Available Energy Assessment and Recovery in Water Distribution Systems

Ilker T. Telci
Graduate Student

MESL
February 7 2012

Problem Definition

- Given a water distribution system (WDS) under operation:
  - Evaluation of available excess energy and
  - Optimal design of an energy recovery system for WDSs.

Dover Township WDS, Toms River, NJ

Micro hydropower plants:

- Number
- Location
- Capacity
- Operation schedule

Constraints of a Water Distribution System

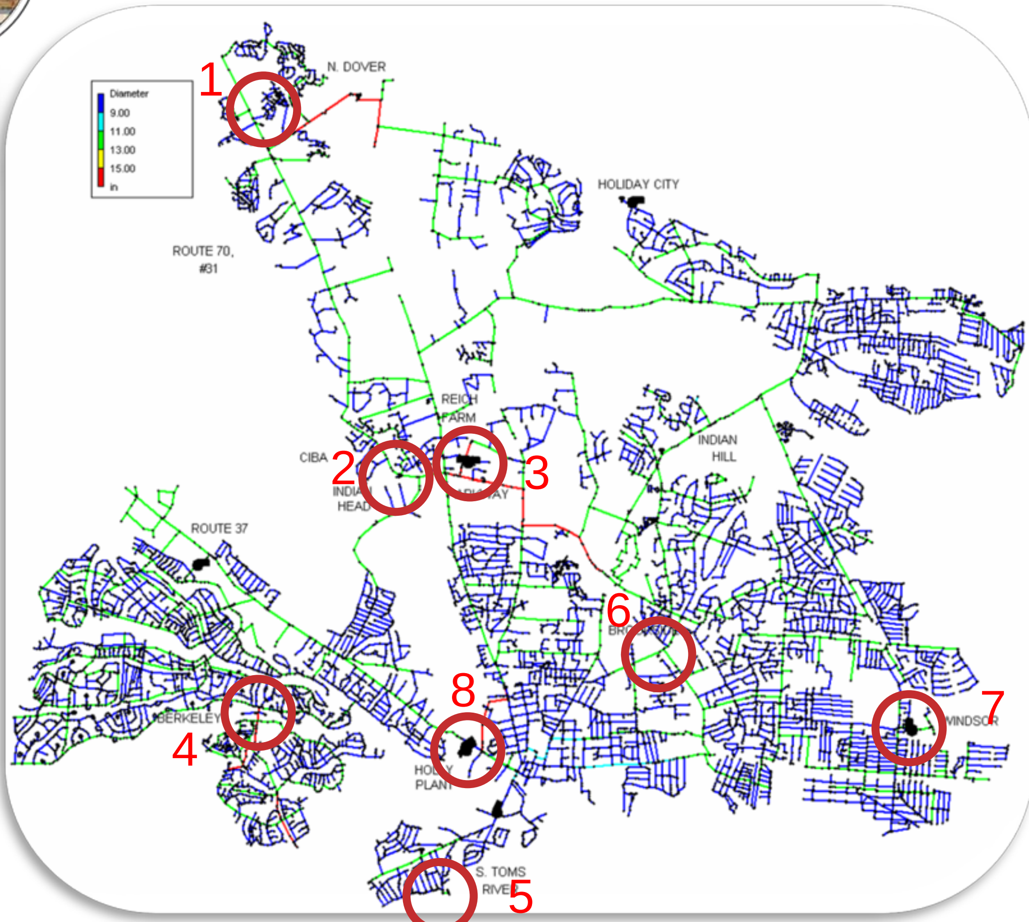
Dover Township WDS, Toms River, NJ

- Demand Flows
- Pressure Heads
  - Excess:

    Leakage and structural damage
  - Too low: Operational problems

Study Area

- 8 pumping locations
- No pressure reducing valves



Diameter (in)	Number of links
16	124
12	3434
10	52
8	6007
6	5361
4	510
2	560
Total	16048

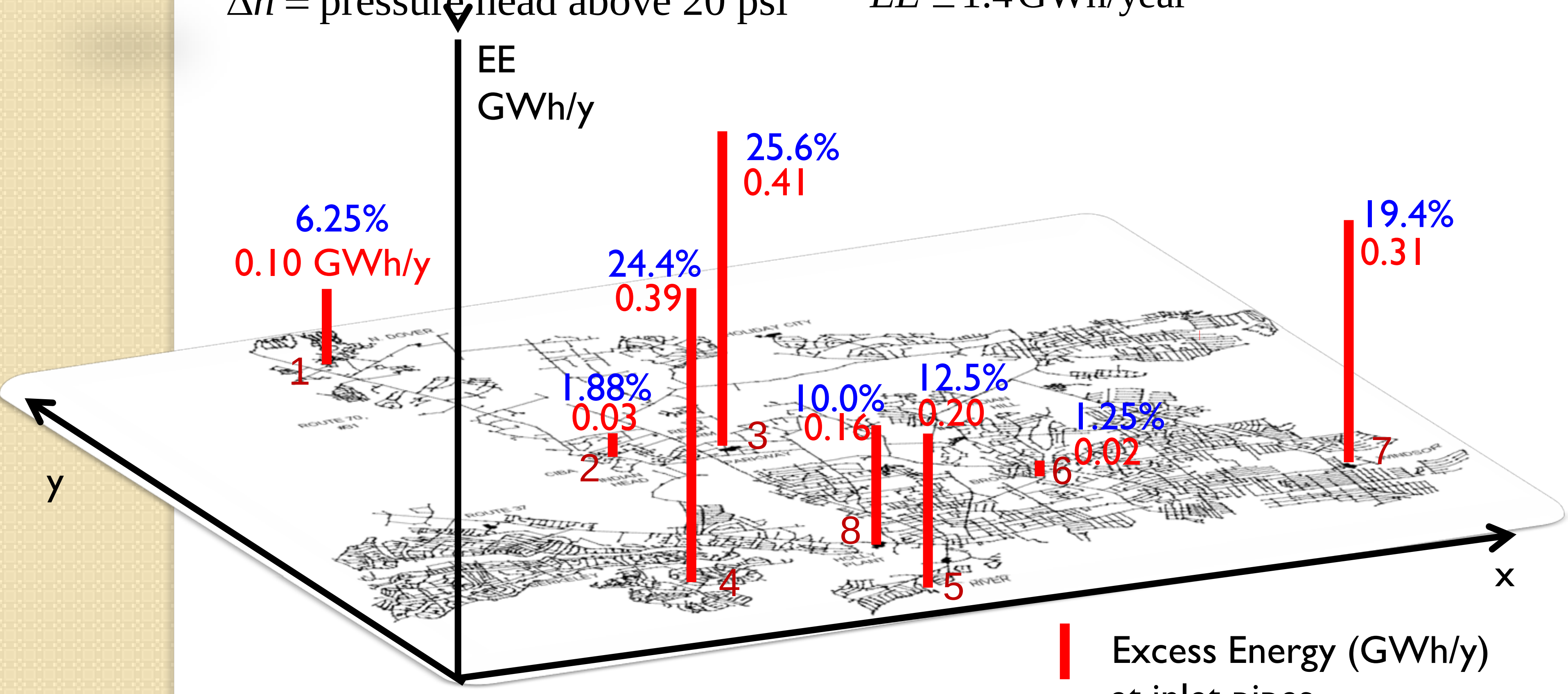
Dover Township WDS, Toms River, NJ

Available Excess Energy

$$\Delta E_i = \int \gamma q \Delta h dt = \gamma \sum_{t=1}^{t=T} q_t \Delta h_t \Delta t$$ excess energy at demand node i

$$EE = \sum_{i=1}^{N} \Delta E_i$$ total excess energy in the system in the period from $t = 1$ to $t = T$.

