	Ozone, peroxide, UV reactor
Disinfection (Dis)	Chemical, radiation	Chlorine dosage, Acid/Alkali treatment, UV radiation
Rotating Biological Contactors (Rbc)	Biological mechanism	Biological film on rotational discs, speed of rotation, aeration rate
Membranes (Mbr)	Particle/molecular size Sorption/Diffusion Pressure	Pore size, Mol. wt. cut-off Average flux, Pressure gradient Type of membranes – MF, UF, NF and RO
Activated Sludge (Acs)	Microbial activity	Detention time, mixing efficiency, aeration rate

P-graph Methodology

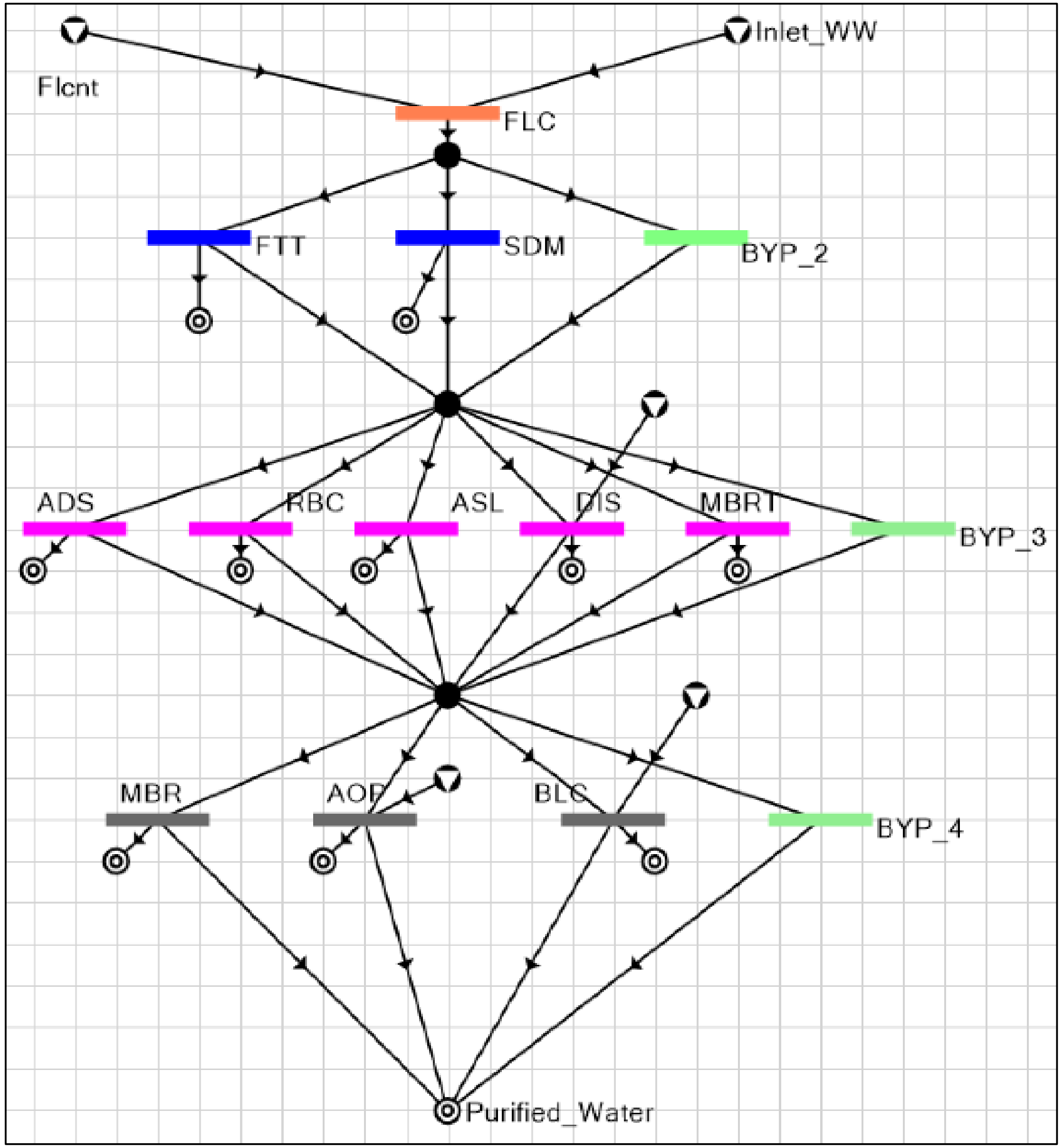
- P-graph (process graph) studio uses vertices and nodes to represent materials & operating units connected by arcs represent streams
- Includes two types of nodes
  - ✓ M-type: Materials

