LP Optimization: Industrial Cogeneration Operation

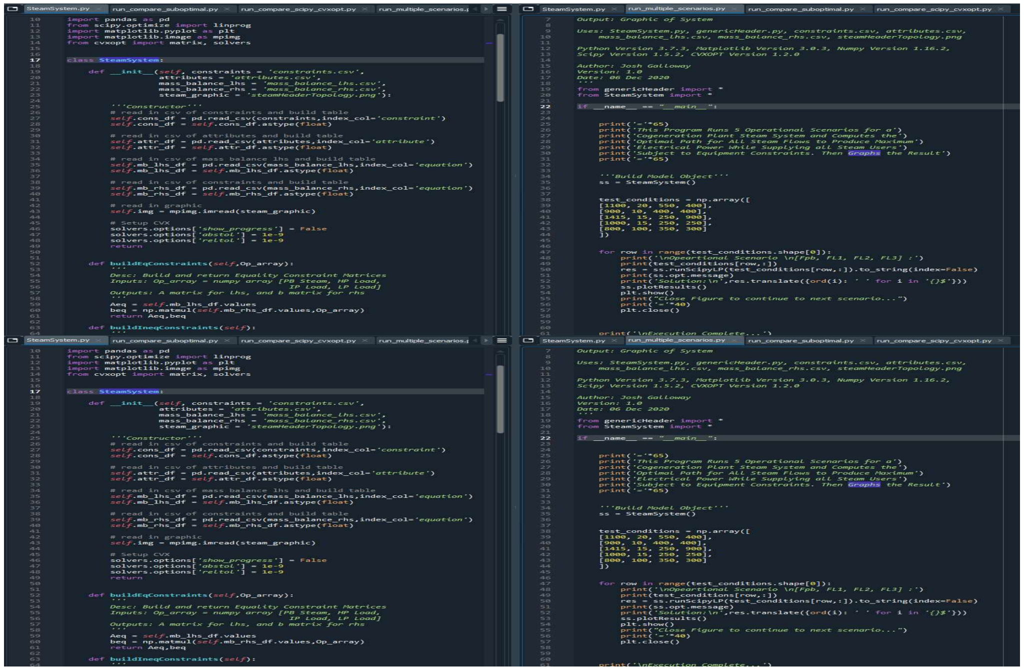
MATH 7205-Fall 2020

Joshua Galloway

Northeastern University

Presentation Outline

1. **Introduction**
   - Cogeneration Plant Operation Overview
2. **Problem Statement**
   - Fitting to Constrained Optimization Paradigm
3. **Process Model and Constraints**
   - Process Model
   - Process Constraints via Mass Balances and Equipment Limits
   - Objective Function via Energy Balance
   - Canonical Form
4. **Results**
   - LP Optimization
   - Solution Slightly Off LP Optimization Solution
5. **Conclusion**



