

AM 121: Intro to Optimization Models and Methods Fall 2018

Lecture 3: Applications, Examples, Exercises.



Yiling Chen
SEAS



Lecture 3: Lesson plan

- The Post Office Problem
- The SailCo Problem
- The SAVE-IT Company

- A Simple AMPL Example
(AMPL: A Modeling Language for
Mathematical Programming)

- From problem to LP (+ a little AMPL)

Post Office Problem

Union rules state that each full-time employee must work 5 consecutive days and then receive 2 days off.

Formulate an LP to minimize number of full-time employees who must be hired.

(Assume solution will be integral)

Day	Number of full-time employees required
1=Monday	17
2=Tuesday	13
3=Wednesday	15
4=Thursday	19
5=Friday	14
6=Saturday	16
7=Sunday	11

$$\begin{aligned}
 \min z &= \sum_i x_i \\
 \text{s.t.} \quad & \sum_i x_i - x_2 - x_3 \geq 17 \\
 & \sum_i x_i - x_3 - x_4 \geq 13 \\
 & \sum_i x_i - x_4 - x_5 \geq 15 \\
 & \sum_i x_i - x_5 - x_6 \geq 19 \\
 & \sum_i x_i - x_6 - x_7 \geq 14 \\
 & \sum_i x_i - x_7 - x_1 \geq 16 \\
 & \sum_i x_i - x_1 - x_2 \geq 11 \\
 & x_i \geq 0
 \end{aligned}$$

x_i : number of people with shift start on day i

Note: will need solution to be integral!

Variation 1: Forced overtime

- Post office can ask employees to work a 6th day each week (i.e. work for 6 consecutive days)
- Pay \$500/wk, \$130 for the overtime day.
- Formulate an LP to minimize weekly labor costs
- (Assume solution will be integral)

Day	Number of full-time employees required
1=Monday	17
2=Tuesday	13
3=Wednesday	15
4=Thursday	19
5=Friday	14
6=Saturday	16
7=Sunday	11

$$\min z = 500 \sum_i x_i + 130 \sum_i o_i$$

s.t.

$$\sum_i x_i - x_2 - x_3 + o_3 \geq 17$$

$$\sum_i x_i - x_3 - x_4 + o_4 \geq 13$$

$$\sum_i x_i - x_4 - x_5 + o_5 \geq 15$$

$$\sum_i x_i - x_5 - x_6 + o_6 \geq 19$$

$$\sum_i x_i - x_6 - x_7 + o_7 \geq 14$$

$$\sum_i x_i - x_7 - x_1 + o_1 \geq 16$$

$$\sum_i x_i - x_1 - x_2 + o_2 \geq 11$$

x_i : number of people with shift start on day i

o_i : number of people who work one day overtime who start on day i

Note: will need solution to be integral!

$$o_i \leq x_i, \quad \forall i$$

$$x_i, o_i \geq 0, \quad \forall i$$

Variation 2: Maximizing Weekends!

- Post office has 25 full-time employees.
Cannot hire or fire.
- Formulate an LP to schedule employees to maximize the number of weekend days off
- (Assume solution will be integral)

Day	Number of full-time employees required
1=Monday	17
2=Tuesday	13
3=Wednesday	15
4=Thursday	19
5=Friday	14
6=Saturday	16
7=Sunday	11

$$\max z = x_7 + 2x_1 + x_2$$

$$\text{s.t. } \sum_i x_i - x_2 - x_3 \geq 17$$

$$\sum_i x_i - x_3 - x_4 \geq 13$$

$$\sum_i x_i - x_4 - x_5 \geq 15$$

$$\sum_i x_i - x_5 - x_6 \geq 19$$

$$\sum_i x_i - x_6 - x_7 \geq 14$$

$$\sum_i x_i - x_7 - x_1 \geq 16$$

$$\sum_i x_i - x_1 - x_2 \geq 11$$

x_i : number of people who start shift on day i

$$\sum_i x_i = 25$$

$$x_i \geq 0$$

Note: will need solution to be integral!

