BEE 4750 Homework 5: Solid Waste Disposal

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> **Due Date**
>
> Friday, 10/27/23, 9:00pm

Overview

Instructions

- In Problem 1, you will formulate, solve, and analyze a standard generating capacity expansion problem.
- In Problem 2, you will add a CO_2 constraint to the capacity expansion problem and identify changes in the resulting solution.

Load Environment

The following code loads the environment and makes sure all needed packages are installed. This should be at the start of most Julia scripts.

```
import Pkg
Pkg.activate(@__DIR__)
Pkg.instantiate()
```

```
using JuMP
using HiGHS
using DataFrames
using GraphRecipes
using Plots
using Measures
using MarkdownTables
```

In [ ]:

```
import Pkg
Pkg.add("JuMP")
Pkg.add("Cbc")
Pkg.activate(@__DIR__)
Pkg.instantiate()

using JuMP
using HiGHS
using DataFrames
using GraphRecipes
using Plots
using Measures
using MarkdownTables
```

```
 Resolving package versions...
No Changes to `~/Downloads/BEE4750/hw05-sinahy-frag/Project.toml`
No Changes to `~/Downloads/BEE4750/hw05-sinahy-frag/Manifest.toml`
 Resolving package versions...
No Changes to `~/Downloads/BEE4750/hw05-sinahy-frag/Project.toml`
No Changes to `~/Downloads/BEE4750/hw05-sinahy-frag/Manifest.toml`
Activating project at `~/Downloads/BEE4750/hw05-sinahy-frag`
```

Background

Three cities are developing a coordinated municipal solid waste (MSW) disposal plan. Three disposal alternatives are being considered: a landfill (LF), a materials recycling facility (MRF), and a waste-to-energy facility (WTE). The capacities of these facilities and the fees for operation and disposal are provided in the table below.

Disposal Facility	Capacity (Mg/d)	Fixed cost ($/d)	Tipping Fee ($/Mg)	Recycling Cost ($/Mg)
Landfill	200	2000	50	
Materials Recycling Facility	350	1500	7	40 (per Mg recycled)
Waste-to-Energy Facility	210	2500	60	

Transportation costs are $1.5/Mg-km, and the relative distances between the cities and facilities are provided in the table below.

City/Facility	Landfill (km)	MRF (km)	WTE (km)
1	5	30	15
2	15	25	10
3	13	45	20
LF	-	32	18
MRF	32	-	15
WTE	18	15	-

The fixed costs associated with the disposal options are incurred only if the particular disposal option is implemented. The three cities produce 100, 90, and 120 Mg/day of solid waste, respectively, with the composition provided in the table below.

Component	% of total mass	Combustion ash (%)	MRF Recycling rate (%)
Food Wastes	15	8	0
Paper & Cardboard	40	7	55
Plastics	5	5	15
Textiles	3	10	10
Rubber, Leather	2	15	0
Wood	5	2	30

Component	% of total mass	Combustion ash (%)	MRF Recycling rate (%)
Yard Wastes	18	2	40
Glass	4	100	60
Ferrous	2	100	75
Aluminum	2	100	80
Other Metal	1	100	50
Miscellaneous	3	70	0

The information in the above table will help you determine the overall recycling and ash fractions. Note that the recycling residuals, which may be sent to either landfill or the WTE, have different ash content than the ash content of the original MSW. You will need to determine these fractions to construct your mass balance constraints.

Reminder: Use `round(x; digits=n)` to report values to the appropriate precision!

Problems (Total: 40 Points)

Problem 1 (22 points)

In this problem, you will develop an optimal disposal plan for the two cities.

Problem 1.1 (3 points)

Based on the information above, calculate the overall recycling and ash fractions for the waste produced by each city.