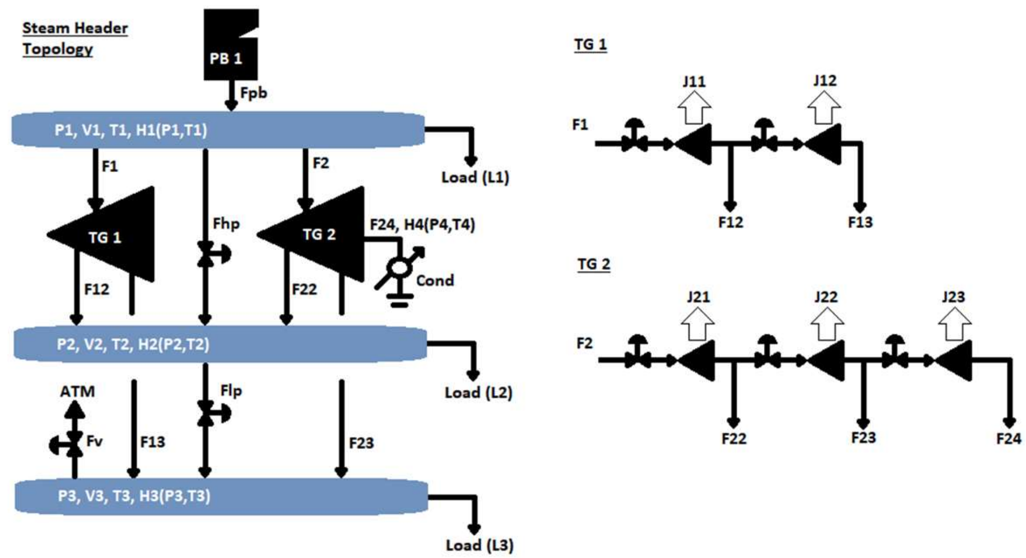
Introduction

Cogeneration Plant:

- Also called Combined Heat and Power (CHP)
- Produce Superheated Steam of Varying Pressures to Supply Industrial and Other Processes
- Steam is Produced By Large Industrial Boilers from Combustion of Fuels
    - Biomass (Saw Dust, Bark, Corn Cobbs, Peanut Shells….)
    - Fossil Fuels (Natural Gas, Fuel Oils, Coal)
- Steam is Generated at Higher than Required Pressure and Then Stepped-Down Through A Steam Turbine Generator to Produce Electrical Power

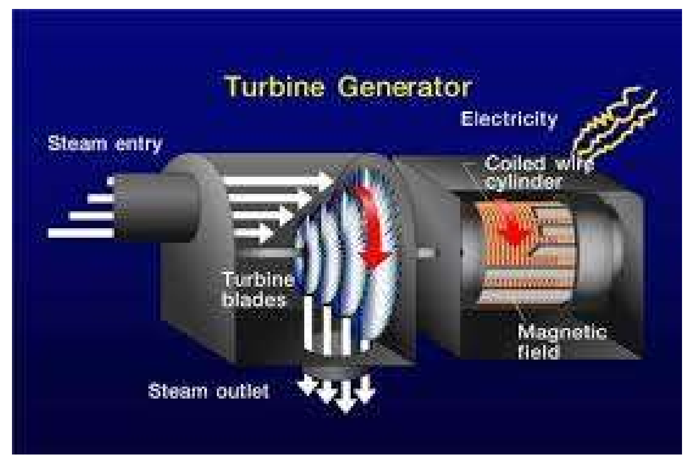
Kendall Square Cogeneration Station

Introduction



Header System:

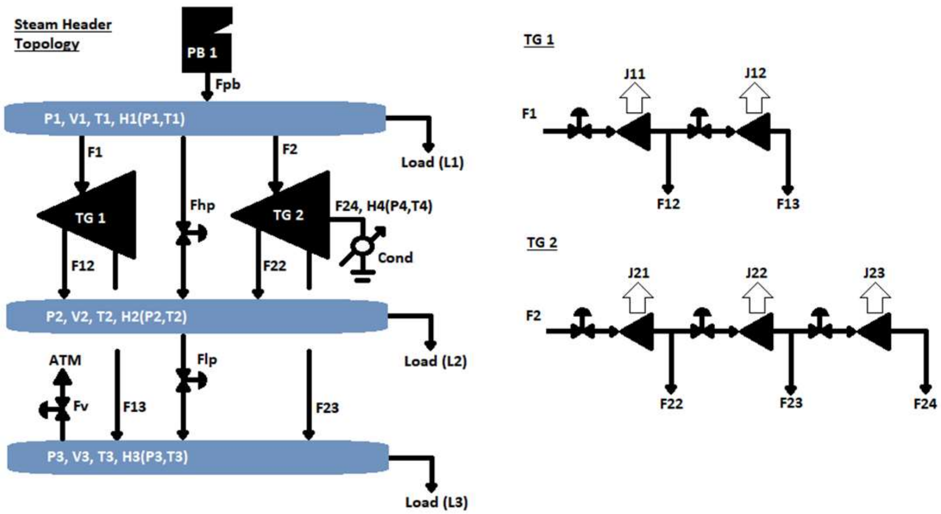
- Equipment
  - Distribution Headers
  - Industrial Boiler (Steam Producer)
  - Turbine Generators
  - Condenser
  - Pressure Reducing Valves
  - Steam Vent Valve
- Superheated Steam Enters Turbine and Is Run Across Fins to Rotate a Coil of Wire In a Magnetic Field Producing Current
- TG1 has 2 Sets of Fins (called generating sections)
- TG2 has 3 Sets and a Condenser



