

Solve TSP by ILP

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Abstract

In this report, I formulate *Traveling Salesman Problem* (TSP) as *Integer Linear Program* (ILP), crawl data for landmarks, solve the ILP by SageMath and visualize the routes on GMap. For 50 landmarks symmetric TSP, I try to formulate it as undirected graph model to keep the size of problem small-scale and successfully receive a solution in fast speed. I do not explore the method that detect and eliminate subtour dynamically at running-time, because I prefer to elegant closed-form ILP. I want to focus on symmetric formulation of symmetric TSP and hope to compose a elegant report. I find all the procedure quite interesting and exciting and I feel quite grateful for Dear Prof. Thomas Honold who gives us a lot help!

Keywords: Symmetric/Asymmetric TSP, ILP

1 TSP

TSP is a combinatorial optimization problem to find the shortest possible Hamiltonian circuit for a complete weighted graph. For the notation that will be used, Ref. to Tab [1 on the following page](#)

1.1 Notation

$\mathbf{s} = (s_i)$	At i step, the index of visited city is s_i , $0 \leq i \leq n - 1$
$\mathbf{t} = (t_i)$	City i is visited at step t_i , $0 \leq i \leq n - 1$
$\mathbf{X} = (x_{ij})$	Decision variable Symmetric TSP : $x_{ij} = 1$ when there is a path from No. i to No. j $0 \leq i, j \leq n - 1, i \neq j$ Aymmetric TSP : $x_{ij} = 1$ when there is a connect between No. i and No. j $0 \leq i < j \leq n - 1$
$\pi(\cdot)$	$\pi(i) = j$ if $x_{ij} = 1$, $0 \leq i, j \leq n - 1$
$\mathbf{C} = (c_{ij})$	Cost Matrix with arbitrary c_{ii} since we do not consider $x_{ij} _{i=j}$ Symmetric TSP : $\mathbf{C} = \mathbf{C}^T$ Aymmetric TSP : no certain relation between \mathbf{C} and \mathbf{C}^T

Table 1: The notations that will be used

There are several key components in the definition of TSP:

- Hamiltonian circuit means the travel route starting from vertex No. 0, **ending at No. 0** and visiting all vertexes **once and only once**. Note that **ending at No. 0** and **once and only once** are not contradict! Because we consider this in our notation: $x_{ij}|_{i=n-1, j=0}$ denote the distance go back from No. $n-1$ to No. 0 while t_i will not consider the time consumed when going back since there is *no* $t_i|_{i=n}$.
- **Asymmetric TSP** is more general and easy to formulate. But it can increase the size of problem doubly, Ref. to Sec. 1.2 on page 4. In this case, be careful that \mathbf{C} is symmetric because the data I collect is distance while the solution \mathbf{X} is unsymmetrical because it describe *directed* graph.
- **Symmetric TSP** will be formulate by undirected graph model and reduce the number of variable by 50%. In this case, be careful that \mathbf{C} and the solution \mathbf{X} are both symmetric, which means the subindex of \mathbf{X} will be in lexicographic order (*i.e.* $\mathbf{X} = (x_{ij}), i < j$)

1.2 Formulation as ILP

Asymmetric TSP

Let us formulate asymmetric TSP using undirected graph model straightly. We will add some constraints (*i.e.* n auxiliary variables and $n(n - 1)$ constrain) to avoid subtours and we will find that TSP belong to NP hard class

$$\text{Minimize } \sum_{i=0}^{n-1} \sum_{j=0, j \neq i}^{n-1} c_{ij} x_{ij} \quad (1)$$

$$\begin{aligned} \text{subject to } & \sum_{i=0, i \neq j}^{n-1} x_{ij} = 1 & j = 0, \dots, n - 1; \\ & \sum_{j=0, j \neq i}^{n-1} x_{ij} = 1 & i = 0, \dots, n - 1; \\ & t_j \geq t_i + 1 - n(1 - x_{ij}) & 0 \leq i \leq n - 1, 1 \leq j \leq n - 1, i \neq j \\ & x_{ij} \geq 0, x_{ij} \in \mathbb{Z} & i, j = 0, \dots, n - 1. \end{aligned} \quad (2)$$

In the objective function (1), we simply drop x_{ii} , because $c_{ii} = 0$ if we use **adjacent matrix** C, but if we use ‘*graph.CompleteGraph*’ in Sage, we do not need to consider $j \neq i$, because there will not be self-loop.