    raw materials ; products & intermediates
  - ✓ O-type: Operating units
- Based on axioms for structurally feasible process networks
- Algorithms available:
  - ✓ MSG (Maximal Structure Generator): generates the maximal structure
  - ✓ SSG (Solution-Structure Generator): generates all the structurally feasible process networks
  - ✓ ABB (Accelerated Branch and Bound): generates the optimal or n-best feasible networks

Friedler, F., Tarján, K., Huang, Y.W., Fan, L.T., 1992. Graph-theoretic approach to process synthesis: axioms and theorems. Chem. Eng. Sci. 47, 1973-1988.
Heckl, I., Friedler, F., Fan, L.T., 2010. Solution of separation-network synthesis problems by the P-graph methodology. Comput. Chem. Eng., Selected Paper of Symposium ESCAPE 19, June 14-17, 2009, Krakow, Poland 34, 700-706.

Stage-wise Wastewater Treatment Superstructure

Key:
Pretreatment;
Primary Treatment;
Secondary Treatment;
Tertiary Treatment;
Bypass



Superstructure Generated: P-Graph

What is a superstructure?

It is a systematic representation of all possible treatment technologies available in the 4 stages of wastewater treatment.

It also shows the flow from the initial wastewater stream towards the final purified water stream

FLC – Flocculation, SDM – Sedimentation, FTT – Filtration, ADS – Adsorption, RBC – Rotating Biological Containers, ASL – Activated Sludge, DIS – Disinfection, MBRT – Membrane Bioreactor, MBR – Membrane Processes, AOP – Advanced Oxidation Processes, BLC – Bleaching, BYP - Bypasses

Framework for Design & Evaluation

- Provide input wastewater composition and define output purity specifications
- Construct the wastewater treatment network design as an optimization model
  - ✓ Mass and energy balances
  - ✓ Investment and Operating Costs
  - ✓ Integer variables to select technologies by holding a (0,1) value
- Method: P-Graph Studio (Graph Theory based Process Synthesis);

  MILP (Mixed integer linear programming) solver

Case Study: Municipal Wastewater Treatment

Entering flowrate of wastewater in the treatment system: 100 m^3/hr

Operating days per year: 330

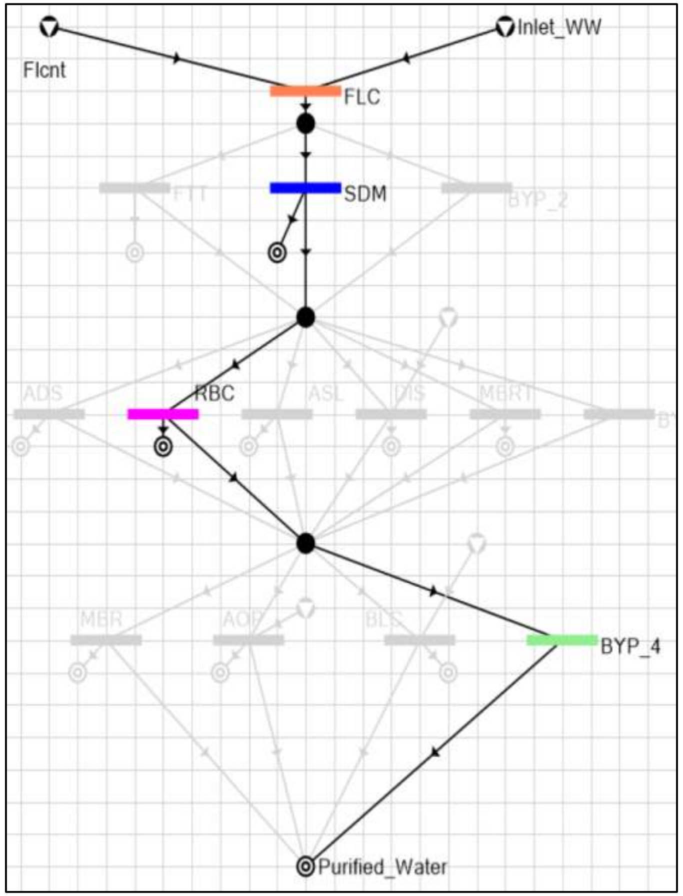
Wastewater contaminant concentrations and purity levels