Problem Statement

<u>Physical System Requirements and Optimization:</u>

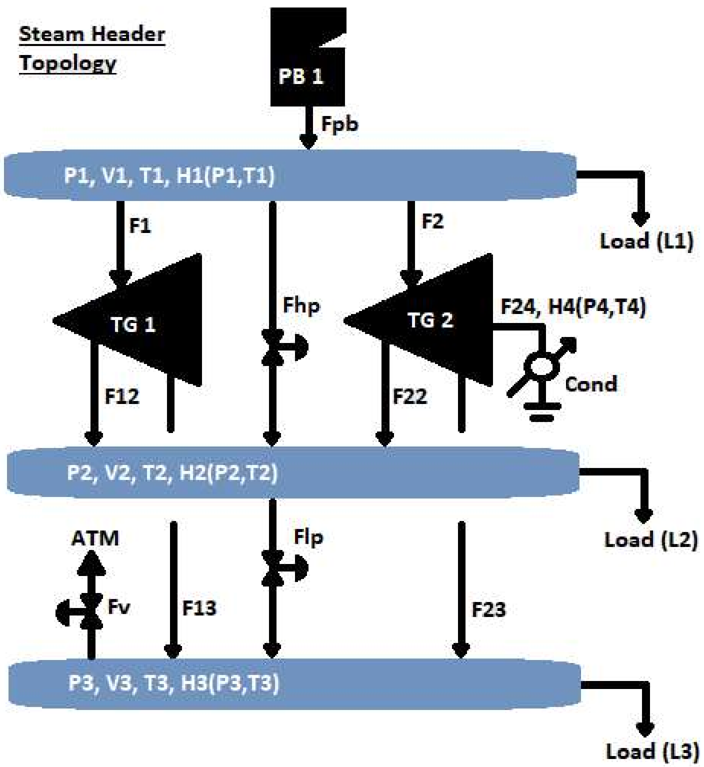
- Mass Balance
  - Steam Flows at All Nodes (Headers and Forks in Path) Must Sum to Zero
- Energy Balance
  - Energy (Enthalpy Flows) must Sum to Zero at all Nodes
- Process Requirements
  - Steam Users Must Receive Required Steam
  - Equipment Design Limits Must be Obeyed or the Equipment will Fail
- Optimization:
  - Choose the Best Path for Steam to Supply all Users and Obey Equipment Limits While Producing the Most Electricity Possible

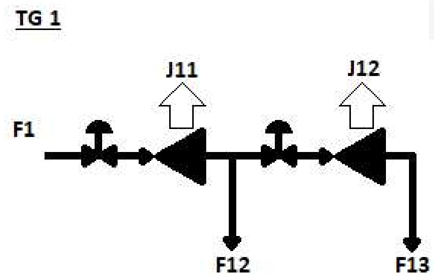


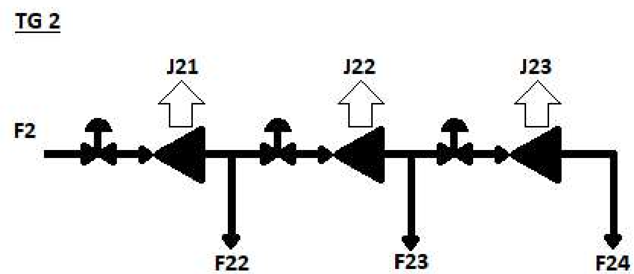
Steam Pipe Failure, New York; Hydroelectric Turbine Failure, Russia