Variation 3: Part-time Employees

- Can hire part-time employees
- Full-time: 8 hours a day, 5 consecutive days (2 days off). Cost \$15/hour.
- Part-time: 4 hours a day, 5 consecutive days (2 days off). Cost \$10/hour.
- Part-time limited by union to fill 25% of weekly labor (in terms of working hours).
- **Formulate an LP to minimize weekly labor costs. (Assume solution will be integral)**

Day	Number of hours required
1=Monday	8*17=136 hrs
2=Tuesday	8*13=104 hrs
3=Wednesday	8*15=120 hrs
4=Thursday	8*19=152 hrs
5=Friday	8*14=112 hrs
6=Saturday	8*16=128 hrs
7=Sunday	8*11=88 hrs

$$\min z = 120 \sum_i x_i + 40 \sum_i p_i$$

$$\text{s.t. } 8\left(\sum_i x_i - x_2 - x_3\right) + 4\left(\sum_i p_i - p_2 - p_3\right) \geq 136$$

$$8\left(\sum_i x_i - x_3 - x_4\right) + 4\left(\sum_i p_i - p_3 - p_4\right) \geq 104$$

$$8\left(\sum_i x_i - x_4 - x_5\right) + 4\left(\sum_i p_i - p_4 - p_5\right) \geq 120$$

$$8\left(\sum_i x_i - x_5 - x_6\right) + 4\left(\sum_i p_i - p_5 - p_6\right) \geq 152$$

$$8\left(\sum_i x_i - x_6 - x_7\right) + 4\left(\sum_i p_i - p_6 - p_7\right) \geq 112$$

$$8\left(\sum_i x_i - x_7 - x_1\right) + 4\left(\sum_i p_i - p_7 - p_1\right) \geq 128$$

$$8\left(\sum_i x_i - x_1 - x_2\right) + 4\left(\sum_i p_i - p_1 - p_2\right) \geq 88$$

x_i : number full time who start shift on day i

p_i : number part-time who start shift on day i

Note: will need solution to be integral!

$$4 \sum_i p_i \leq 0.25(4 \sum_i p_i + 8 \sum_i x_i)$$

$$x_i, p_i \geq 0$$

The SailCo Problem

SailCo must determine how many sailboats to produce in each quarter in order to meet demand. Boats can be used in same quarter produced, and held-over to future quarter.

Formulate an LP to determine a production schedule for Q1-Q4 to min total production and inventory costs. (Assume there is no demand after Q4.)

	Q1	Q2	Q3	Q4
Forecast demand	40	60	75	25

Production cost

\$400/boat, first 40 boats in a quarter

\$450/boat for additional boats

Inventory cost

\$20/boat/quarter for boats on hand at end of a quarter (after production has occurred and demand satisfied)

Initial inventory: 10 sailboats at start of Q1

$$\begin{aligned}
 \min z &= 400 \sum_t x_t + 450 \sum_t y_t + 20 \sum_t h_t \\
 \text{s.t. } &x_t \leq 40, \quad \forall t \\
 &h_1 = 10 + x_1 + y_1 - 40 \\
 &h_2 = h_1 + x_2 + y_2 - 60 \\
 &h_3 = h_2 + x_3 + y_3 - 75 \\
 &h_4 = h_3 + x_4 + y_4 - 25 \\
 &h_t, y_t, x_t \geq 0
 \end{aligned}$$

h_t : represents # boats on hand at end of quarter

x_t : number of boats made up to 40

y_t : number of boats made above 40

Variation 1: A Rolling Horizon

- Suppose make 40 in Q1, and actual demand is 35.
- Start Q2 with $10+40-35=15$ boats on hand.
- New *planning period* is Q2-Q5.
- Currently the optimal solution to the LP will not try to keep boats on hand at end of Q5.
- Modify the formulation to work for Q2-Q5, and ensure that we end the Q5 “planning horizon” with 10 boats in inventory.
- Forecast for Q2-Q5:

	Q1	Q2	Q3	Q4	Q5
forecast demand	40	60	75	25	36
actual demand	35				

Formulate an LP for Q2-Q5 to determine a production schedule to minimize sum of costs and meet new constraint.