Note that $j \geq 1$ in (2) means we do not consider salesman going back to No.0. In fact, if we let t_n denote the time step salesman go back to No.0, we have:

$$t_n = t_{n-1} + 1 = n \quad (3)$$

Then we prove that this ILP is equivalent to TSP. **(I).** cyclic permutation without subtour conclude constraint (2). Because (2) is equivalent to statement that if the next visited city for i is j ($x_{ij} = 1$), then $t_j = t_i + 1$. If $x_{ij} = 0$, then we add a trivial constraint $t_j \geq t_i + 1 - n$. The equivalent statement is satisfied. **(II).** constraint (2) eliminates all subtour. We can prove it by tricky reductio ad absurdum. Suppose the feasible solution \mathbf{X} contain more than one subtour. Then there exist $s = (i_1, \dots, i_r)$ not containing 0. Note that i_r in this circle will go back to i_1 , so there is additional equation $t_{i_1} = t_{i_r} + 1$ quite different with (3). Go along this cycle, we find that $0 = r$, and the contradiction lies in the fact that the cycle do not containing 0.

Symmetric TSP

However, I find it takes a long time to solve 50 landmarks TSP, Ref to Fig 3 on page 6. So I try to formulate it by directed graph model($G = (V, E)$, $|V| = n - 1$).

If we use adjacent matrix, degree constraint becomes $\sum_{i=0}^{j-1} x_{ij} + \sum_{k=j+1}^{n-1} x_{jk} = 2, 0 \leq j \leq n - 1$. If we use sparse incident matrix \mathbf{A} , degree constrain becomes $\sum_{v=0}^{n-1} A_{ve} = 2, 0 \leq e \leq |E|$.

For subtour elimination constraint, I try to express it by

$$|t_j - t_i| \geq \begin{cases} 1 & x_{ij} = 1 \text{ and } j \neq 1 \\ 1 - n & x_{ij} = 0 \end{cases}$$

But it is difficult to transform into linear constraints.

So I look into Sage’s code[2]. We can introduce auxiliary variables $r_{ij}, 0 \leq i, j \leq n - 1, i \neq j$ with different meaning.

$$r_{ij} + r_{ji} \geq x_{ij} \quad , \text{ for } 0 \leq i < j \leq n - 1 \quad (4)$$

$$\sum_{i=0, i \neq j}^{n-1} r_{ij} \leq 1 - \frac{1}{2n} \quad , \text{ for } 0 \leq j \leq n - 1 \quad (5)$$

We give (r_{ij}) some physical meaning. We want to move $\frac{1}{n}$ from every node to 1 through now network flow (r_{ij}) . There is a straight sense that it can be done if the circle we find is Hamilton Circle.

Then let me prove the correctness of these constrains strictly: **(I).** If existing a Hamilton Circle, then exists (r_{ij}) satisfies constraints. Even if the original graph is not a complete graph, so we still can simply construct a **virtual** network flow. Construct in these way: if No. i is connect with No.0 in the Hamilton circle we find, then modified $r_{i0} = 1 - 1/2n$, and $r_{0i} = 1/2n$. If No. i is not directly connect with No.0, then $r_{i0} = -1/2n$, $r_{0i} = 1/2n$. Then I think r_{ij} will satisfies all constrains. **(II).** If existing a subtour not containing No.0, then constrains will not be satisfied. Sum along the subtour, we will get $k - k/2n \geq k$, which is contradictory.

Finally I want to formulate TSP use language of Graph which become elegant and straight in Sage. For $G = (V, E)$:

$$\begin{aligned}
 & \text{Minimize} && \sum_{(\mu, \nu) \in E} c_{\mu\nu} x_{\mu\nu} \\
 & \text{subject to} && \sum_{\mu \in N_G(\nu)} x_{\mu'\nu'} = 2 && \text{for all } \nu \in V \\
 & && r_{\mu\nu} + r_{\nu\mu} \geq x_{\mu\nu} && \text{for all } (\mu, \nu) \in E \\
 & && \sum_{\mu \in N_G(\nu)} r_{\mu\nu} \leq 1 - \frac{1}{2n} && \text{for all } \nu \in V \wedge \nu \neq 0 \\
 & && x_{\mu\nu} \geq 0, x_{\mu\nu} \in \mathbb{Z} && \text{for all } (\mu, \nu) \in E.
 \end{aligned}$$

Note that $(\mu, \nu) \in E$ makes sure $\mu < \nu$, and μ', ν' in above satisfies $\begin{cases} \mu' = \min(\mu, \nu) \\ \nu' = \max(\mu, \nu) \end{cases}$ to make sure $\mu' < \nu'$. I write in this way to keep optimization equalities and inequalities elegant.