Process Model and Constraints

Steam System Overview







constraint	F_{HP}	F_{LP}	F_1	F_{12}	F_{13}	F_2	F_{22}	F_{23}	F_{24}	F_V
Min	0.0	0.0	50.0	0.0	50.0	50.0	0.0	0.0	50.0	0.0
Max	400.0	400.0	500.0	450.0	500.0	500.0	200.0	350.0	150.0	500.0

attribute	HP Header	IP Header	LP Header	Condenser
PSIG	850.0	170.0	50.0	-13.5
deg F	825.0	440.0	300.0	110.0
BTU/LB	1410.0	1237.0	1180.0	1109.0

F_{PB}, F_{HP}, F_{LP} = Power Boiler, HP Pressure Reducing Valve (PRV), & LP PRV Mass Flows $[kpph]$

F_1, F_{12}, F_{13} = TG1 Steam Mass Flows $[kpph]$

$F_2, F_{22}, F_{23}, F_{24}$ = TG2 Steam Mass Flows $[kpph]$

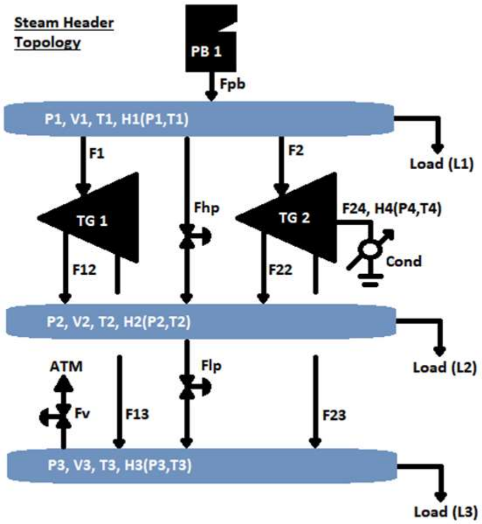
P_i = Steam Pressures $[psig]$

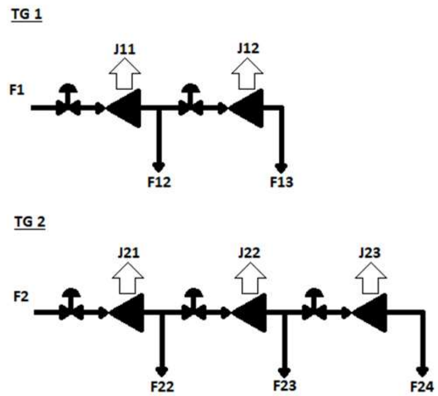
T_i = Steam Temperatures $[^oF]$

H_i = Steam Specific Enthalpies $[btu/lb]$

J_{ik} = Generator Section Electricity Productions $[MW]$

Process Model and Constraints





Mass Balances / Equality Constraints

$$F_{PB} - F_1 - F_2 - F_{HP} - F_{L1} = 0 \qquad \text{(HP)}$$

$$F_{12} + F_{22} + F_{HP} - F_{LP} - F_{L2} = 0 \qquad \text{(IP)}$$

$$F_{13} + F_{23} + F_{LP} - F_V - F_{L3} = 0 \qquad \text{(LP)}$$

$$F_1 - F_{12} - F_{13} = 0 \qquad \text{(TG1)}$$

$$F_2 - F_{22} - F_{23} - F_{24} = 0 \qquad \text{(TG2)}$$

Consider $F_{PB}, F_{L1}, F_{L2}, F_{L3}$ as constants for a given operational scenario, then:

$$\begin{bmatrix} -1 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 & -1 & 0 \end{bmatrix} \begin{bmatrix} F_{HP} \\ F_{LP} \\ F_1 \\ F_{12} \\ F_{13} \\ F_2 \\ F_{22} \\ F_{23} \\ F_{24} \\ F_V \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} F_{PB} \\ F_{L1} \\ F_{L2} \\ F_{L3} \end{bmatrix}$$