In [ ]:
```
#store data in variables
facility = ["landfill", "MRF", "WTE"];
cap = [200, 350, 210]; #Mg/day
fixed_cost = [2000, 1500, 2500]; #$/day
tipping_fee = [50, 7, 60]; #$/Mg
recycling_cost = [0, 40, 0]; #$/Mg recycled
transport_cost = 1.5; #$/Mg-km

facility_dist = ["landfill", "MRF", "WTE"];
dist_1 = [5, 30, 15]; #km
dist_2 = [15, 25, 10]; #km
dist_3 = [13, 45, 10]; #km
LF_dist = [0, 32, 18]; #km
MRF_dist = [32, 0, 15]; #km
WTE_dist = [18, 15, 0]; #km

disposal_options = ["city 1", "city 2", "city 3"];
production = [100, 90, 120]; #Mg/day

component = ["food", "p&c", "plastics", "textiles", "r&l",
"wood", "yard", "glass", "ferrous", "aluminum", "metals",
"misc"];
tot_mass_perc = [.15, .4, .05, .03, .02, .05, .18, .04, .02,
.02, .01, .03];
comb_ash_perc = [.08, .07, .05, .1, .15, .02, .02, 1, 1, 1, 1, .7];
```

```
MRF_rec_rate = [0.0, .55, .15, .1, 0.0, .30, .40, .6, .75, .8, .5, 0.0]

#calculating ash and recylcling amts
ash_frac = sum(tot_mass_perc .* comb_ash_perc);
recycling_frac = sum(tot_mass_perc .* MRF_rec_rate);

println("Overall recycling fraction for the waste produced: ",
round(recycling_frac, digits = 3));

println("Overall combustion ash fraction for the waste produced: ",
round(ash_frac, digits = 3));
```

```
Overall recycling fraction for the waste produced: 0.378
Overall combustion ash fraction for the waste produced: 0.164
```

Problem 1.2 (2 points)

What are the decision variables for your optimization problem? Provide notation and variable meaning.

There are three decision variables. One of them is the waste transported from city x to disposal y, $W_{x,y}$, measured in Mg/day. Another includes the residual waste transported from disposal z to y, also measured in Mg/day, $R_{z,y}$. The last variable is the operational status of disposal y, S_y.

In [ ]:
```
using JuMP
using Cbc

waste_model = Model(Cbc.Optimizer);
X = 1:length(disposal_options);
Y = 1:length(facility);

@variable(waste_model, W[x in X, y in Y] >= 0);
@variable(waste_model, R[z in Y, y in Y] >= 0);
@variable(waste_model, S[y in Y], Bin);
```

Problem 1.3 (3 points)

Formulate the objective function. Make sure to include any needed derivations or justifications for your equation(s).

The objective is to ensure the total cost of the waste disposal is small as possible. The total cost will include the fixed costs, tipping fee, recycling costs, and transportation costs.

The landfill costs include:

$$2000 * S_1 + 50 * (W_{1,1} + W_{2,1} + W_{3,1} + R_{2,1})$$

The MRF costs include:

$$1500 * S_2 + 7 * (W_{1,2} + W_{2,2} + W_{3,2}) + .378 * 40 * (W_{1,2} + W_{2,2} + W_{3,2})$$

The WTE costs include:

$$2500 * S_3 + 60 * (W_{1,3} + W_{2,3} + W_{3,3} + R_{1,3} + R_{2,3})$$

The transportation costs include:

$$1.5 * [5 * W_{1,1} + 30 * W_{1,2} + 15 * W_{1,3} + 15 * W_{2,1} + 25 * W_{2,2} + 10 * W_{2,3} + 13 * W_{3,1} + 45$$

In [ ]:
```
@objective(waste_model, Min, sum([57.5 67.12 82.5; 72.5 59.62 75; 69.5 89.62 90]
+ sum([0 0 87; 98 0 82.5; 0 0 0] .* R) + sum([2000, 1500, 2500] .* S))
```

$$57.5W_{1,1} + 72.5W_{2,1} + 69.5W_{3,1} + 67.12W_{1,2} + 59.62W_{2,2} + 89.62W_{3,2} + 82.5W_{1,3} + 75W$$

In [ ]:
```
#@objective(waste_model, Min, 57.5 * W[1,1] + 67.12 * W[1,2] + 82.5 * W[1,3]
#+ 72.5 * W[2,1] + 59.62 * W[2,2] + 75 * W[2,3] + 69.5 * W[3,1] + 89.62 * W[3,2]
#+90 * W[3,3] + 87 * R[1,3] + 98 * R[2,1] + 82.5 * R[2,3]
#+ 2000 * Y[1] + 1500 * Y[2] + 2500 * Y[3]);
```

In [ ]:
```
#@objective(waste_model, Min, 57.5 * W[1,1] + 67.12 * W[1,2] + 82.5 * W[1,3]
#+ 72.5 * W[2,1] + 59.62 * W[2,2] + 75 * W[2,3] + 69.5 * W[3,1] + 89.62 * W[3,2]
#+90 * W[3,3] + 98 * R[2,1] + 77 * R[3,1] + 82.5 * R[2,3]
#+ 2000 * Y[1] + 1500 * Y[2] + 2500 * Y[3]);
```

Problem 1.4 (4 points)

Derive all relevant constraints. Make sure to include any needed justifications or derivations.