$\Delta h =$ pressure head above 20 psi $\qquad EE \cong 1.4\,\text{GWh/year}$

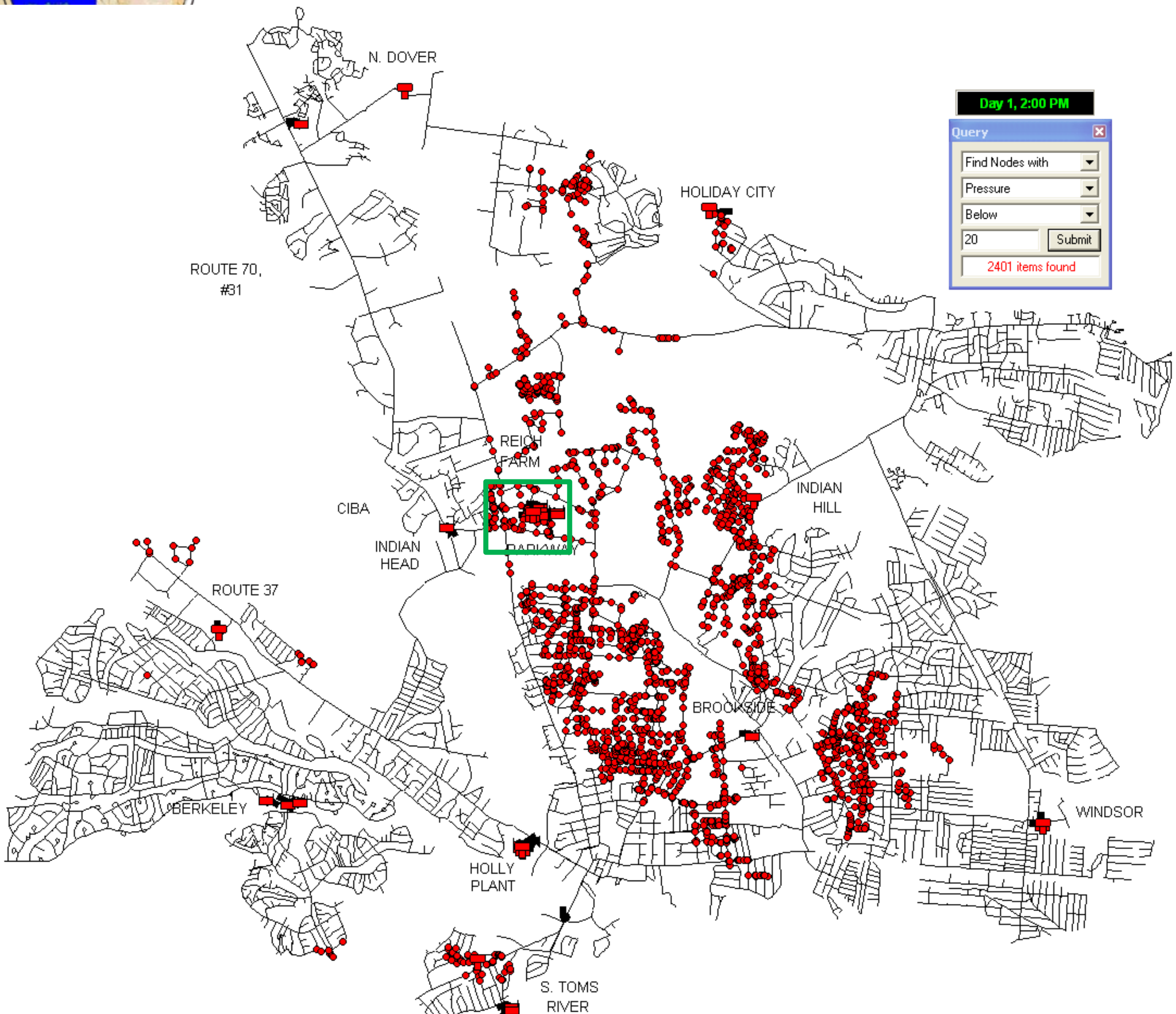


Results

Total excess energy input by the pumps = 1.6 GWh/y

Pressure Violations

- Turbine at location 3.
- Full operation.



-Simulation Time: 1Year

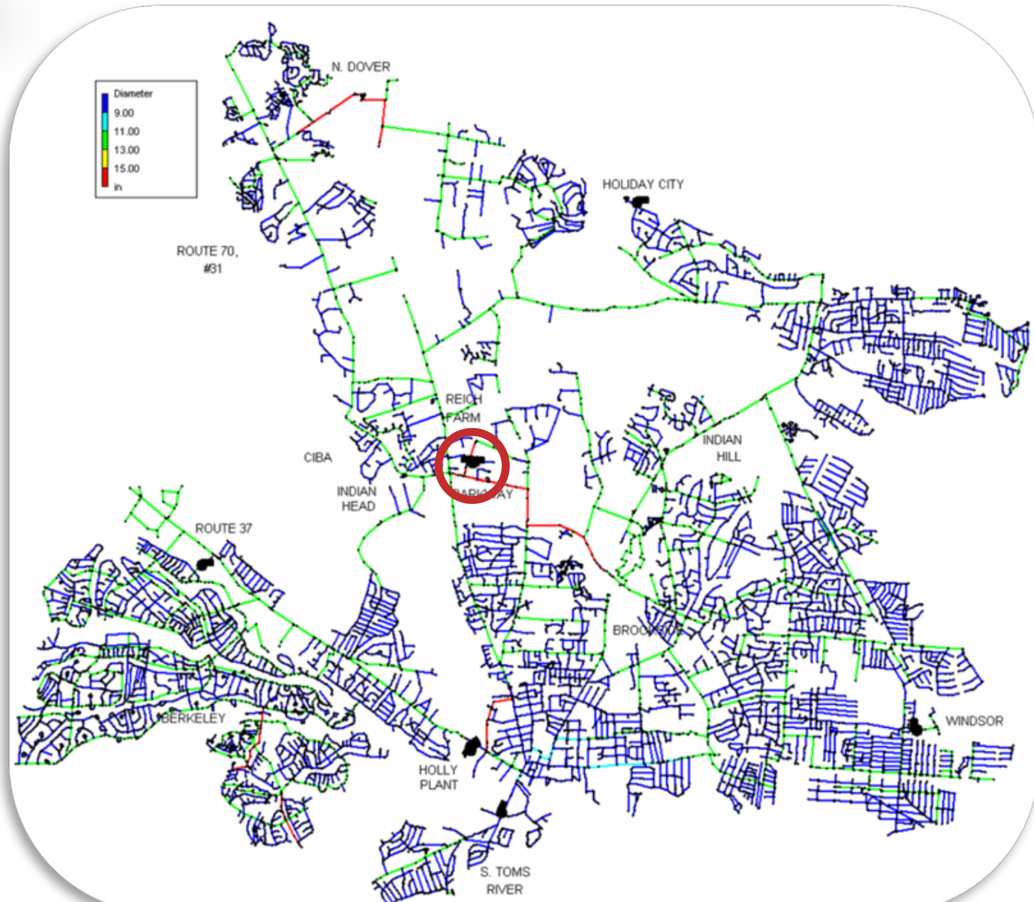
-One month is represented by 1 day of simulation.

- Time step=1hour

- Number of time steps 12x24=288

Turbine Operation Scheduling Problem

- A turbine is located at the pumping station 3.
  - Continuous operation causes pressure constraint violations.
- What is the optimal operation schedule for this turbine?



