Optimizing Strategic Railway Capacity Planning

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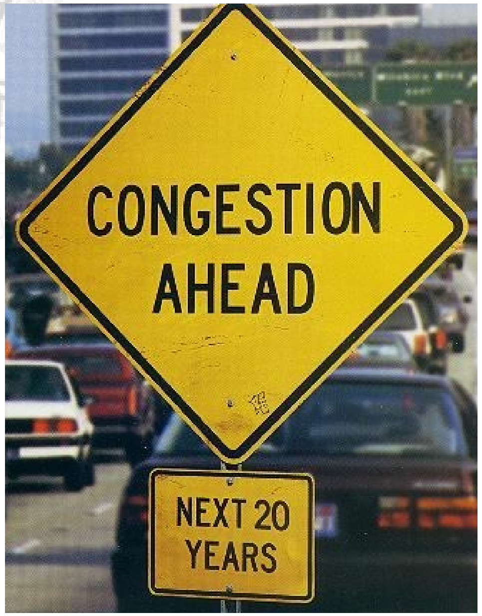
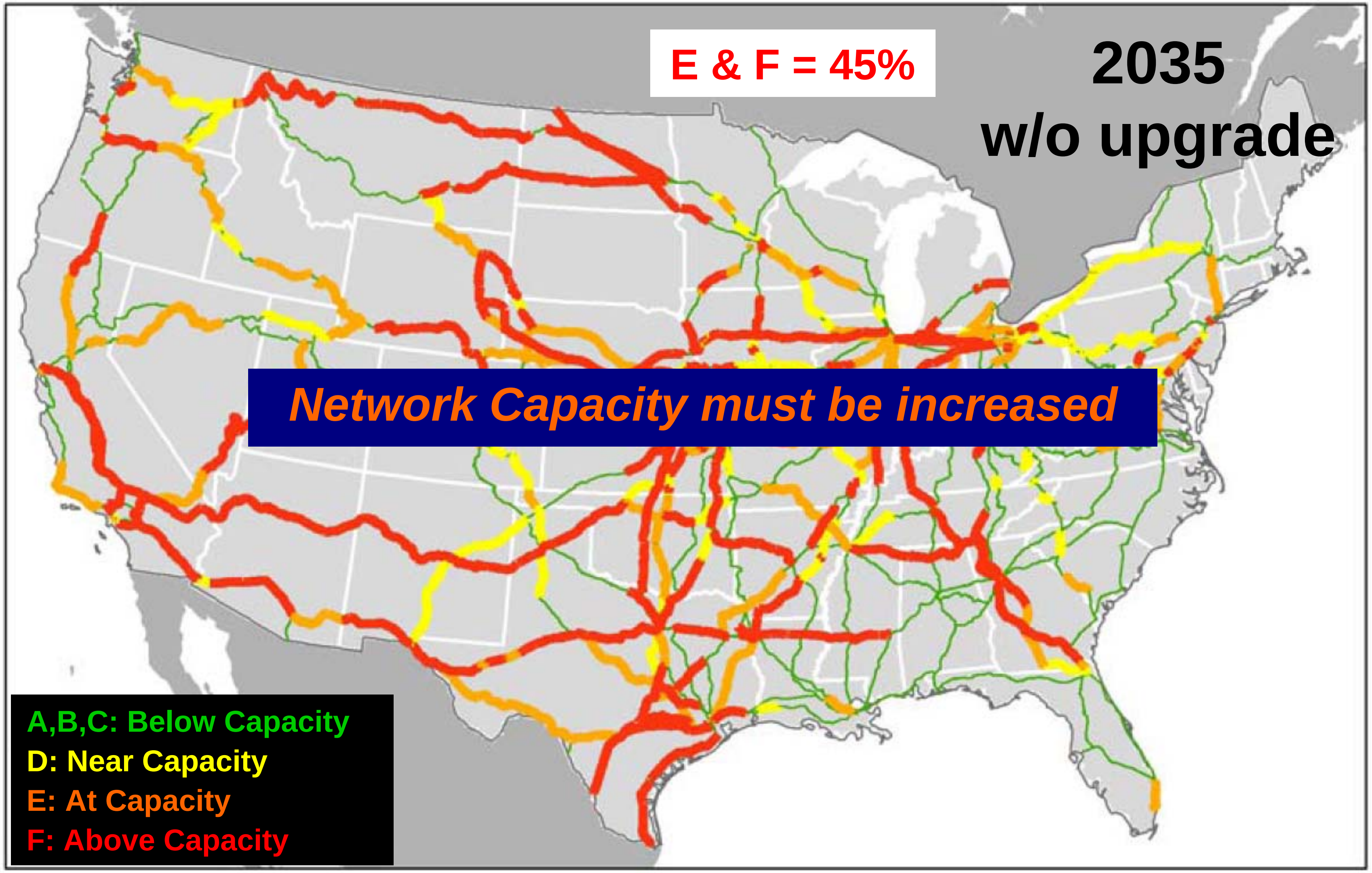
The North American railroad industry is facing capacity problems