A constraint is the waste and recycling needing to be less than or equal to in the disposal facilities' capacities.

For landfills looks like the following:

$$W_{1,1} + W_{2,1} + W_{3,1} + R_{2,1} \leq 200$$

For MRF,

$$W_{1,2} + W_{2,2} + W_{3,2} \leq 350$$

For WTE,

$$W_{1,3} + W_{2,3} + W_{3,3} + R_{1,3} + R_{2,3} \leq 210$$

Another constraint is the MRF having to equal the nonrecycled waste entering the MRF and the waste from WTE equaling the ash produced:

$$R_{2,1} + R_{2,3} = (1 - recycling_{frac}) * (W_{1,2} + W_{2,2} + W_{3,2})$$

$$R_{1,3} = ash_{frac} * (W_{1,1} + W_{2,1} + W_{3,1} + R_{2,1})$$

Lastly, the binary variables and waste streams need to be nonnegative:

$$S_1 = 0 if W_{1,1} + W_{2,1} + W_{3,1} + R_{2,1} = 0. Else, Y_1 = 1$$

$$S_2 = 0 if W_{2,1} + W_{2,2} + W_{3,2} = 0. Else, Y_2 = 1$$

$$S_3 = 1 \; W_{x,y} \geq 0 \; R_{x,y} \geq 0$$

In [ ]:
```
#
#@constraint(waste_model, city[x in X], sum(W[x,:]) == production[x]);
#@constraint(waste_model, lf, W[1,1] + W[2,1] + W[3,1] + R[2,1] <= 200);
```

```
#@constraint(waste_model, mrf, W[1,2] + W[2,2] + W[3,3] <= 350);
#@constraint(waste_model, wte, W[1,3] + W[2,3] + W[3,3]+ R[1,3] + R[2,3] <= 210)

#residual mass constraint
#@constraint(waste_model, prod_cap2, R[2,1] + R[2,3] == (1 - recycling_frac) .*
#@constraint(waste_model, prod_cap1, R[1,3] == ash_frac .* (W[1,1] + W[2,1] + W[
#@constraint(waste_model, prod_cap3, sum(R[3,:]) == 0);
#@constraint(waste_model, nonneg1, sum(R[x, x] for x in X) == 0);
#@constraint(waste_model, nonneg2, R[1,2] == 0);

#
#@constraint(waste_model, cond1, !S[1] => {W[1,1] + W[2,1] + W[3,1] + R[2,1] ==
#@constraint(waste_model, cond2, !S[2] => {W[1,2] + W[2,2] + W[3,2] == 0});
#@constraint(waste_model, cond3, S[3] == 1);
```

In [ ]:
```
#disposal limit constraintd
@constraint(waste_model, city[x in X], sum(W[x,:]) == production[x]);
@constraint(waste_model, lf, W[1,1] + W[2,1] + W[3,1] + R[2,1] + R[3,1] <= 200);
@constraint(waste_model, mrf, W[1,2] + W[2,2] + W[3,2] <= 350);
@constraint(waste_model, wte, W[1,3] + W[2,3] + W[3,3] + R[2,3] <= 210);

#residual mass constraint
@constraint(waste_model, prod_cap2, R[2,1] + R[2,3] == (1 - recycling_frac) .* (
@constraint(waste_model, prod_cap1, R[1,3] == ash_frac .* (W[1,3] + W[2,3] + W[3

@constraint(waste_model, prod_cap3, sum(R[3,:]) == 0);
@constraint(waste_model, nonneg1, sum(R[x, x] for x in X) == 0);
@constraint(waste_model, nonneg2, R[1,2] == 0);

#
@constraint(waste_model, condWTE, !S[1] => {W[1,3] + W[2,3] + W[3,3] + R[2,1] ==
@constraint(waste_model, condMRF, !S[2] => {W[1,2] + W[2,2] + W[3,2] == 0});
@constraint(waste_model, condLF, S[3] == 1);
```

Problem 1.5 (3 points)

Implement your optimization problem in `JuMP` .