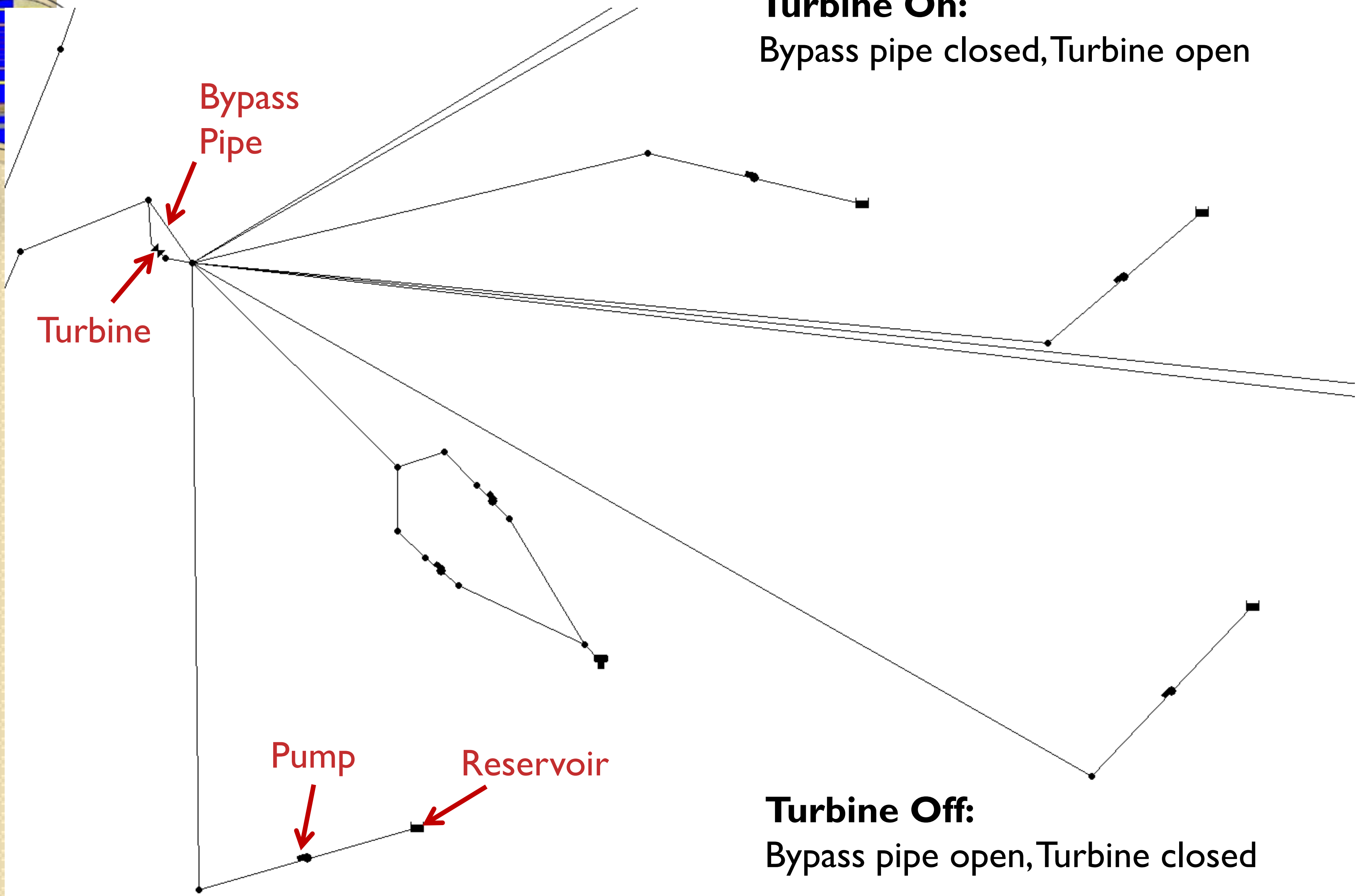
Optimization Problem:

Decision variable:
operation schedule

Objective:
Maximize the amount of energy recovered

such that
Minimum pressure in the network is above some limit.

Turbine Scheduling

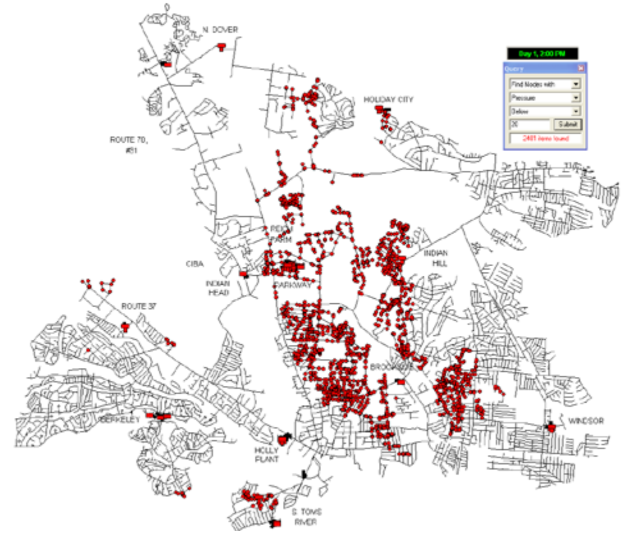


Turbine On:
Bypass pipe closed, Turbine open

Turbine Off:
Bypass pipe open, Turbine closed

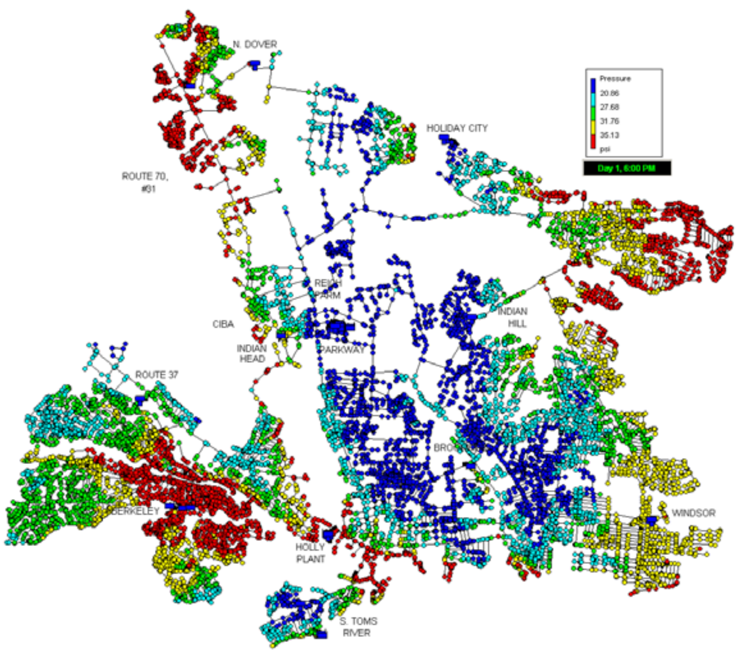
Turbine Operation Scheduling

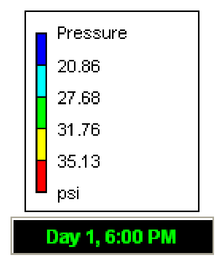
Trial and error example

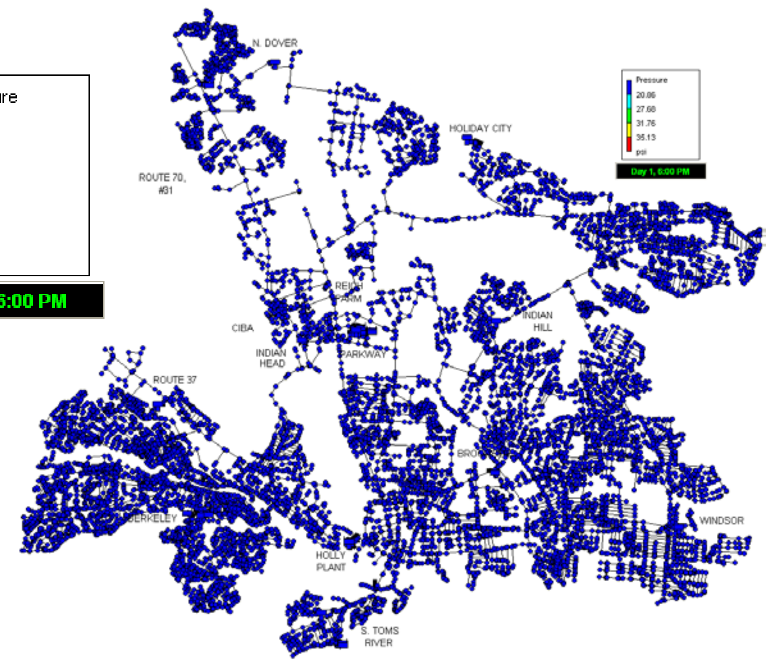


Pressure violations occur at t=14 hr.

Decision on the turbine at this time affects the pressure distributions at future times.







Pressure Distribution at t=18h when turbine was closed only at t=14h

Pressure Distribution t=18h for full turbine operation

Turbine Operation Scheduling Problem

Trial and error

- Turn off the turbine for the times when pressure constraint violations occur.
- Trial and error procedure did not work.
- The operational decision for a given time step affects the pressure distribution in the future time steps.
- Also trial and error procedure does not guarantee maximum energy recovery.
- Genetic algorithm is used to solve this optimization problem.