Formulation for Q2-Q5:

$$\begin{aligned} \min z &= 400 \sum_t x_t + 450 \sum_t y_t + 20 \sum_t h_t \\ \text{s.t. } & x_t \leq 40, \quad \forall t \\ & h_2 = 15 + x_2 + y_2 - 60 \\ & h_3 = h_2 + x_3 + y_3 - 75 \\ & h_4 = h_3 + x_4 + y_4 - 25 \\ & h_5 = h_4 + x_5 + y_5 - 36 \\ & h_5 \geq 10 \\ & h_t, y_t, x_t \geq 0 \end{aligned}$$

h_t : represents # boats on hand at end of quarter

x_t : number of boats made up to 40

y_t : number of boats made above 40

decision variables for periods 2, ..., 5

Variation 2: Production Smoothing

- Make production “smooth” across periods:
 - an increase in production costs \$400/boat (training)
 - a decrease in production costs \$500/boat (severance pay, loss in morale)
- Assume 50 boats made during the Q preceding Q1, initial inventory of 10.
- Need at least 10 boats on hand at end of planning horizon

	Q1	Q2	Q3	Q4
Forecast demand	40	60	75	25

- Formulate an LP for Q1-Q4 to determine a production schedule to minimize sum of production and inventory costs.

$$\min z = 400 \sum_t x_t + 450 \sum_t y_t + 20 \sum_t h_t + 400 \sum_t c_t^+ + 500 \sum_t c_t^-$$

$$\text{s.t. } x_t \leq 40, \quad \forall t$$

$$h_1 = 10 + x_1 + y_1 - 40$$

$$h_2 = h_1 + x_2 + y_2 - 60$$

$$h_3 = h_2 + x_3 + y_3 - 75$$

$$h_4 = h_3 + x_4 + y_4 - 25$$

$$h_4 \geq 10$$

$$x_1 + y_1 - 50 = c_1^+ - c_1^-$$

$$x_2 + y_2 - (x_1 + y_1) = c_2^+ - c_2^-$$

$$x_3 + y_3 - (x_2 + y_2) = c_3^+ - c_3^-$$

$$x_4 + y_4 - (x_3 + y_3) = c_4^+ - c_4^-$$

$$h_t, y_t, x_t, c_t^+, c_t^- \geq 0$$

Solution: $x=(40,40,40,40)$; $y=(15,15,15,15)$

h_t : # boats on hand at end of quarter

x_t, y_t : number of boats made up to (above) 40

c_t^+ : #boat increase from last period

c_t^- : #boat decrease from last period

- Why will the optimal solution not have both $c_t^+ > 0$ and $c_t^- > 0$?
- Suppose production 60 in period 1 and 70 in period 2. What assignments to c_2^+ and c_2^- are *feasible*?

$$70 - 60 = c_2^+ - c_2^-$$

$$c_2^+, c_2^- \geq 0$$

- What assignments are *optimal*?

$$\min \dots + 400c_2^+ + 500c_2^- + \dots$$

Variation 3: Allowing demands to be backlogged

- Suppose demands can be met in future periods.
- Penalty \$100/boat per quarter demand is unmet.
- Must meet all demand by end of Q4.
- Build from variation 2 (still face smoothing costs with 50 in previous period and 10 on hand at start of Q1; still want 10 on hand at end of Q4.)