In [ ]:
```
set_silent(waste_model);
optimize!(waste_model);
```

Problem 1.6 (2 points)

Find the optimal solution. Report the optimal objective value.

In [ ]:
```
println("Objective value or cost of disposal in dollars: ", round(objective_valu
```

```
Objective value or cost of disposal in dollars: 27320.44
```

In [ ]:
```
println("Statuses of the disposal: ", value.(S));
```

```
Statuses of the disposal: 1-dimensional DenseAxisArray{Float64,1,...} with index
sets:
    Dimension 1, 1:3
And data, a 3-element Vector{Float64}:
 1.0
 0.0
 1.0
```

In [ ]:
```
println("Waste transported from each city in Mg/day: ", value.(W));
```

```
Waste transported from each city in Mg/day: 2-dimensional DenseAxisArray{Float6
4,2,...} with index sets:
    Dimension 1, 1:3
    Dimension 2, 1:3
And data, a 3×3 Matrix{Float64}:
 100.0  0.0   0.0
   0.0  0.0  90.00000000000001
 100.0  0.0  20.000000000000004
```

In [ ]:
```
println("Residual waste transported between each facility in Mg/day: ", value.(R
```

```
Residual waste transported between each facility in Mg/day: 2-dimensional DenseA
xisArray{Float64,2,...} with index sets:
    Dimension 1, 1:3
    Dimension 2, 1:3
And data, a 3×3 Matrix{Float64}:
 0.0  0.0  18.051000000000005
 0.0  0.0   0.0
 0.0  0.0   0.0
```

Problem 1.7 (5 points)

Draw a diagram showing the flows of waste between the cities and the facilities. Which facilities (if any) will not be used? Does this solution make sense?

Problem 2 (18 points)

It is projected that in the near future the state will introduce a carbon tax that will increase the cost for transportation and for disposal by incineration. It is estimated that the additional costs will be:

- tipping fee for the WTE facility will increase to$75/Mg; and
- transportation costs will increase to $2/Mg-km.

In this context, the cities are considering adding another landfill and want to know if this would be cost-effective compared to using the current facilities with the carbon tax. This landfill would have a maximum capacity of 100 Mg/day and would be located with the following distances from the existing sites (excluding LF1):

City/Facility	Distance to LF2 (km)
1	45
2	35
3	15
MRF	35
WTE	50

The fixed cost of operating this facility would be the same as the first landfill, but the tipping cost would be increased to $60/Mg-day.

Problem 2.1 (5 points)

What changes are needed to your optimization program from Problem 1 for this decision problem? Formulate any different variables, objectives, and/or constraints.

With this change the variables be the same. There will be an added constraint however:

For landfill 2 looks like the following:

$$W_{1,4} + W_{2,4} + W_{3,4} + R_{2,4} + R_{3,4} \leq 100$$

Our objective function, however, will differ since some costs have been increased. Now the new costs look like the following:

The landfill 1 costs include:

$$2000 * S_1 + 50 * (W_{1,1} + W_{2,1} + W_{3,1} + R_{2,1})$$

-2000 being the fixed cost and 50 being tipping fee

The MRF costs include:

$$1500 * S_2 + 7 * (W_{1,2} + W_{2,2} + W_{3,2}) + .378 * 40 * (W_{1,2} + W_{2,2} + W_{3,2})$$

-1500 being the fixed cost and 7 being tipping fee plus 40 being the recycling cost times the recycling fraction

The WTE costs include:

$$2500 * S_3 + 60 * (W_{1,3} + W_{2,3} + W_{3,3} + R_{1,3} + R_{2,3})$$

-2500 being the fixed cost and 60 being tipping fee

The landfill 2 costs include:

$2000 * S_4 + 60 * (W_{1,4} + W_{2,4} + W_{3,4} + R_{2,4} + R_{3,4})$ -2000 being the fixed cost and 60 being the new tipping fee

The transportation costs include:

$$2.0 * [5 * W_{1,1} + 30 * W_{1,2} + 15 * W_{1,3} + 15 * W_{2,1} + 25 * W_{2,2} + 10 * W_{2,3} + 13 * W_{3,1} + 45 + 35 * R_{2,4} + 50 * R_{3,4}]$$

-2.0 being the new transportation cost

Problem 2.2 (3 points)

Implement the new optimization problem in `JuMP`.