Relation between Symmetric/Asymmetric TSP

For example[4], adjacent matrix for Symmetric TSP can transform into Asymmetric TSP by adding some *ghost nodes* A', B', C' . And the link weight between original node and ghost node can be set to small negative number.

	A	B	C
A		1	2
B	6		3
C	5	4	

→

	A	B	C	A'	B'	C'
A				-w	6	5
B				1	-w	4
C				2	3	-w
A'	-w	1	2			
B'	6	-w	3			
C'	5	4	-w			

Apparently, the equivalent symmetric formulation of a asymmetric TSP have double variables. Since exact algorithm(ILP) for TSP can only be fast for small-scale problem, it is important to capture symmetric structure for 50 landmarks TSP to keep problem small-scale. Thanks a lot for Dear Prof. Honold's advice!

2 Experiments

The steps to solve the ILP include:

- Crawl location data for landmarks around HangZhou and China.
- Transform from (latitude,longitude) to distance matrix C, following guide of [Wiki/Haversine_formula](#)[3].
- Solve the ILP by MILP class. The equivalent code for ILP system (2) is more human-friendly and powerful compared with 'intlinprog' function of Matlab. Ref. to Sec. [B.1 on page 6](#). I put the code in the Appendix, hope do not impact the compactness of this report.
- Visualize on GMap. [1]

Apply ILP to a toy case with 50 landmarks around China, we get a optimal strategy to travel around China. It is quite interesting and exciting. Ref. to Fig [2a on page 6](#). I also try

to travel around JiangZheHu Region(Yangtze River delta) and visualize it on the map, Ref. to Fig 2b on the next page.

I have some test about time of different formulations. Ref. to Fig 3 on the following page. We can observe that Symmetric formulation can solve 50 landmarks TSP while Asymmetric formulation can solve 23 landmarks TSP. We can expect them to grow explosively after $n = 50$ and 23.

Appendices

Appendix A Figure

I put all figures in appendices to keep description of problem compact.