- Capacity and network efficiency have become more important as traffic volumes increase
- ***In North America, the demand for freight rail services is projected to increase by 88% in 2035 compared to 2007***
- Capacity constraints are affecting network efficiency
- Problems range across many aspects of the railroad operation including:
  - Infrastructure
  - Equipment
  - Train dispatching, traffic mix
  - Human resources



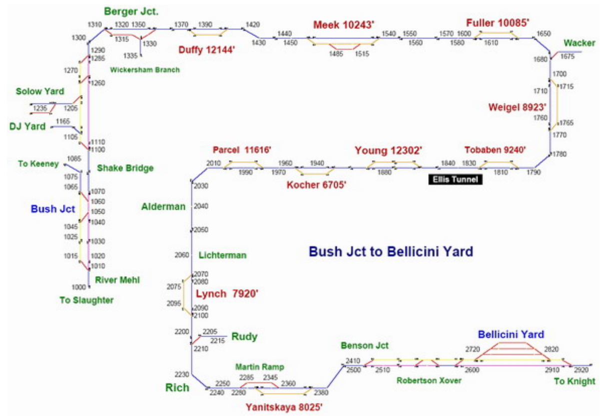
Source: Reebie TRANSEARCH and FHWA Freight Analysis Framework Project

The demand for freight rail services is projected to increase by 88% in 2035 compared to 2007

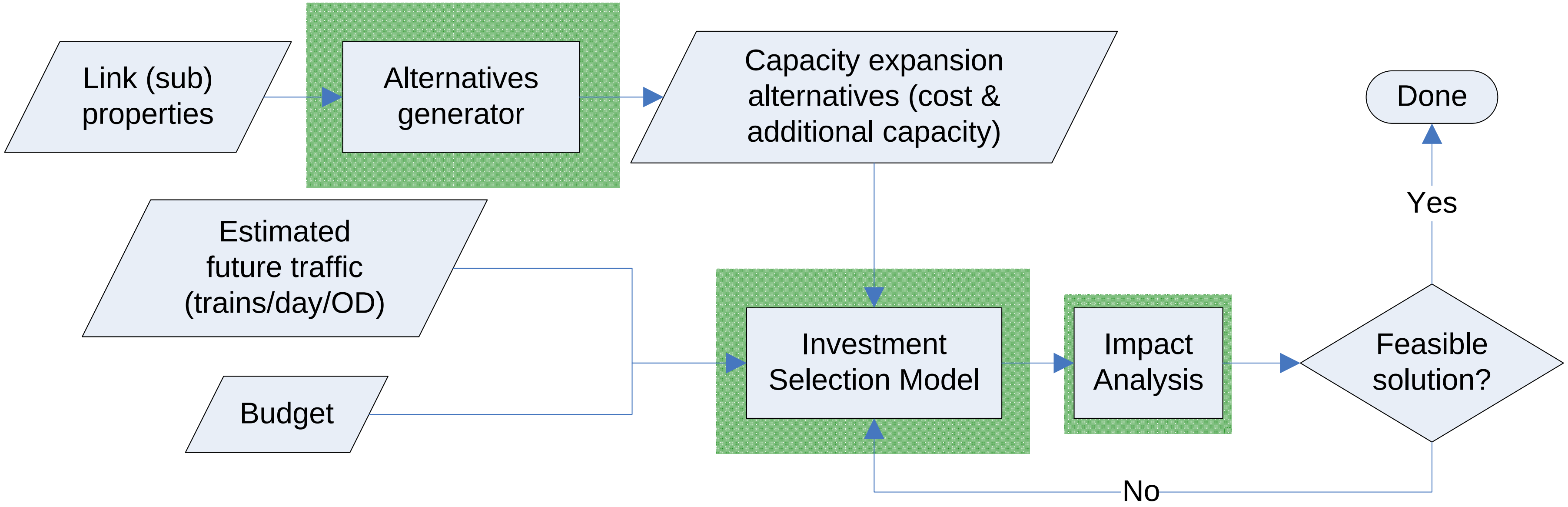


A "Decision Support Framework" to determine how to allocate capital in the best possible way