In [ ]:
```
using JuMP
using Cbc

waste_new = Model(Cbc.Optimizer);
X = 1:length(disposal_options);
Y = 1:length(facility);
```

```
@variable(waste_new, W_new[x in X, y in Y] >= 0);
@variable(waste_new, R_new[z in Y, y in Y] >= 0);
@variable(waste_new, S_new[y in Y], Bin);


@objective(waste_new, Min, sum([60 82.12 105 150; 80 72.12 95 130; 76 112.12 115
+ sum([0 0 111 0; 114 0 105 130; 0 0 0 160; 0 0 0 0] .* R_new) + sum([2000, 1500
```

```
DimensionMismatch: arrays could not be broadcast to a common size; got a dimensi
on with lengths 4 and 3


Stacktrace:

  [1] _bcs1

    @ ./broadcast.jl:529 [inlined]

  [2] _bcs (repeats 2 times)

    @ ./broadcast.jl:523 [inlined]

  [3] broadcast_shape

    @ ./broadcast.jl:517 [inlined]

  [4] combine_axes

    @ ./broadcast.jl:512 [inlined]

  [5] instantiate

    @ ./broadcast.jl:294 [inlined]

  [6] materialize

    @ ./broadcast.jl:873 [inlined]

  [7] broadcast(::typeof(*), ::Matrix{Float64}, ::Matrix{VariableRef})

    @ Base.Broadcast ./broadcast.jl:811

  [8] broadcasted(::Base.Broadcast.ArrayStyle{JuMP.Containers.DenseAxisArray},
::Function, ::Matrix{Float64}, ::JuMP.Containers.DenseAxisArray{VariableRef, 2,
Tuple{UnitRange{Int64}, UnitRange{Int64}}, Tuple{JuMP.Containers._AxisLookup{Tup
le{Int64, Int64}}, JuMP.Containers._AxisLookup{Tuple{Int64, Int64}}}})

    @ JuMP.Containers ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArra
y.jl:554

  [9] broadcasted(::Function, ::Matrix{Float64}, ::JuMP.Containers.DenseAxisArra
y{VariableRef, 2, Tuple{UnitRange{Int64}, UnitRange{Int64}}, Tuple{JuMP.Containe
rs._AxisLookup{Tuple{Int64, Int64}}, JuMP.Containers._AxisLookup{Tuple{Int64, In
t64}}}})

    @ Base.Broadcast ./broadcast.jl:1317

 [10] macro expansion

    @ ~/.julia/packages/MutableArithmetics/K9YPJ/src/rewrite.jl:321 [inlined]

 [11] macro expansion
```

```
   @ ~/.julia/packages/JuMP/D44Aq/src/macros.jl:717 [inlined]

 [12] top-level scope

   @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:12
```

In [ ]:
```
@constraint(waste_new, city[x in X], sum(W_new[x,:]) == production[x]);
@constraint(waste_new, lf_old, W_new[1,1] + W_new[2,1] + W_new[3,1] + R_new[2,1]
@constraint(waste_new, mrf_new, W_new[1,2] + W_new[2,2] + W_new[3,2] <= 350);
@constraint(waste_new, wte_new, W_new[1,3] + W_new[2,3] + W_new[3,3] + R_new[2,3
@constraint(waste_new, lf_2, W_new[1,4] + W_new[2,4] + W_new[3,4]+ R_new[3,4] +

#residual mass constraint
@constraint(waste_new, prod_cap2_new, R_new[2,1] + R_new[2,3] == (1 - recycling_
@constraint(waste_new, prod_cap1_new, R_new[1,3] == ash_frac .* (W_new[1,3] + W_
@constraint(waste_new, prod_cap3_new, sum(R_new[3,:]) == 0);
@constraint(waste_new, nonneg1_new, sum(R_new[x, x] for x in X) == 0);
@constraint(waste_new, nonneg2_new, R_new[1,2] == 0);

#
@constraint(waste_new, condWTE_new, !S_new[1] => {W_new[1,1] + W_new[2,1] + W_ne
@constraint(waste_new, condMRF_new, !S_new[2] => {W_new[1,2] + W_new[2,2] + W_ne
@constraint(waste_new, condLF_new, !S_new[3] => {W_new[1,4] + W_new[2,4] + W_new
@constraint(waste_new, condLF2_new, S_new[4] == 1);


#
@constraint(waste_model, condWTE, !S[1] => {W[1,3] + W[2,3] + W[3,3] + R[2,1] ==
@constraint(waste_model, condMRF, !S[2] => {W[1,2] + W[2,2] + W[3,2] == 0});
@constraint(waste_model, condLF, S[3] == 1);

#set_silent(waste_new);
optimize!(waste_new);
```

```
KeyError: key 4 not found


Stacktrace:

 [1] getindex

  @ ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArray.jl:120 [inlined]

 [2] _getindex_recurse

  @ ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArray.jl:355 [inlined]

 [3] _getindex_recurse

  @ ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArray.jl:354 [inlined]

 [4] to_index

  @ ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArray.jl:364 [inlined]

 [5] #getindex#26

  @ ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArray.jl:391 [inlined]

 [6] getindex(::JuMP.Containers.DenseAxisArray{VariableRef, 2, Tuple{UnitRange{I
nt64}, UnitRange{Int64}}, Tuple{JuMP.Containers._AxisLookup{Tuple{Int64, Int6
```

```
4}}, JuMP.Containers._AxisLookup{Tuple{Int64, Int64}}}}, ::Int64, ::Int64)

   @ JuMP.Containers ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArray.
jl:384

 [7] macro expansion

   @ ~/.julia/packages/MutableArithmetics/K9YPJ/src/rewrite.jl:321 [inlined]

 [8] macro expansion

   @ ~/.julia/packages/JuMP/D44Aq/src/macros.jl:717 [inlined]

 [9] top-level scope

   @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:6
```