Turbine Operation Scheduling Problem

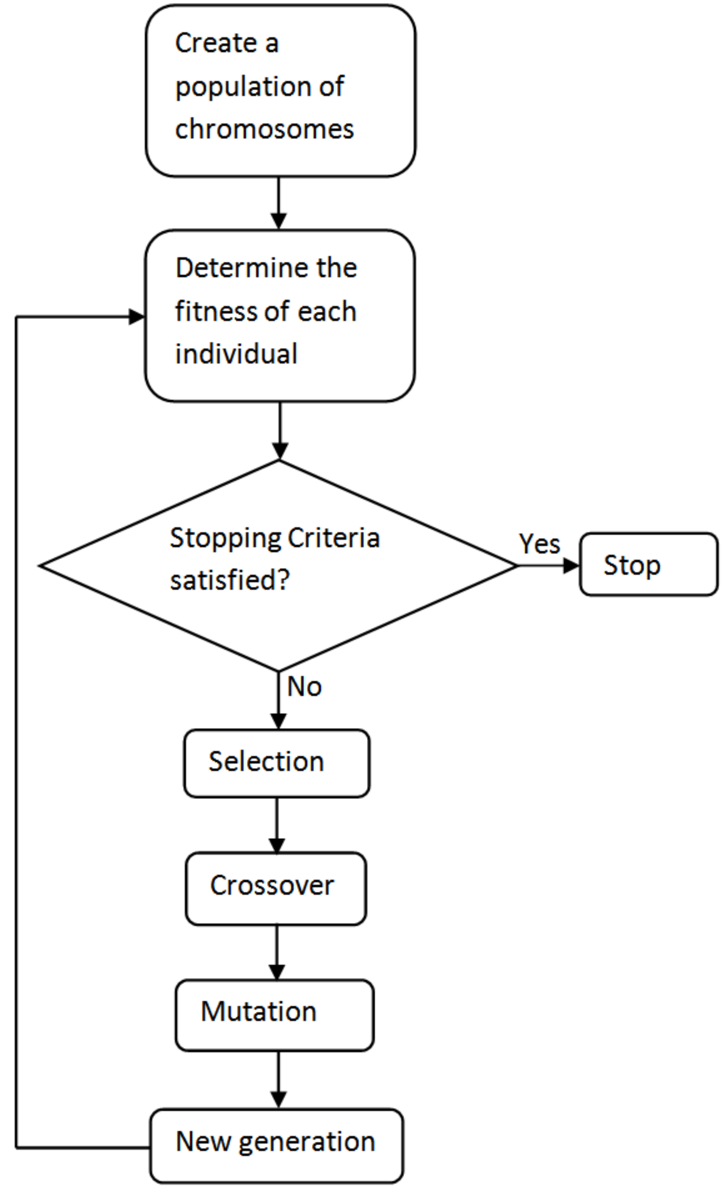
Genetic Algorithms

An individual's chromosome

(1: Turbine is on; 0: Turbine is off)

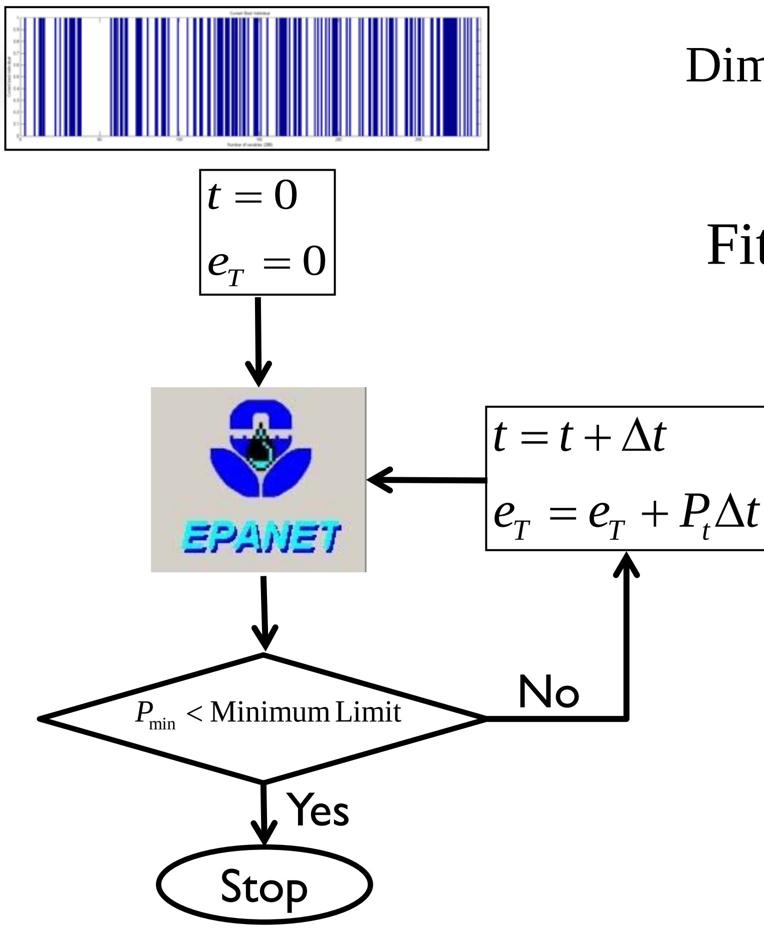
Population
Type: Integer
Size : 100-500

Stopping Criteria
Generations: 200
Consecutive Stall Generations: 40
Fitness Function Tolerance: 10^{-8}



Turbine Operation Scheduling Problem

Fitness Function



$$\text{Dimensionless Time, } T = \frac{t}{t_{sim}} = \frac{t}{288\,\text{h}}$$

$$\text{Dimensionless Energy, } E = \frac{e_T}{e_o} = \frac{e_T}{17633.52\ \text{kWh}}$$

$$\text{Fitness Value} = 1000(1 - T) - E$$

Minimize (Fitness Value):
Lower the fitness value, better the individual.

t : First pressure constraint violation time.

t_{sim}: Simulation time.

Δt: Time step.

P_t : Power generated by the turbine at time t.

e_T : Energy produced at the turbine.

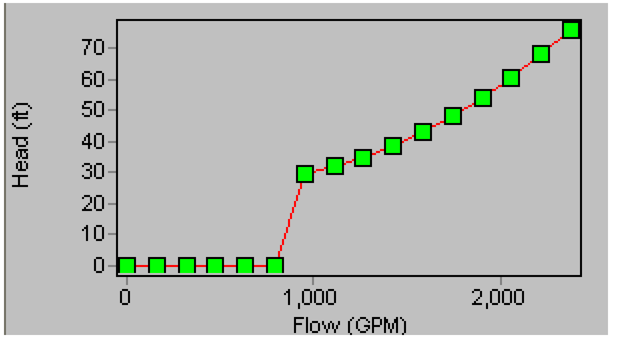
e_o : Energy of the flow passing through the turbine pipe without the turbine.

$$e_o = \int_0^{t_{sim}} \gamma Q H dt$$

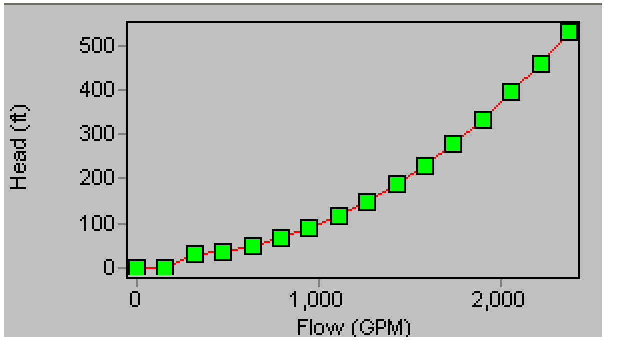
Turbine Operation Scheduling Problem

Parameters

Turbine 1: NC150200



Turbine 2: NC100200



Pressure Limits:

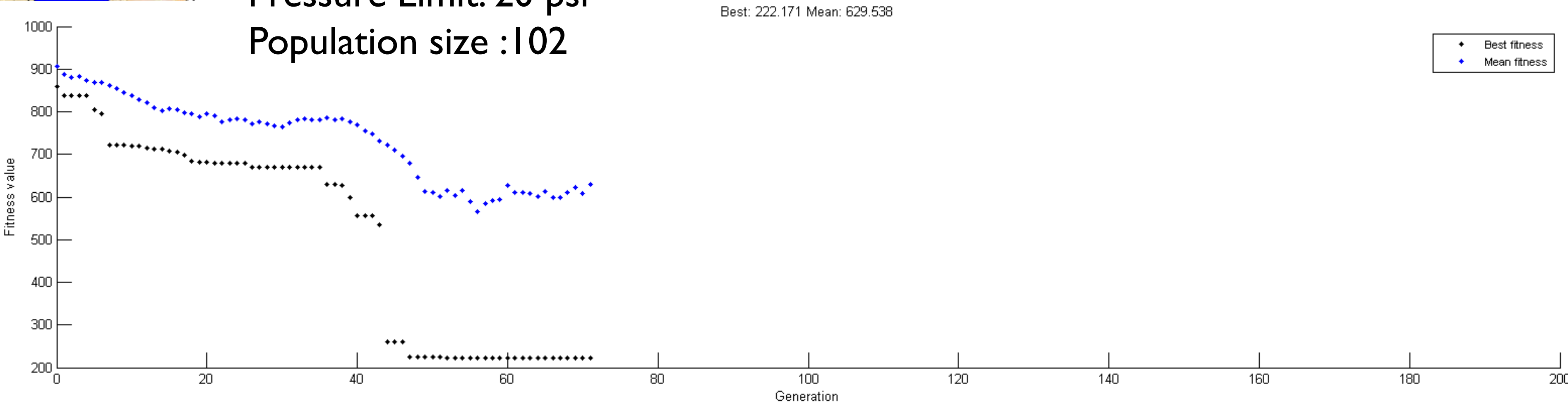
1) P_{min}=20 psi
2) P_{min}=15 psi

Population size:

Different population sizes are tried.

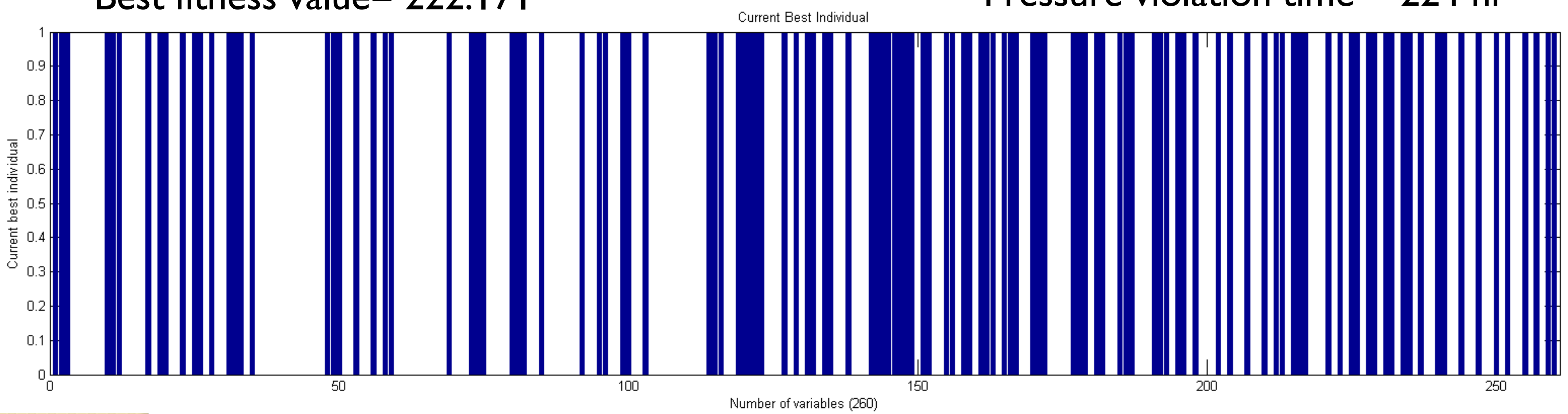
Turbine Operation Scheduling Problem
Discarded, non-feasible results

Turbine: NC100200
Pressure Limit: 20 psi
Population size :102



Best fitness value= 222.171

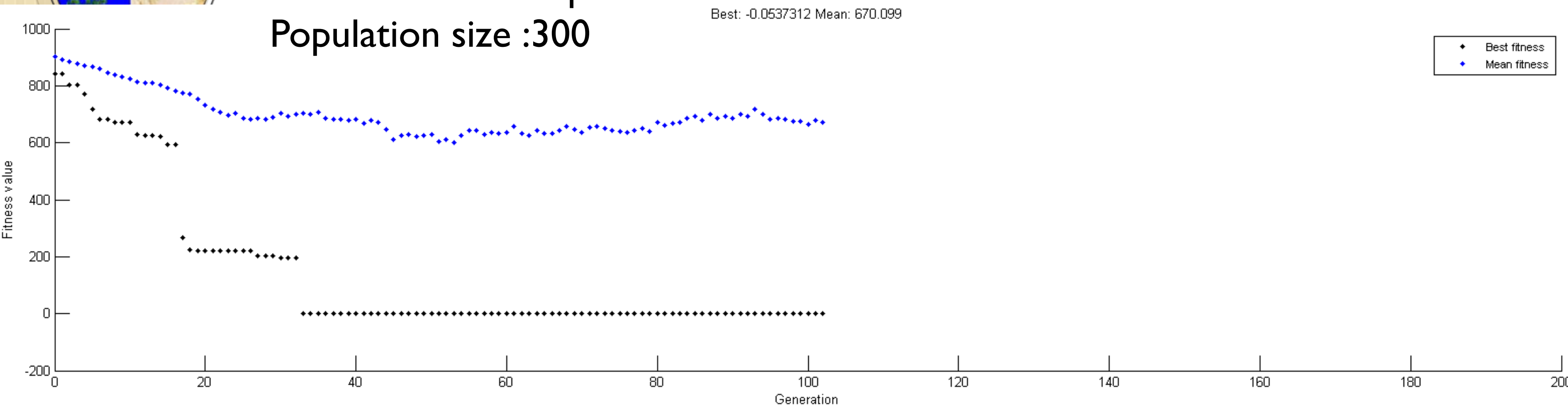
Pressure violation time = 224 hr



Turbine Operation Scheduling Problem

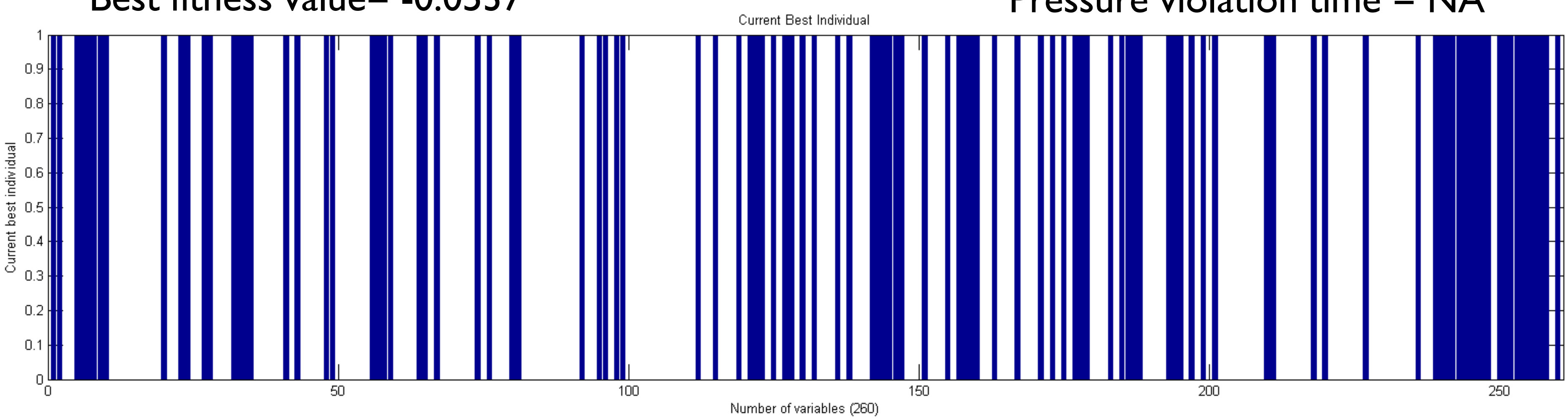
Feasible results

Turbine: NC100200
Pressure Limit: 20 psi
Population size :300



Best fitness value= -0.0537

Pressure violation time = NA



Turbine Operation Scheduling Problem

Results – Energy Budget for the System

Turbine	Pressure Limit	Population Size	Turb En. (kWh/y)	Pump En. Decrease * (kWh/y)	Net Energy Gain (kWh/y)	% Energy Production of the Turb.
NC150200	20	108	53368	54282	107650	49.6
		152	59464	74586	134050	44.4
	15	104	51882	124068	175950	29.5
		152	74028	118442	192470	38.5
NC100200	20	300	28424	136726	165150	17.2
	15	300	32331	148219	180550	17.9