	Q1	Q2	Q3	Q4
Forecast demand	40	60	75	25

Formulate an LP to determine a production schedule to minimize the sum of the production and inventory costs.

$$\begin{aligned} \min z = & 400 \sum_t x_t + 450 \sum_t y_t + 20 \sum_t h_t^+ + 400 \sum_t c_t^+ + 500 \sum_t c_t^- \\ & + 100 \sum_t h_t^- \\ \text{s.t. } & x_t \leq 40, \quad \forall t \\ & h_1^+ - h_1^- = 10 + x_1 + y_1 - 40 \\ & h_2^+ - h_2^- = h_1^+ - h_1^- + x_2 + y_2 - 60 \\ & h_3^+ - h_3^- = h_2^+ - h_2^- + x_3 + y_3 - 75 \\ & h_4^+ - h_4^- = h_3^+ - h_3^- + x_4 + y_4 - 25 \\ & x_1 + y_1 - 50 = c_1^+ - c_1^- \\ & x_2 + y_2 - (x_1 + y_1) = c_2^+ - c_2^- \\ & x_3 + y_3 - (x_2 + y_2) = c_3^+ - c_3^- \\ & x_4 + y_4 - (x_3 + y_3) = c_4^+ - c_4^- \\ & h_4^+ \geq 10 \\ & h_4^- \leq 0 \\ & h_t^+, h_t^-, y_t, x_t, c_t^+, c_t^- \geq 0 \end{aligned}$$

h_t^+ : #boats on hand at end Q
 h_t^- : #boats backlogged at end Q

The SAVE-IT Company

- Operates a *recycling center*. Collects four types *materials*, treats, and amalgamates to make an insulation product of three different *grades*.
- Formulate an LP to determine the amount of each grade and the mix of materials for each grade, maximizing profit (sales – cost)

Have grant of \$30,000/wk for treatment cost (can't treat more than this)

At least half of each type of material must be treated.

Material	Availability (lbs /wk)	Treatment cost (\$/lb)
1	3000	3
2	2000	6
3	4000	4
4	1000	5

Grade	Spec	Amalg. cost (\$/lb)	Sales price (\$/lb)
A	1 ≤ 30% 2 ≥ 40 % 3 ≤ 50% 4 =20%	3	8.5
B	1 ≤ 50% 2 ≥ 10% 3: any 4 = 10%	2.5	7
C	1 ≤ 70% 2,3,4: any	2	5.5

$$\begin{aligned}
& \max 5.5 \sum_j x_{Aj} + 4.5 \sum_j x_{Bj} + 3.5 \sum_j x_{Cj} \\
& \text{s.t. } x_{A1} \leq 0.3 \sum_j x_{Aj} \\
& \quad x_{A2} \geq 0.4 \sum_j x_{Aj} \\
& \quad x_{A3} \leq 0.5 \sum_j x_{Aj} \\
& \quad x_{A4} = 0.2 \sum_j x_{Aj} \\
& \quad x_{B1} \leq 0.5 \sum_j x_{Bj} \\
& \quad x_{B2} \geq 0.1 \sum_j x_{Bj} \\
& \quad x_{B4} = 0.1 \sum_j x_{Bj} \\
& \quad x_{C1} \leq 0.7 \sum_j x_{Cj} \\
& \quad 1500 \leq x_{A1} + x_{B1} + x_{C1} \leq 3000 \\
& \quad 1000 \leq x_{A2} + x_{B2} + x_{C2} \leq 2000 \\
& \quad 2000 \leq x_{A3} + x_{B3} + x_{C3} \leq 4000 \\
& \quad 500 \leq x_{A4} + x_{B4} + x_{C4} \leq 1000 \\
& \quad 3(x_{A1} + x_{B1} + x_{C1}) + 6(x_{A2} + x_{B2} + x_{C2}) \\
& \quad + 4(x_{A3} + x_{B3} + x_{C3}) + 5(x_{A4} + x_{B4} + x_{C4}) \leq 30000 \quad (*) \\
& \quad x_{A1}, x_{A2}, \dots, x_{C4} \geq 0
\end{aligned}$$

x_{A2} : quantity of material type 2 used for product A

Variation 1: Pay for Treatment

- SAVE-IT recognizes that it might be able to to make more profits and improve the environment.
- Gets matching funds: provide a 80% rebate on treatment cost above \$30,000 per week.
- Formulate an LP that (a) uses all of \$30,000, (b) treats at least half of each type of material, (c) may treat more material if this is profitable.