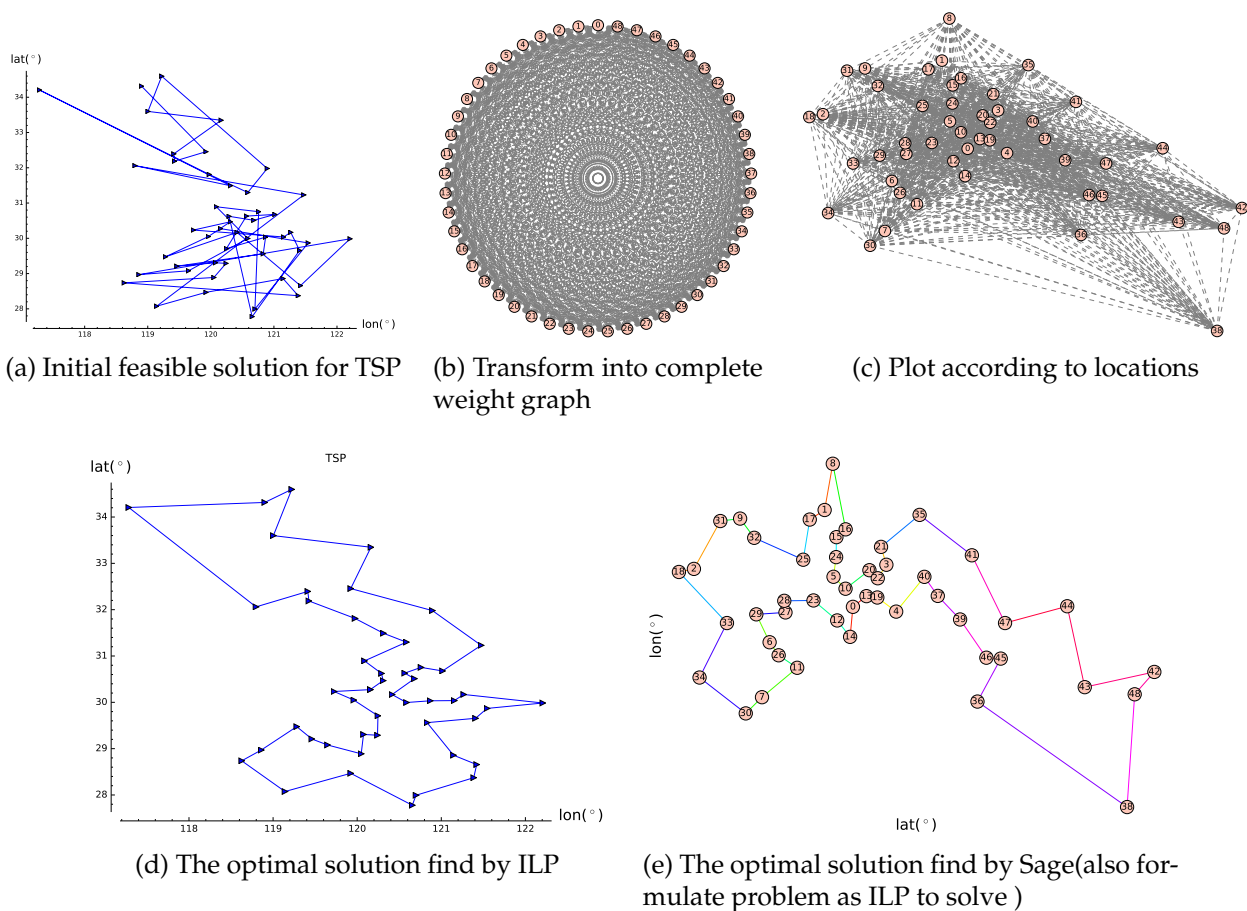


Figure 1: Fig 1d is equivalent to Fig 2b on the next page with correct (longitude, latitude) as coordinate. But when set the position information for graph, I use (latitude, longitude) mistakenly. We can see the solution find by B.2 on page 7 is the same as Sage. In fact, I look into Sage's Source code, inspired by it and write new formulation of symmetric TSP.

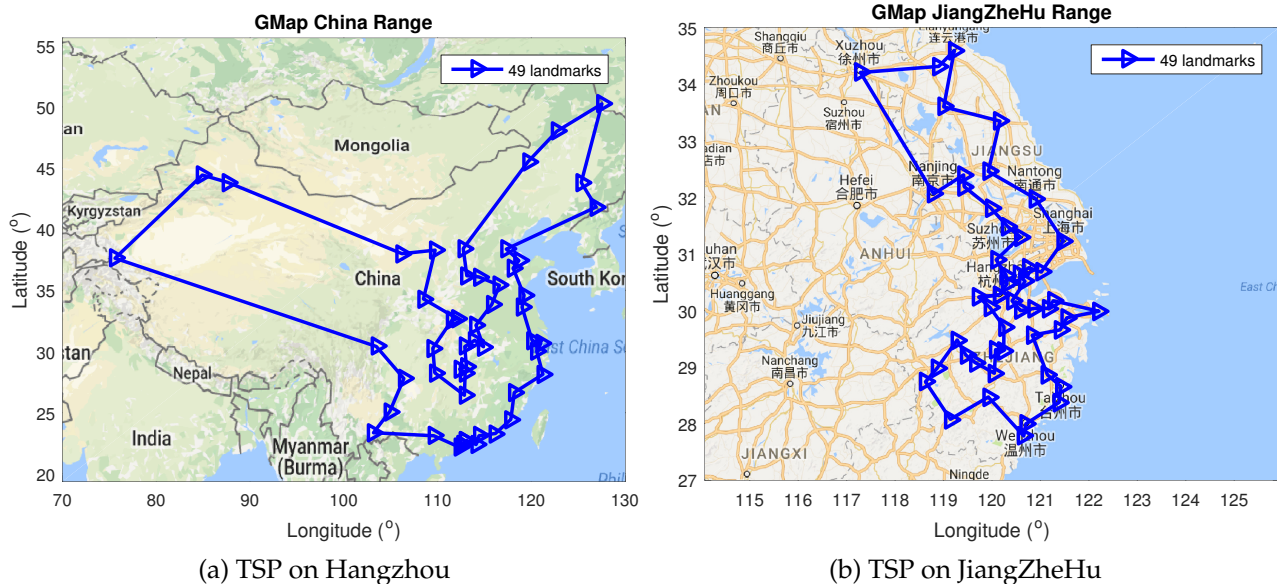


Figure 2: JiangZheHu is a wider range than Hangzhou. I am quite happy to solve a TSP on China range.