Contaminant	Inlet Amount	Outlet Amount	Units
Acids/Chlorides	5000	300	mg/L
COD (Inorganic)	2000	70	mg/L
BOD (Organic)	1100	25	mg/L
Settable solids	200000	500	mg/L
Metals (Pb, Cu, Ni, Zn)	1340	5	µg/L

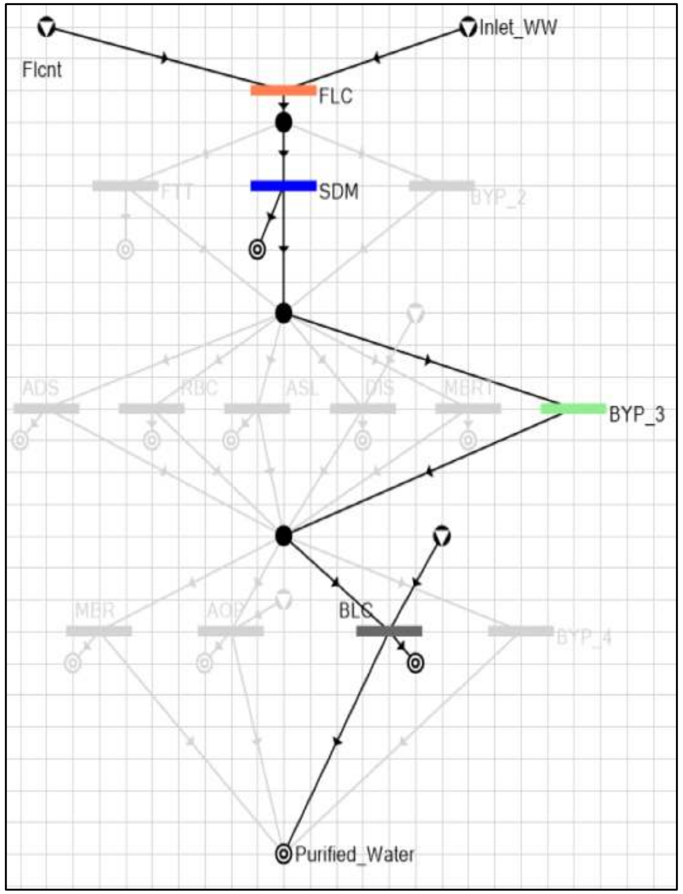
Source: Page et.al., 1996 "Use of Reclaimed Water and Sludge in Food Crop Production", The National Academy Press for publications in Sciences, Engineering and Medicine.