Equipment Limits/Inequality Constraints

$$-F_{HP} \le -F_{HP,min} \qquad (F_{HP}\ \text{min})$$
$$F_{HP} \le F_{HP,max} \qquad (F_{HP}\ \text{max})$$

$$-F_{LP} \le -F_{LP,min} \qquad (F_{HP}\ \text{min})$$
$$F_{LP} \le F_{LP,max} \qquad (F_{LP}\ \text{max})$$

$$-F_1 \le -F_{1,min} \qquad (F_1\ \text{min})$$
$$F_1 \le F_{1,max} \qquad (F_1\ \text{max})$$

$$-F_{12} \le -F_{12,min} \qquad (F_{12}\ \text{min})$$
$$F_{12} \le F_{12,max} \qquad (F_{12}\ \text{max})$$

$$-F_{13} \le -F_{13,min} \qquad (F_{13}\ \text{min})$$
$$F_{13} \le F_{13,max} \qquad (F_{13}\ \text{max})$$

$$-F_2 \le -F_{2,min} \qquad (F_2\ \text{min})$$
$$F_2 \le F_{2,max} \qquad (F_2\ \text{max})$$

$$-F_{22} \le -F_{22,min} \qquad (F_{22}\ \text{min})$$
$$F_{22} \le F_{22,max} \qquad (F_{22}\ \text{max})$$

$$-F_{23} \le -F_{23,min} \qquad (F_{23}\ \text{min})$$
$$F_{23} \le F_{23,max} \qquad (F_{23}\ \text{max})$$

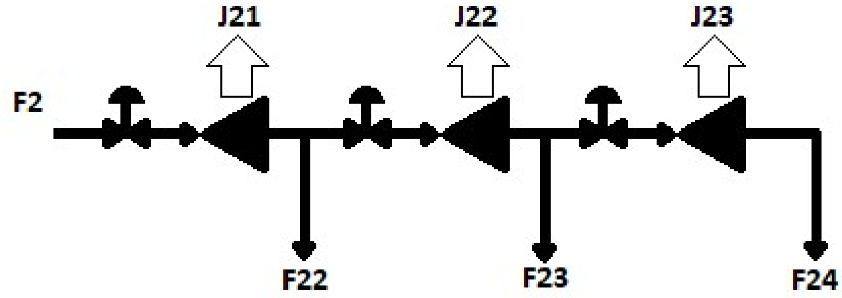
$$-F_{24} \le -F_{24,min} \qquad (F_{24}\ \text{min})$$
$$F_{24} \le F_{24,max} \qquad (F_{24}\ \text{max})$$

$$-F_V \le -F_{V,min} \qquad (F_V\ \text{min})$$
$$F_V \le F_{V,max} \qquad (F_V\ \text{max})$$

Process Model and Constraints

Energy Balance for Objective Function

TG 2



Electrical Production/Objective Function

$$J_{11} = F_1(H_1 - H_2)$$

$$J_{12} = F_{13}(H_2 - H_3)$$

$$J_{21} = F_2(H_1 - H_2)$$

$$J_{22} = (F_2 - F_{22})(H_2 - H_3)$$

$$J_{23} = F_{24}(H_3 - H_4)$$

Maximize

$$J = \begin{bmatrix} 0, & 0, & (H_1 - H_2), & 0, & (H_2 - H_3), & (H_1 - H_3), & (H_3 - H_2), & 0, & (H_3 - H_4), & 0 \end{bmatrix} \begin{bmatrix} F_{HP} \\ F_{LP} \\ F_1 \\ F_{12} \\ F_{13} \\ F_2 \\ F_{22} \\ F_{23} \\ F_{24} \\ F_V \end{bmatrix}$$

So the Problem Statement in Canonical Form is:

Minimize

$$-J = -\sum_i \sum_k J_{i,k}$$

Subject To

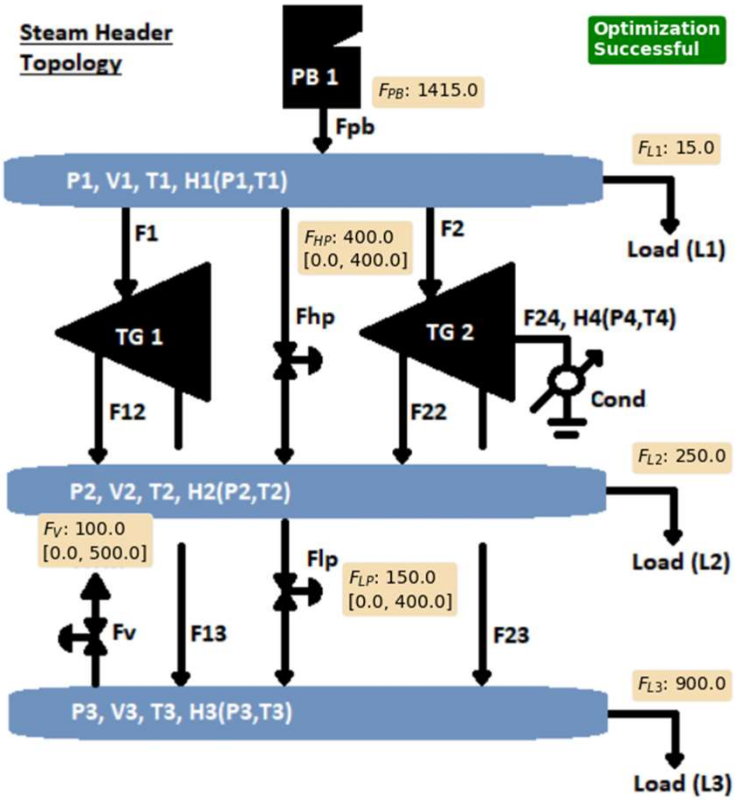
Mass Balances / Equality Constraints

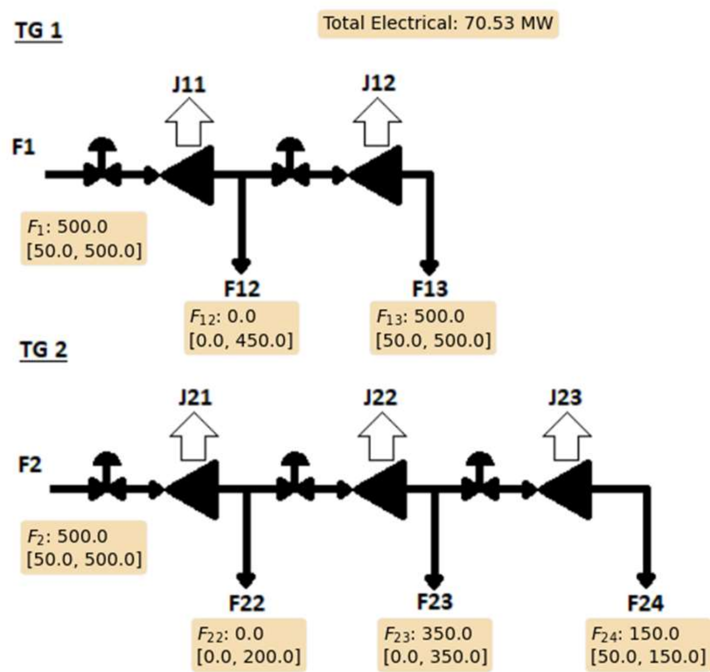
Equipment Limits/Inequality Constraints

Results

LP Solution:

- J23 is Most Efficient so TG's are Loaded to Send Max Steam Through to Condenser
- An Overall Excess of Steam is Produced, So Vent is Open
- Low Press Extraction is at Max so F_LP PRV is Open