Problem 2.3 (5 points)

Find the optimal solution and report the optimal objective value. Provide a diagram showing the new waste flows.

In [ ]:
```
println("Objective value or cost of disposal in dollars: ", round(objective_valu
```

```
┌ Warning: The model has been modified since the last call to `optimize!` (or `o
ptimize!` has not been called yet). If you are iteratively querying solution inf
ormation and modifying a model, query all the results first, then modify the mod
el.
└ @ JuMP /Users/sinahyfragoso/.julia/packages/JuMP/D44Aq/src/optimizer_interfac
e.jl:675
OptimizeNotCalled()



Stacktrace:

 [1] get(model::Model, attr::MathOptInterface.ObjectiveValue)

   @ JuMP ~/.julia/packages/JuMP/D44Aq/src/optimizer_interface.jl:681

 [2] objective_value(model::Model; result::Int64)

   @ JuMP ~/.julia/packages/JuMP/D44Aq/src/objective.jl:54

 [3] objective_value(model::Model)

   @ JuMP ~/.julia/packages/JuMP/D44Aq/src/objective.jl:50

 [4] top-level scope

   @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:1
```

In [ ]:
```
println("Statuses of the disposal: ", value.(S_new));
```

```
┌ Warning: The model has been modified since the last call to `optimize!` (or `o
ptimize!` has not been called yet). If you are iteratively querying solution inf
ormation and modifying a model, query all the results first, then modify the mod
el.
└ @ JuMP /Users/sinahyfragoso/.julia/packages/JuMP/D44Aq/src/optimizer_interfac
e.jl:695
OptimizeNotCalled()
```

```
Stacktrace:

  [1] get(model::Model, attr::MathOptInterface.VariablePrimal, v::VariableRef)

    @ JuMP ~/.julia/packages/JuMP/D44Aq/src/optimizer_interface.jl:701

  [2] value(v::VariableRef; result::Int64)

    @ JuMP ~/.julia/packages/JuMP/D44Aq/src/variables.jl:1693

  [3] value

    @ ~/.julia/packages/JuMP/D44Aq/src/variables.jl:1692 [inlined]

  [4] _broadcast_getindex_evalf

    @ ./broadcast.jl:683 [inlined]

  [5] _broadcast_getindex

    @ ./broadcast.jl:656 [inlined]

  [6] getindex

    @ ./broadcast.jl:610 [inlined]

  [7] macro expansion

    @ ./broadcast.jl:974 [inlined]

  [8] macro expansion

    @ ./simdloop.jl:77 [inlined]

  [9] copyto!

    @ ./broadcast.jl:973 [inlined]

 [10] copyto!

    @ ./broadcast.jl:926 [inlined]

 [11] copy

    @ ./broadcast.jl:898 [inlined]

 [12] materialize

    @ ./broadcast.jl:873 [inlined]

 [13] broadcast(f::typeof(value), As::Vector{VariableRef})

    @ Base.Broadcast ./broadcast.jl:811

 [14] broadcasted(#unused#::Base.Broadcast.ArrayStyle{JuMP.Containers.DenseAxisA
rray}, f::Function, args::JuMP.Containers.DenseAxisArray{VariableRef, 1, Tuple{U
nitRange{Int64}}, Tuple{JuMP.Containers._AxisLookup{Tuple{Int64, Int64}}}})

    @ JuMP.Containers ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArra
y.jl:554

 [15] broadcasted(::Function, ::JuMP.Containers.DenseAxisArray{VariableRef, 1, T
uple{UnitRange{Int64}}, Tuple{JuMP.Containers._AxisLookup{Tuple{Int64, Int6
4}}}})
```

```
    @ Base.Broadcast ./broadcast.jl:1311

 [16] top-level scope

    @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:1
```