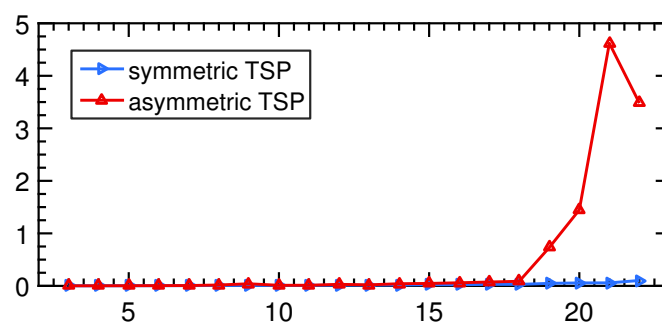


Figure 3: X-axis: number of landmarks, Y-axis: elapsed time in seconds. For Asymmetric TSP, running time starts to grow explosively at $n = 19$. We can expect Symmetric TSP starts to grow explosively after $n = 50$.

Appendix B Lab Code

Here let me put some important code(the part for different ILP formulation of TSP).

B.1 Symmetric Formulation

Here I use adjacent matrix.

```
# For small problem:
#dist=Matrix([[0,1,2],[2,0,1],[1,2,0]])
dist=Matrix(dist)
p=MixedIntegerLinearProgram(maximization=False) #,solver="PPL"
x=p.new_variable(nonnegative=True,integer=True)
t=p.new_variable(nonnegative=True,integer=True)
n=dist.nrows()
obj_func=0
```

```

for i in range(n):
    for j in range(n):
        obj_func+=x[i,j]*dist[i,j] if i!=j else 0
p.set_objective(obj_func)
for i in range(n):
    p.add_constraint(sum([x[i,j] for j in range(n) if i!=j])==1)
for j in range(n):
    p.add_constraint(sum([x[i,j] for i in range(n) if i!=j])==1)
for i in range(n):
    for j in range(1,n):
        if i==j:
            continue
        p.add_constraint(t[j]>=t[i]+1-n*(1-x[i,j]))
for i in range(n):
    p.add_constraint(t[i]<=n-1)

#p.show()
p.solve()

```

B.2 Asymmetric Formulation

Here I use language of graph.

```

p = MixedIntegerLinearProgram(maximization = False)

f = p.new_variable()
r = p.new_variable()

eps = 1/(2*Integer(g.order()))
x = g.vertex_iterator().next()

R = lambda x,y : (x,y) if x < y else (y,x)

# returns the variable corresponding to arc u,v
E = lambda u,v : f[R(u,v)]

# All the vertices have degree 2
for v in g:
    p.add_constraint(sum([ f[R(u,v)] for u in g.neighbors(v)]),
                    min = 2,
                    max = 2)

# r is greater than f
for u,v in g.edges(labels = None):
    p.add_constraint( r[(u,v)] + r[(v,u)] - f[R(u,v)], min = 0)
# defining the answer when g is not directed
tsp = Graph()
# no cycle which does not contain x
weight = lambda l : l if (l is not None and l) else 1
for v in g:
    if v != x:
        p.add_constraint(sum([ r[(u,v)] for u in g.neighbors(v)]),max = 1-eps)
p.set_objective(sum([ weight(l)*E(u,v) for u,v,l in g.edges()]) )
p.set_binary(f)

```

References

- [1] <http://www.openstreetmap.org/export#map=16/30.2802/120.1700>
- [2] https://github.com/sagemath/sagelib/blob/master/sage/graphs/generic_graph.py
- [3] https://en.wikipedia.org/wiki/Haversine_formula
- [4] https://en.wikipedia.org/wiki/Travelling_salesman_problem#Solving_by_conversion_to_symmetric_TSP