- Railroads rely on experienced personnel and simulation software to identify bottlenecks and propose methods to reduce the congestion
- Experienced railroaders often identify good solutions but ***this does not guarantee that all possible alternatives have been evaluated***
- Simulation usually deals with a section of the network, which ***may result in moving bottleneck around*** instead of solving it
- We propose a decision support framework to generate & evaluate possible alternatives and tackle the capacity planning problems in network level



This decision support framework contains three individual strategic planning tools



- Alternatives Generator (AG):
  - Enumerate possible expansion options with their cost and additional capacity
- Investment Selection Model (ISM):
  - Determine which subdivisions need to be upgraded with what kind of improvements (alternatives)
- Impact Analysis Module (IAM):
  - Evaluate the tradeoff between capital investment and delay cost

CN Parametric Capacity Model was selected to be the basis of AG

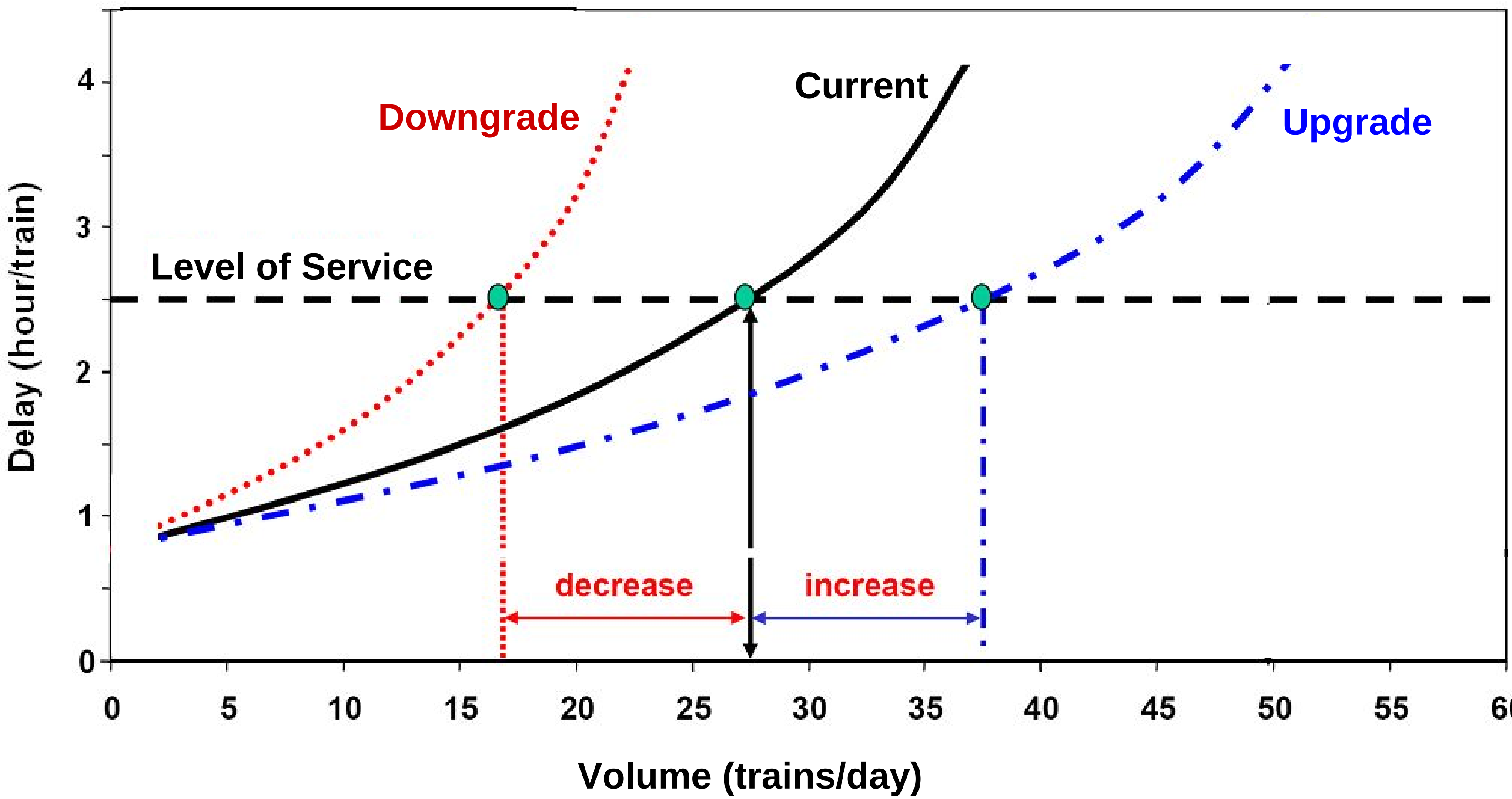
- Capacity is computed based on a set of key parameters
- Link Properties:
  - Plant parameters:
    - Length of Subdivision
    - Meet & Pass Locations
    - Signal Spacing
  - Traffic parameters:
    - Traffic Peaking
    - Priority Probability
    - Speed Ratio
    - Average Speed
  - Operating parameters
    - Track Maintenance
    - Stop on Line Time