*Energy used by the pumps without the turbine is 3,458,769 kWh/y

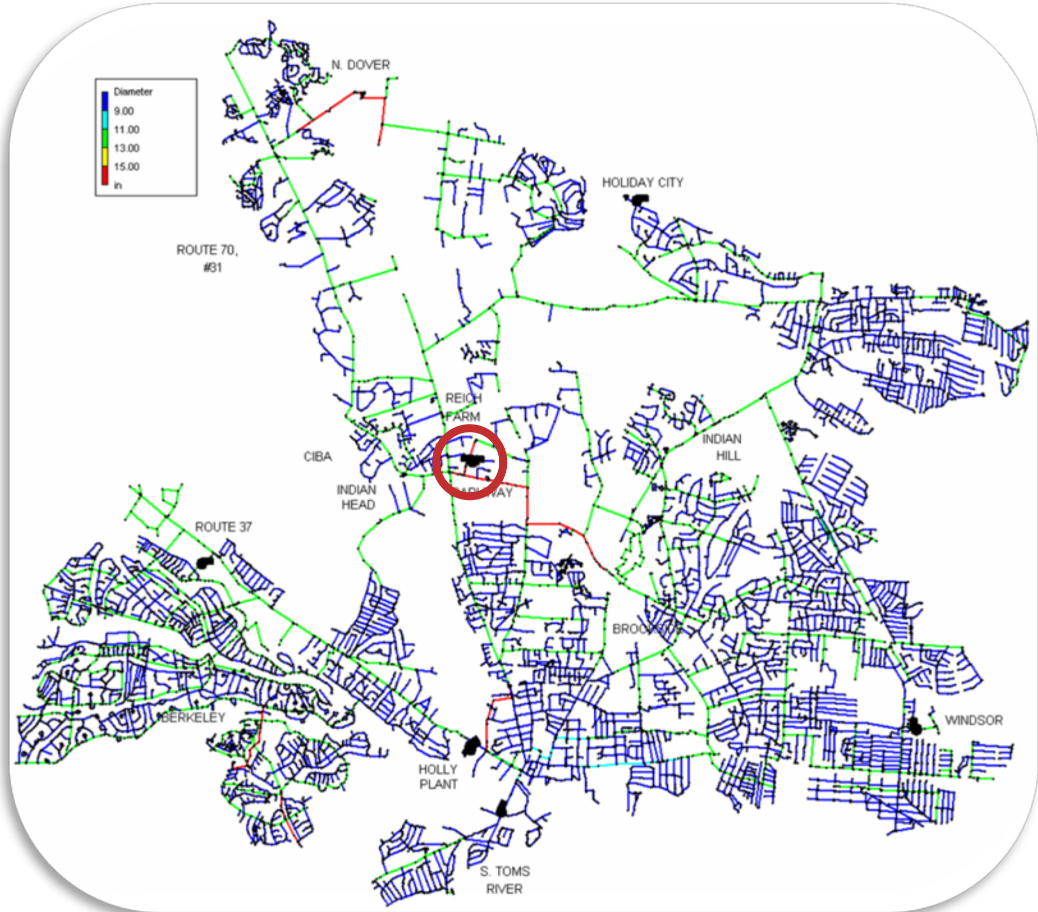
Turbine Operation Scheduling Problem

Results – Energy Budget for the Pumps

	Pump	Energy Consumed by the Pumps: No Turbine (kWh/y)	Energy Consumed by the Pumps: NC100200 Pmin=20 psi (kWh/y)	Difference: NoTurb-Turbine (kWh/y)
	20003	0	0	0
	20004	0	0	0
	20005	0	0	0
	20011	54235.35	56516.6	-2281.25
	20013	0	0	0
	20019	0	0	0
	20020	0	0	0
	20021	0	0	0
	20022	0	0	0
	20023	0	0	0
	20024	0	0	0
	20025	0	0	0
	PAI_1	328974.5	324952.2	4022.3
	PAI_2	64980.95	64313	667.95
Pumps Feeding the Turbine	PAI_3	90567.45	86574.35	3993.1
Pumps Feeding the Turbine	PAI_4	0	0	0
Pumps Feeding the Turbine	PAI_5	197180.3	137991.9	59188.4
Pumps Feeding the Turbine	PAI_6	374559.35	313279.5	61279.85
Pumps Feeding the Turbine	PAI_7	100692.55	94381.7	6310.85
Pumps Feeding the Turbine	PAI_8	0	0	0
Pumps Feeding the Turbine	PAI_9	117570.15	109802.95	7767.2
Pumps Feeding the Turbine	PAI_10	302643.4	237031	65612.4
	PAI_11	204133.55	204651.85	-518.3
	PAI_12	368368.95	364390.45	3978.5
	PAI_13	126990.8	129633.4	-2642.6
	PAI_14	14428.45	15216.85	-788.4
	PAI_15	315630.1	338183.45	-22553.35
	PAI_16	34419.5	38095.05	-3675.55
	PAI_17	505984.9	551591.65	-45606.75
	PAI_18	248083.2	247064.85	1018.35
	PAI_19	9223.55	9121.35	102.2
	PAI_20	0	0	0
	Total En. Consumed	3458667	3322792.1	135874.9

Increased energy consumption at the pump after turb.

Decreased energy consumption at the pump after turb..



Turbine Operation Scheduling Problem

Results – Order of magnitudes

Turbine	Pressure Limit	Population Size	Turb En. (kWh/y)	Pump En. Decrease * (kWh/y)	Net Energy Gain (kWh/y)	% Energy Production of the Turb.
NC150200	20	108	53368	54282	107650	49.6
		152	59464	74586	134050	44.4
	15	104	51882	124068	175950	29.5
		152	74028	118442	192470	38.5
NC100200	20	300	28424	136726	165150	17.2
	15	300	32331	148219	180550	17.9

*Energy used by the pumps without the turbine is 3,458,769 kWh/y

HDR feasibility study for Skagit county public utility district.