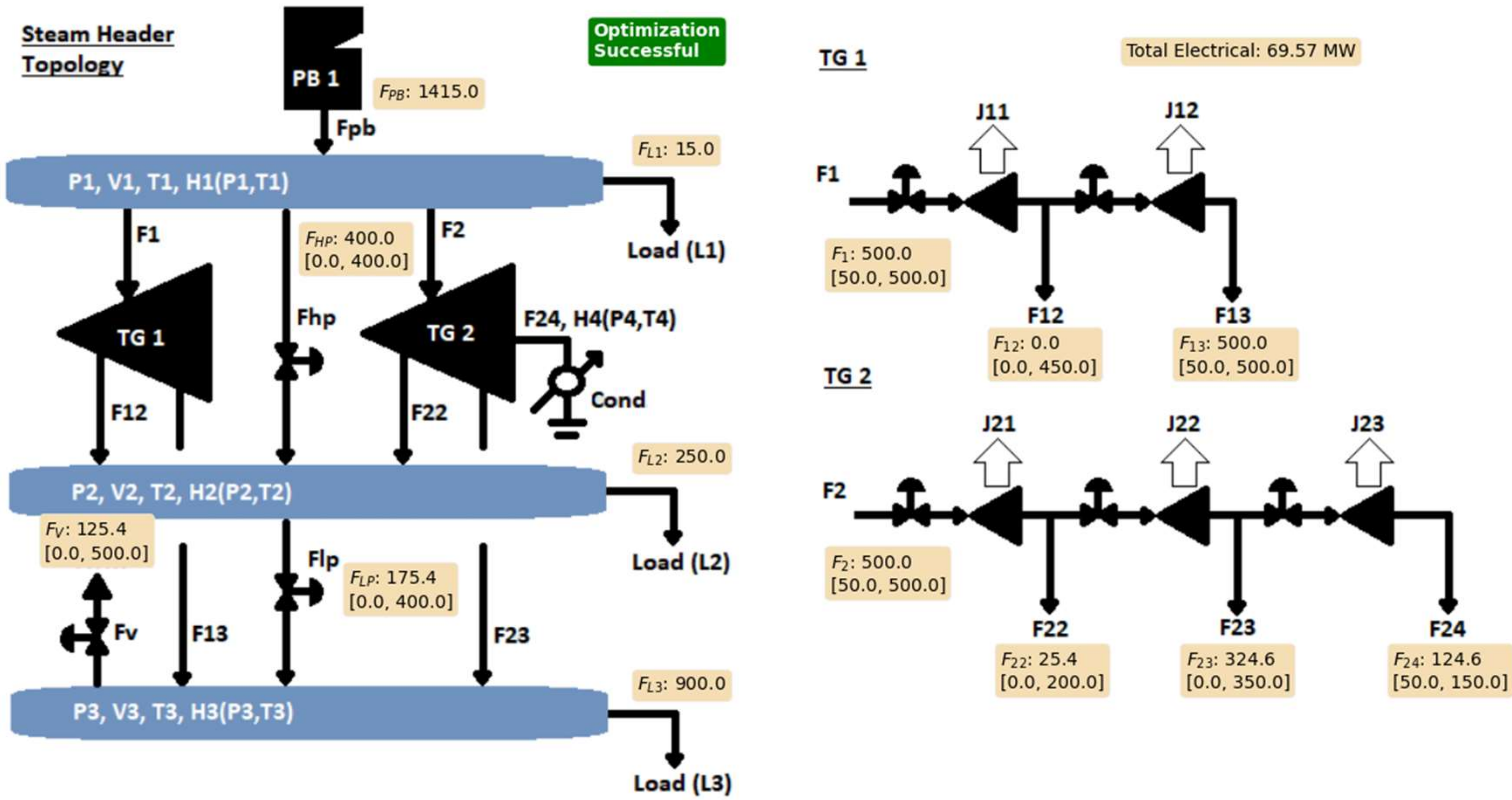




Results

Slightly Off LP Solution:

- Steam Moved From Condenser to Vent
- Slight Redirection of Extractions and PRV's
- Results in Loss of ~1 MW
- Worth ~ $400K per year

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LP Solution MegaWatts: 70.528
Off Solution MegaWatts: 69.574
========================================
Lost Revenue Per Year: $400,558.18
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Conclusion

We Saw…

1. **Introduction**
   - Cogeneration Plant Operation Overview
2. **Problem Statement**
   - Fitting to Constrained Optimization Paradigm
3. **Process Model and Constraints**
   - Mass and Energy Balances Used to Produce LP Canonical Form
4. **Results**
   - LP Optimization and Comparison
   - LP Solution Roughly $400k More Production per Year
5. **Demo and Questions?**