- Introduce new constraint:

$$y = 3(x_{A1} + x_{B1} + x_{C1}) + 6(x_{A2} + x_{B2} + x_{C2}) + 4(x_{A3} + x_{B3} + x_{C3}) + 5(x_{A4} + x_{B4} + x_{C4}) - 30000$$

- Decision variable (total dollar cost of excess treatment) $y \geq 0$
- Add $-0.2y$ to the objective
- Drop inequality (*)
- The new formulation is on the next slide

$$\begin{aligned} \max \quad & 5.5 \sum_j x_{Aj} + 4.5 \sum_j x_{Bj} + 3.5 \sum_j x_{Cj} - 0.2y \\ \text{s.t.} \quad & x_{A1} \leq 0.3 \sum_j x_{Aj} \\ & x_{A2} \geq 0.4 \sum_j x_{Aj} \\ & x_{A3} \leq 0.5 \sum_j x_{Aj} \\ & x_{A4} = 0.2 \sum_j x_{Aj} \\ & x_{B1} \leq 0.5 \sum_j x_{Bj} \\ & x_{B2} \geq 0.1 \sum_j x_{Bj} \\ & x_{B4} = 0.1 \sum_j x_{Bj} \\ & x_{C1} \leq 0.7 \sum_j x_{Cj} \\ & 1500 \leq x_{A1} + x_{B1} + x_{C1} \leq 3000 \\ & 1000 \leq x_{A2} + x_{B2} + x_{C2} \leq 2000 \\ & 2000 \leq x_{A3} + x_{B3} + x_{C3} \leq 4000 \\ & 500 \leq x_{A4} + x_{B4} + x_{C4} \leq 1000 \\ & y = 3(x_{A1} + x_{B1} + x_{C1}) + 6(x_{A2} + x_{B2} + x_{C2}) \\ & \quad + 4(x_{A3} + x_{B3} + x_{C3}) + 5(x_{A4} + x_{B4} + x_{C4}) - 30000 \\ & y, x_{A1}, x_{A2}, \dots, x_{C4} \geq 0 \end{aligned}$$

A Simple AMPL Example

	Product A	Product B
Profit Per Unit	5	8
Machine time	1	1
Storage Space	5	9

$$\begin{aligned}
 \max \quad & 5x_1 + 8x_2 \\
 \text{s.t.} \quad & x_1 + x_2 \leq 6 \\
 & 5x_1 + 9x_2 \leq 45 \\
 & x_1, x_2 \geq 0
 \end{aligned}$$

Total machine time = 6; Total storage space = 45;

example.mod

```

set PRODUCT;
set RESOURCE;
param usage {i in RESOURCE, j in PRODUCT};
param profit {j in PRODUCT};
param avail {i in RESOURCE};
var X {j in PRODUCT}>=0;

maximize Total_Profit: sum {j in PRODUCT} profit[j]*X[j];

subject to Resource_Constraints {i in RESOURCE}:
    sum{j in PRODUCT} usage[i, j]*X[j]<=avail[i];

```

example.dat

```

set PRODUCT := A B;
set RESOURCE := machine space;

param usage: A B:=
    machine 1 1
    space 5 9;
param profit:= A 5 B 8;
param: avail:= machine 6 space 45;

```

Formulate in AMPL, solve with CPLEX

- Install AMPL
- Start AMPL using AMPL IDE or at command line


```

ampl: model example.mod;
ampl: data example.dat;
ampl: option solver cplex;
ampl: solve;
CPLEX 12.5.0.0: optimal solution; objective 41.25
2 dual simplex iterations (1 in phase I)
ampl: display X;
X [*] :=
A 2.25
B 3.75
;

```