$$\text{Train Delay} = A_o e^{BV}$$ ***(Krueger, 2000)***

A_o = Parametric Plant, Traffic, Operating Coefficient
B = Constant
V = Traffic Volume

Delay – Volume Plot

The output of the CN parametric model is a delay-volume relationship

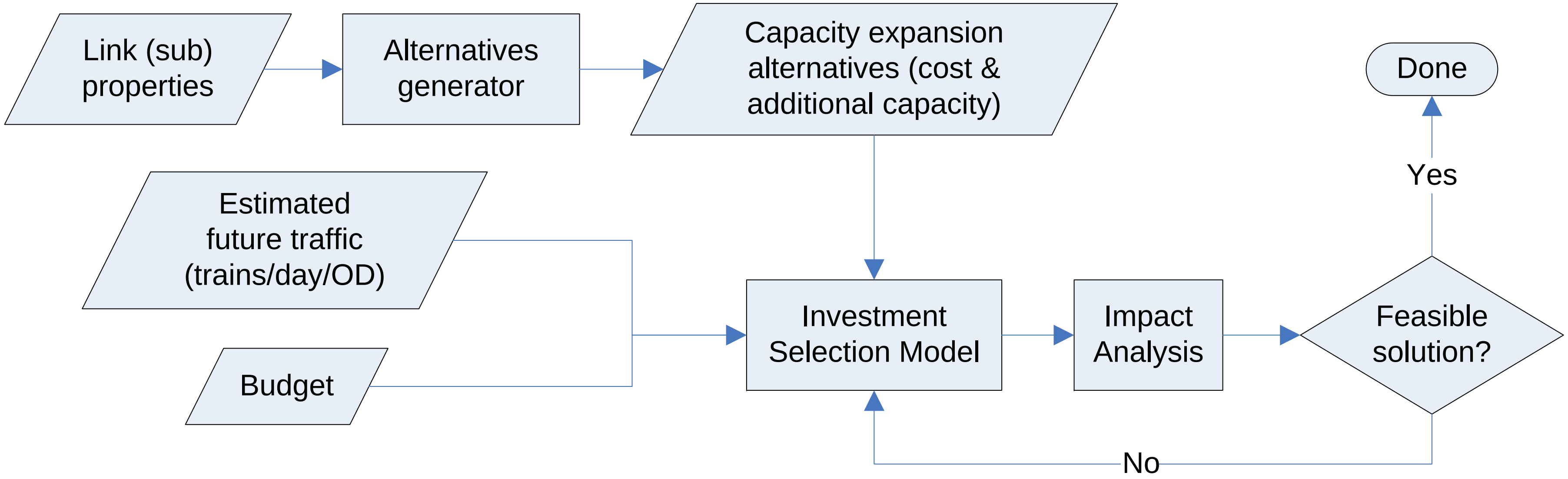


Adding enumeration and cost evaluation modules into CN model to create the alternatives generator