Table 1. Summary of Results of Feasibility Assessment

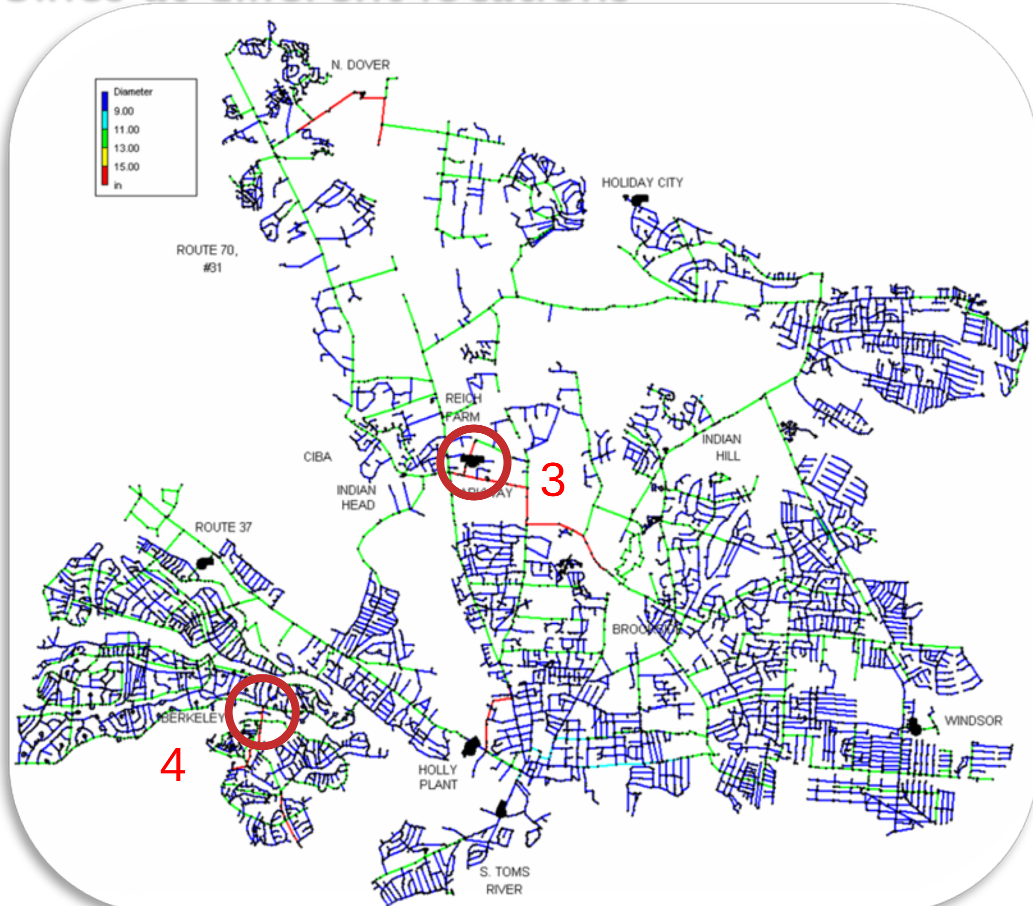
Development Option	Total Capacity	Plant Factor	Energy Production	Capitol Cost	Metering	Annual Revenue	Payback Period	Net Present Value
non-dim	kW	non-dim	kWh/yr	2011 $	non-dim	2013 $/year	years	2013 $
Judy Reservoir – Single-Unit Powerhouse	290	0.4	454,000	$1,363,000	Net Meter	$45,718	30	$1,688,981
Judy Reservoir – Single-Unit Powerhouse with Extended Tailrace	330	0.4	508,000	$1,702,000	Net Meter	$82,956	21	$3,891,131
Judy Reservoir – Two-Unit Powerhouse	670	0.3	754,000	$2,204,000	Net Meter	$75,928	29	$2,925,782
Judy Reservoir – Two-Unit Powerhouse with Extended Tailrace	750	0.3	833,000	2,585,000	Net Meter	$160,203	16	$8,226,272
9th and Highland PRV	30	0.75	197,000	$362,000	PPA	$19,183	19	$260,924
Rhodes Road PRV	50	0.63	278,000	$429,000	PPA	$27,070	16	$554,372

Giugni et. al. 2009

Scenario	PATs	Energy production [MWh/year]
A	3 NC 150-200	300,1
B	1 NC 150-200	153,0
	1 NC 100-200	
D	3 NC 150-200	284,4
	1 NC 100-200	

Turbine Operation Scheduling Problem

Two turbines at different locations



Turbine at location 4

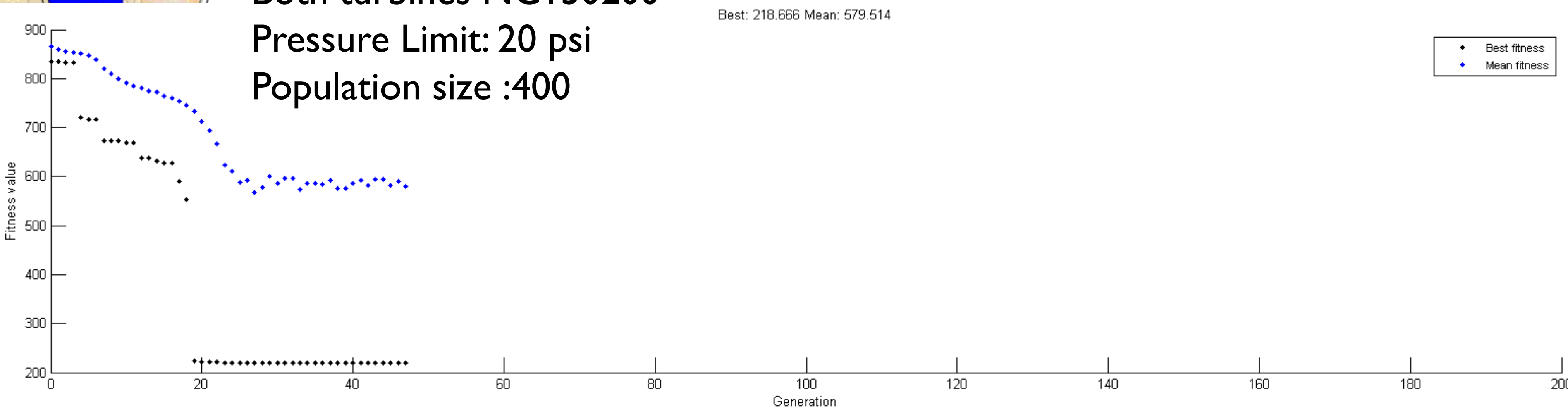
Turbine at location 3

Chromosome length= 2x288=576

Turbine Operation Scheduling Problem

Two turbines at different locations – Results (No feasible solutions yet)

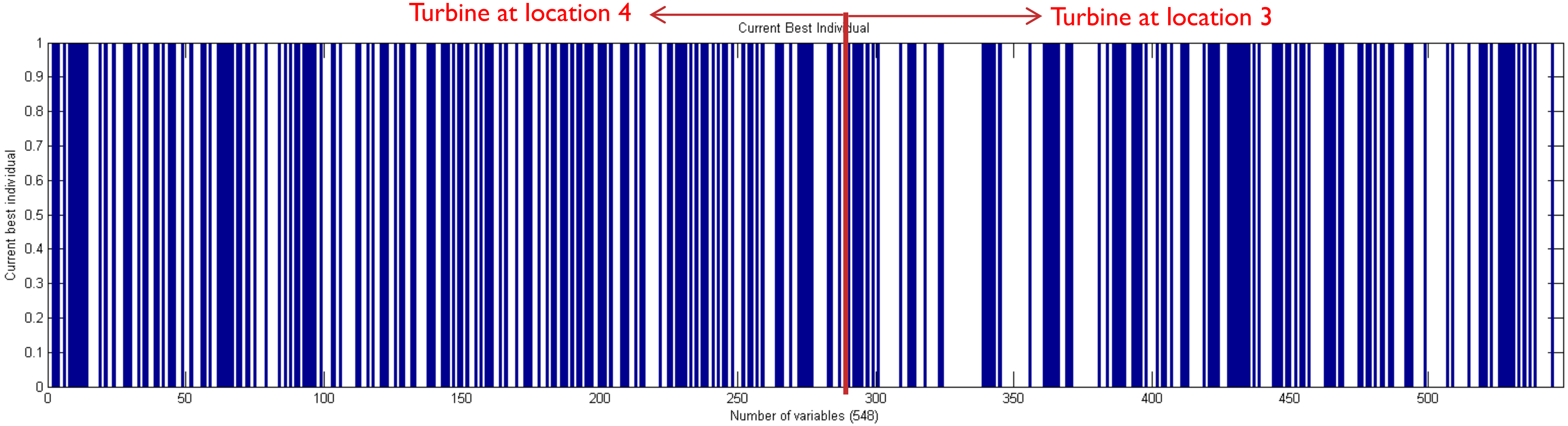
Both turbines NC150200
Pressure Limit: 20 psi
Population size :400