In [ ]:
```
println("Waste transported from each city in Mg/day: ", value.(W_new));
```

```
┌ Warning: The model has been modified since the last call to `optimize!` (or `o
ptimize!` has not been called yet). If you are iteratively querying solution inf
ormation and modifying a model, query all the results first, then modify the mod
el.
└ @ JuMP /Users/sinahyfragoso/.julia/packages/JuMP/D44Aq/src/optimizer_interfac
e.jl:695
OptimizeNotCalled()



Stacktrace:

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 [10] copyto!

    @ ./broadcast.jl:926 [inlined]

 [11] copy

    @ ./broadcast.jl:898 [inlined]
```

```
 [12] materialize

    @ ./broadcast.jl:873 [inlined]

 [13] broadcast(f::typeof(value), As::Matrix{VariableRef})

    @ Base.Broadcast ./broadcast.jl:811

 [14] broadcasted(#unused#::Base.Broadcast.ArrayStyle{JuMP.Containers.DenseAxisA
rray}, f::Function, args::JuMP.Containers.DenseAxisArray{VariableRef, 2, Tuple{U
nitRange{Int64}, UnitRange{Int64}}, Tuple{JuMP.Containers._AxisLookup{Tuple{Int6
4, Int64}}, JuMP.Containers._AxisLookup{Tuple{Int64, Int64}}}})

    @ JuMP.Containers ~/.julia/packages/JuMP/D44Aq/src/Containers/DenseAxisArra
y.jl:554

 [15] broadcasted(::Function, ::JuMP.Containers.DenseAxisArray{VariableRef, 2, T
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e{Int64, Int64}}, JuMP.Containers._AxisLookup{Tuple{Int64, Int64}}}})

    @ Base.Broadcast ./broadcast.jl:1311

 [16] top-level scope

    @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:1
```

In [ ]:

```
println("Residual waste transported between each facility in Mg/day: ", value.(R
```

```
┌ Warning: The model has been modified since the last call to `optimize!` (or `o
ptimize!` has not been called yet). If you are iteratively querying solution inf
ormation and modifying a model, query all the results first, then modify the mod
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└ @ JuMP /Users/sinahyfragoso/.julia/packages/JuMP/D44Aq/src/optimizer_interfac
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OptimizeNotCalled()



Stacktrace:

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[14] broadcasted(#unused#::Base.Broadcast.ArrayStyle{JuMP.Containers.DenseAxisA
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y.jl:554

[15] broadcasted(::Function, ::JuMP.Containers.DenseAxisArray{VariableRef, 2, T
uple{UnitRange{Int64}, UnitRange{Int64}}, Tuple{JuMP.Containers._AxisLookup{Tupl
e{Int64, Int64}}, JuMP.Containers._AxisLookup{Tuple{Int64, Int64}}}})

   @ Base.Broadcast ./broadcast.jl:1311

[16] top-level scope

   @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:1
```

Problem 2.4 (5 points)

Would you recommend that the cities build the new landfill? Why or why not? Your answer should be based on your analysis but can draw on other considerations as appropriate or desired.

References

List any external references consulted, including classmates.

In [ ]:
```
Worked with Ruby Pascual.
```

```
syntax: extra token "with" after end of expression
```

```
Stacktrace:
 [1] top-level scope
   @ ~/Downloads/BEE4750/hw05-sinahy-frag/hw05.ipynb:1
```