- **Enumeration Module**: automatically enumerating alternatives based on possible engineering options – adding (1) passing sidings, (2) intermediate signals, (3) 2nd main track
- **Cost Evaluation Module**: incorporating cost data into the parametric model to compute the construction cost of each alternative
- For example, a 100-mile sub with 9 sidings and no intermediate signal

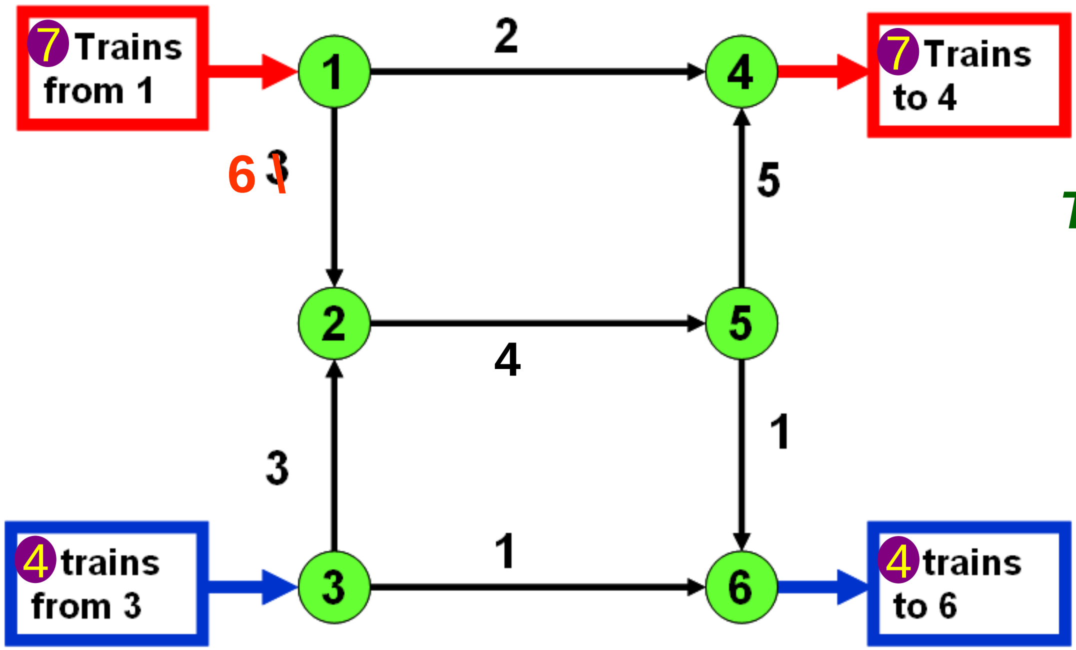
Alternatives	Sidings	Signals/Spacing	Capacity (trains/day)	Cost
1	+ 0	+ 0	+ 0	$0
2	+ 0	+ 1	+ 3	$1,000,000
3	+ 0	+ 2	+ 4	$2,000,000
4	+ 1	+ 0	+ 3	$5,470,000
5	+ 1	+ 1	+ 6	$6,570,000
6	+ 1	+ 2	+ 7	$7,670,000
7	+ 2	+ 0	+ 6	$10,940,000
8	+ 2	+ 1	+ 9	$12,140,000
9	+ 2	+ 2	+ 10	$13,340,000
10	Adding 2nd Main Track		+ 50	$204,750,000

This decision support framework contains three individual strategic planning tools



- Alternatives Generator:
  - Enumerate possible expansion options with their cost and additional capacity
- ***Investment Selection Model (ISM):***
  - ***Determine which subdivisions need to be upgraded with what kind of improvements (alternatives)***
- Impact Analysis Module:
  - Evaluate the tradeoff between capital investment and delay cost

Trains with different ODs are similar to multiple commodities, and they share the line capacity



Task:

- ***Which link(s) to upgrade ?***
- ***With what kind of capacity improvement alternative?***

i	j	Alternatives	Capacity (trains/day)	Cost
1	2	1	+ 3	$1,000,000
1	2	2	+ 4	$2,000,000
1	2	3	+ 6	$6,570,000
.	.	.	.	
.	.	.	.	