Best fitness value= 218.667

Pressure violation time = 225 hrs

Turbine at location 4 ⟷ Turbine at location 3



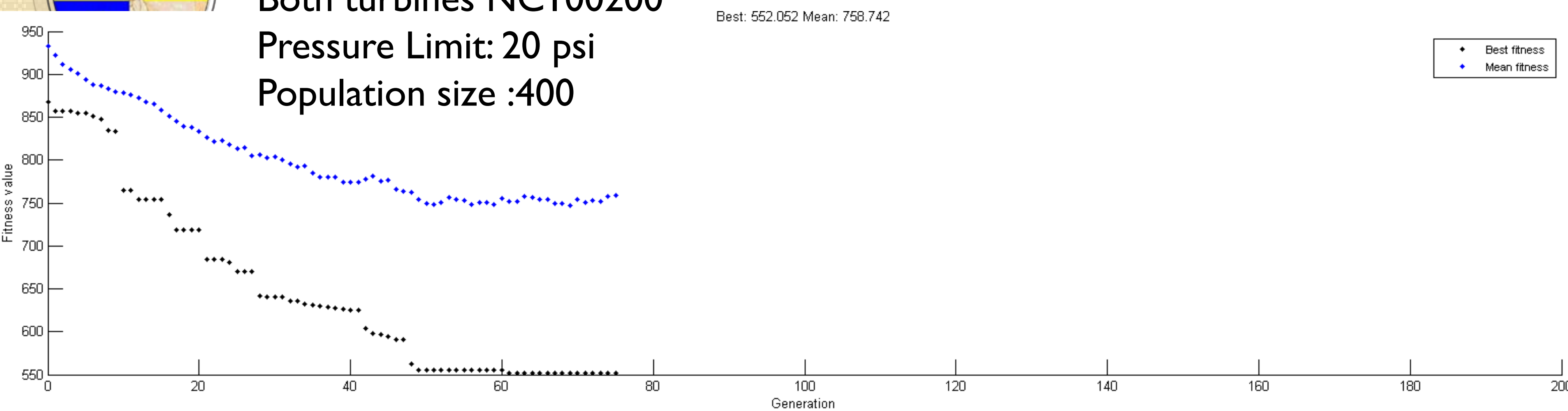
Turbine Operation Scheduling Problem

Two turbines at different locations – Results (No feasible solutions yet)

Both turbines NC100200

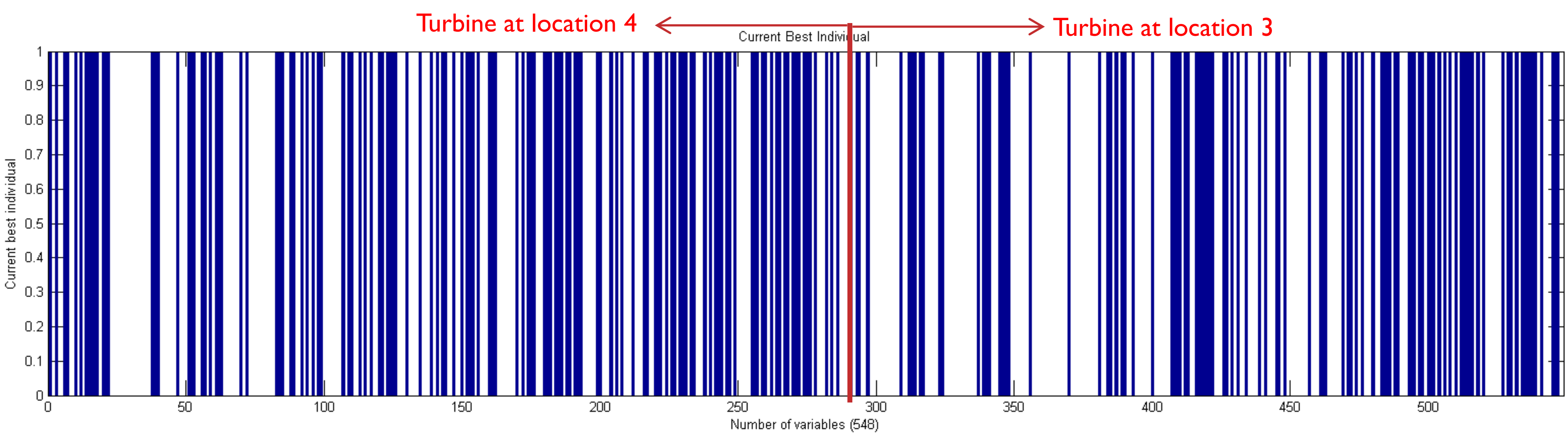
Pressure Limit: 20 psi

Population size :400



Best fitness value= 552.052

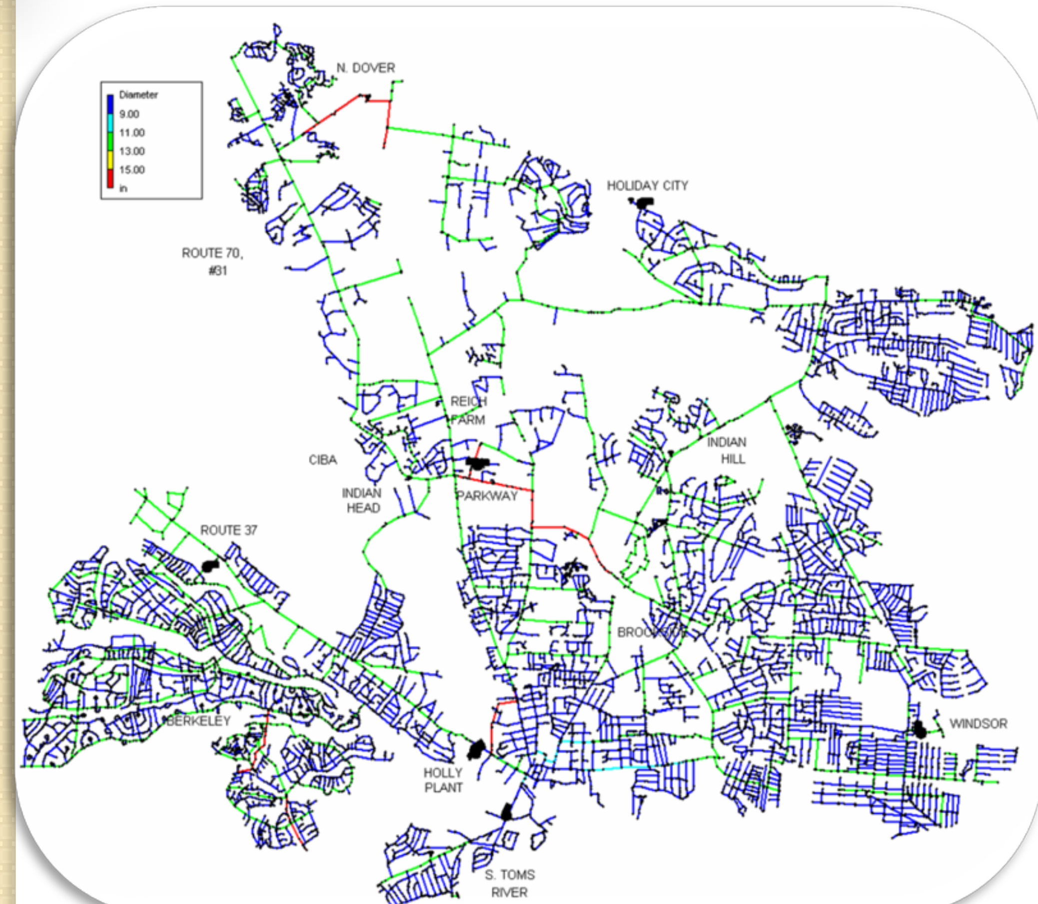
Pressure violation time = 129 hrs



Fitness function based on pressure

$$\text{Pressure Violation Magnitude, } P_v = \sum_{j=1}^{N_t} \sum_{i=1}^{N_n} \left[\min\left(0, P_{\min} - P_{i,j}\right) \right]^2$$

$$\text{Fitness Value} = 1000 P_v - e_T$$



i : Node index.

j : Time index.

N_t : Number of time steps

N_n : Number of nodes

$p_{i,j}$: pressure at i^{th} node at time j.

$p_{\min}$: Minimum pressure constraint.

e_T : Energy produced at the turbine.

- This search was started approximately 1 month ago.
- This fitness function has not produced a best solution yet.

Next Steps

- Appropriate population size for 2-turbine cases is being analyzed.
- Preliminary results show that 3-turbine case will be computationally expensive.
- The network has been converted into a gravity driven system and similar analysis will be performed on this new network.

Thank you…