Solutions from P-Graph formulation

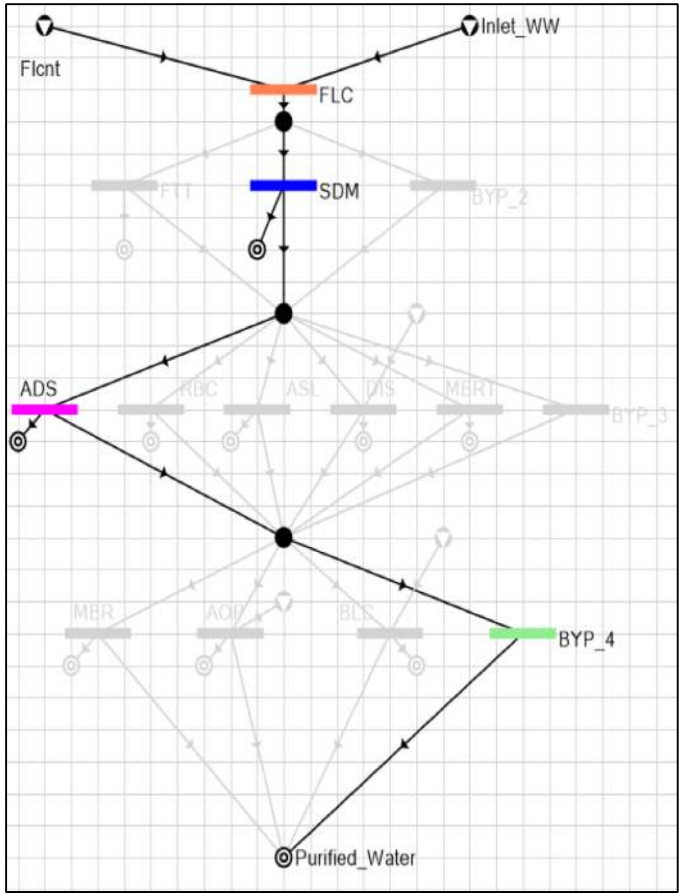
- ❖ The total best network solution generated using the P-Graph approach is 45 with a solution time of 0.035 seconds
- ❖ Costs: Fix and Proportional Investment Costs, Fix and Proportional Operating Costs