General Investment Selection Model (ISM)

$$\min \ \alpha \sum_i \sum_j \sum_q h_{ij}^q y_{ij}^q + \gamma \sum_i \sum_j \sum_k c_{ij} x_{ij}^k$$ ⟵ capital invest + flow cost

$s.t.$

$$\sum_i \sum_j \sum_q h_{ij}^q y_{ij}^q \le B$$ ⟵ budget constraint

$$\sum_k x_{ij}^k \le U_{ij} + \sum_q u_{ij}^q y_{ij}^q \quad \forall\, i, j\ (i \ne j)$$ ⟵ capacity constraint

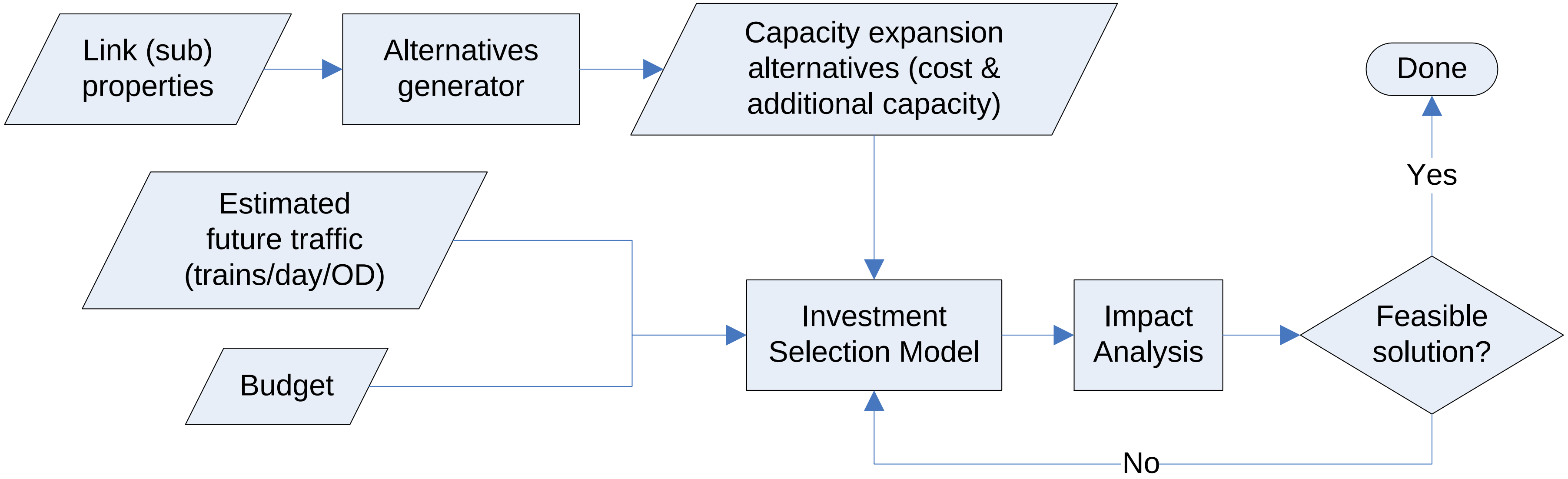
$$\sum_q y_{ij}^q \le 1 \quad \forall\, i, j\ (i \ne j)$$ ⟵ alternative constraint

$$\sum_j x_{ij}^k - \sum_j x_{ji}^k = \begin{cases} d_k & \text{if } i \in s_k \\ -d_k & \text{if } i \in t_k \\ 0 & \text{otherwise} \end{cases} \quad \forall\, k$$ ⟵ flow conservation

and

$x_{ij}^k \in$ *positive integer*, $y_{ij}^q \in \{0,1\}$

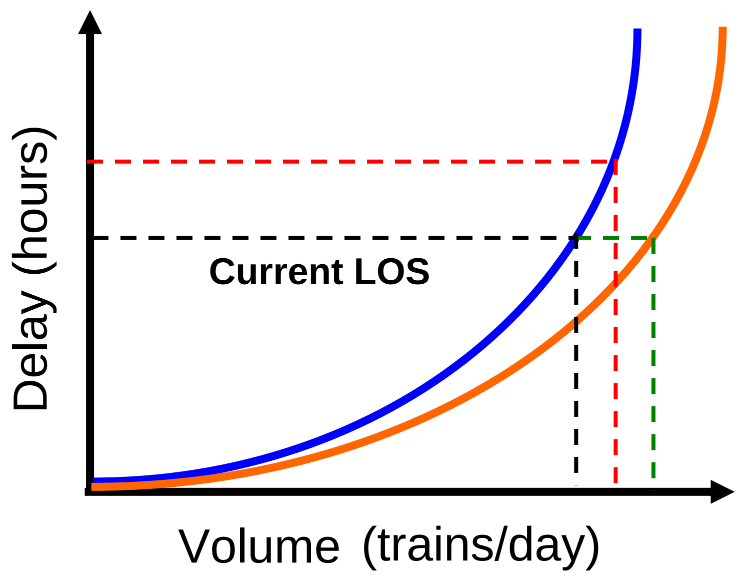
This decision support framework contains three individual strategic planning tools