- Feasible Structure 1: (FLC-SDM-RBC)
- Purification Cost ($/yr.) : 3197040



- Feasible Structure 2: (FLC-SDM-BLC)
- Purification Cost ($/yr.) : 3256250



- Feasible Structure 3 (FLC-SDM-ADS)
- Purification Cost ($/yr.) : 3901470

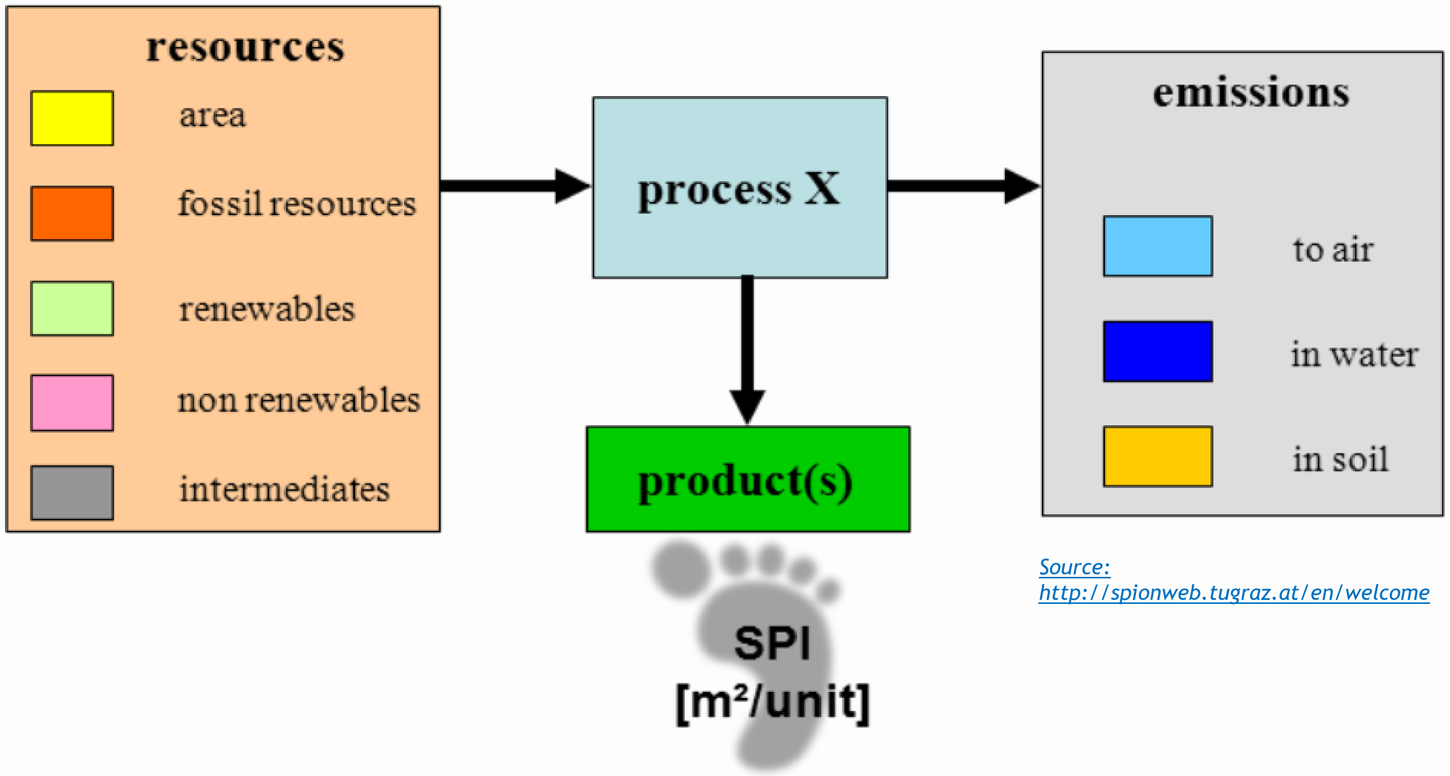
Solutions from P-Graph formulation

Summary of the first best 10 feasible network pathways

No	Network Path	Purification Cost, ($/yr)	Purification Cost/Liter of Purified Water($/L)
1	FLC-SDM-RBC	3197040	0.004249
2	FLC-SDM-BLC	3256250	0.004327
3	FLC-SDM-ADS	3901470	0.005185
4	FLC-FTT	4447680	0.005637
5	FLC-SDM-RBC-BLC	4507400	0.005990
6	FLC-SDM-AOP	4815100	0.006399
7	FLC-SDM-ADS-BLC	5343310	0.007101
8	FLC-FTT-RBC	5417120	0.007199
9	FLC-FTT-BLC	5482110	0.007286
10	FLC-SDM-RBC-AOP	6066250	0.008062

The Sustainable Process Index (SPI)

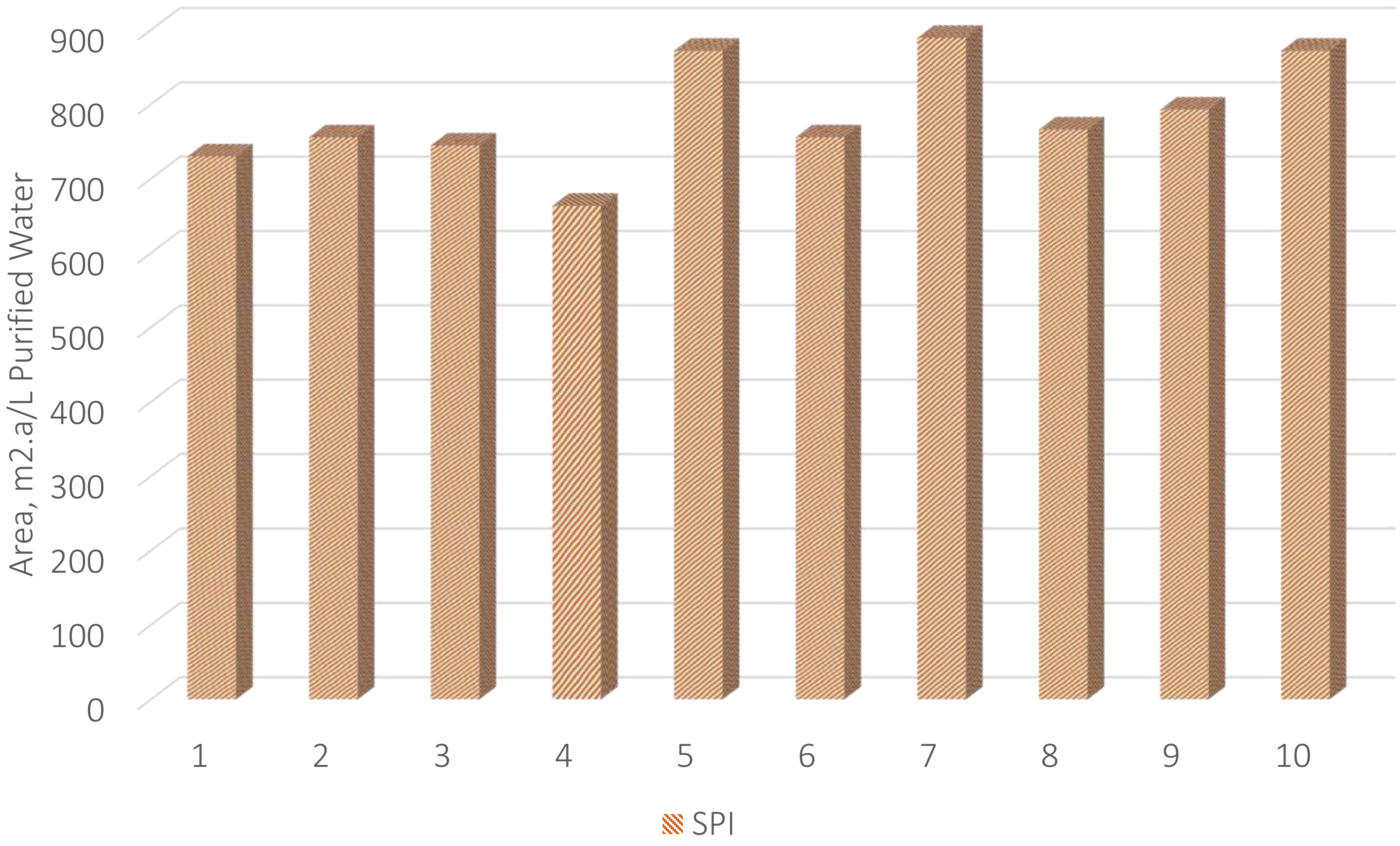
- Ecological Footprint
- Quantification of sustainability based on arable area needed to produce one unit of product
- The burden of a process on the ecosystem
- The higher the SPI, the less sustainable the process is



Source: http://spionweb.tugraz.at/en/welcome

Solutions from SPI

- FLC-SDM-RBC-AOP (7) has the highest SPI Value
- FLC-FTT (4) has the lowest SPI Value



Index	Network Path
1	FLC-SDM-RBC
2	FLC-SDM-BLC
3	FLC-SDM-ADS
4	FLC-FTT
5	FLC-SDM-RBC-BLC
6	FLC-SDM-AOP
7	FLC-SDM-ADS-BLC
8	FLC-FTT-RBC
9	FLC-FTT-BLC
10	FLC-SDM-RBC-AOP

Conclusions from P-Graph and SPI Analysis

- In terms of cost, network path (1) had the minimum, but network path (4) had had the lowest SPI value
- Even though network path (4) had the lowest SPI value, it was the only network path that could not meet purification requirements
- To make a decision, there should be trade-offs between cost and “greenness” of the process

Summary

- An integrated approach involving design and optimization for generation of cost-effective wastewater treatment networks
- P-Graph approach to wastewater treatment using a superstructure optimization (MINLP)
- Generated a rank of network synthesis for wastewater treatment based on purification cost
- Sustainable process index (SPI) evaluation of generated synthesis paths

Thank you for your attention!