- Alternatives Generator:
  - Enumerate possible expansion options with their cost and additional capacity
- Investment Selection Model (ISM):
  - Determine which subdivisions need to be upgraded with what kind of improvements (alternatives)
- ***Impact Analysis Module:***
  - ***Evaluate the tradeoff between capital investment and delay cost***

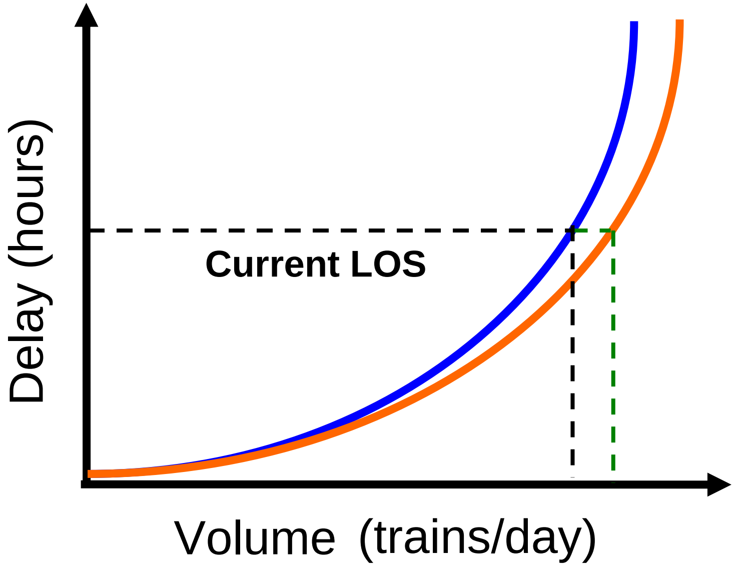
There is a trade-off between "Capital Investment" and "Train Delay Cost"

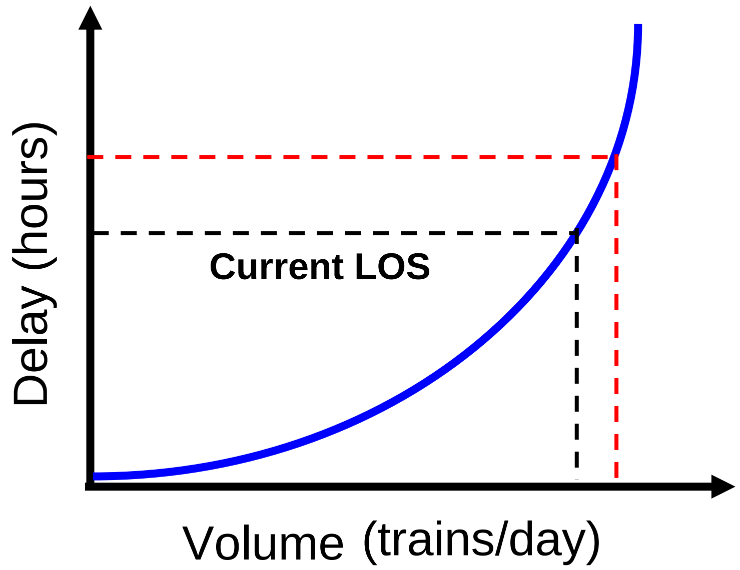
- ISM determines the best set of capacity improvement alternatives with the premise that ***"Level of Service remains the same"***
- However, it is possible to gain modest capacity by increasing delay (lowering Level of Service)



- Impact analysis module determines if the capital investment is cost-effective by comparing the capital investment & delay cost
- The output will be a set of options that eventually the capacity planner will make the final decision

There is a trade-off between "Capital Investment" and "Train Delay Cost"





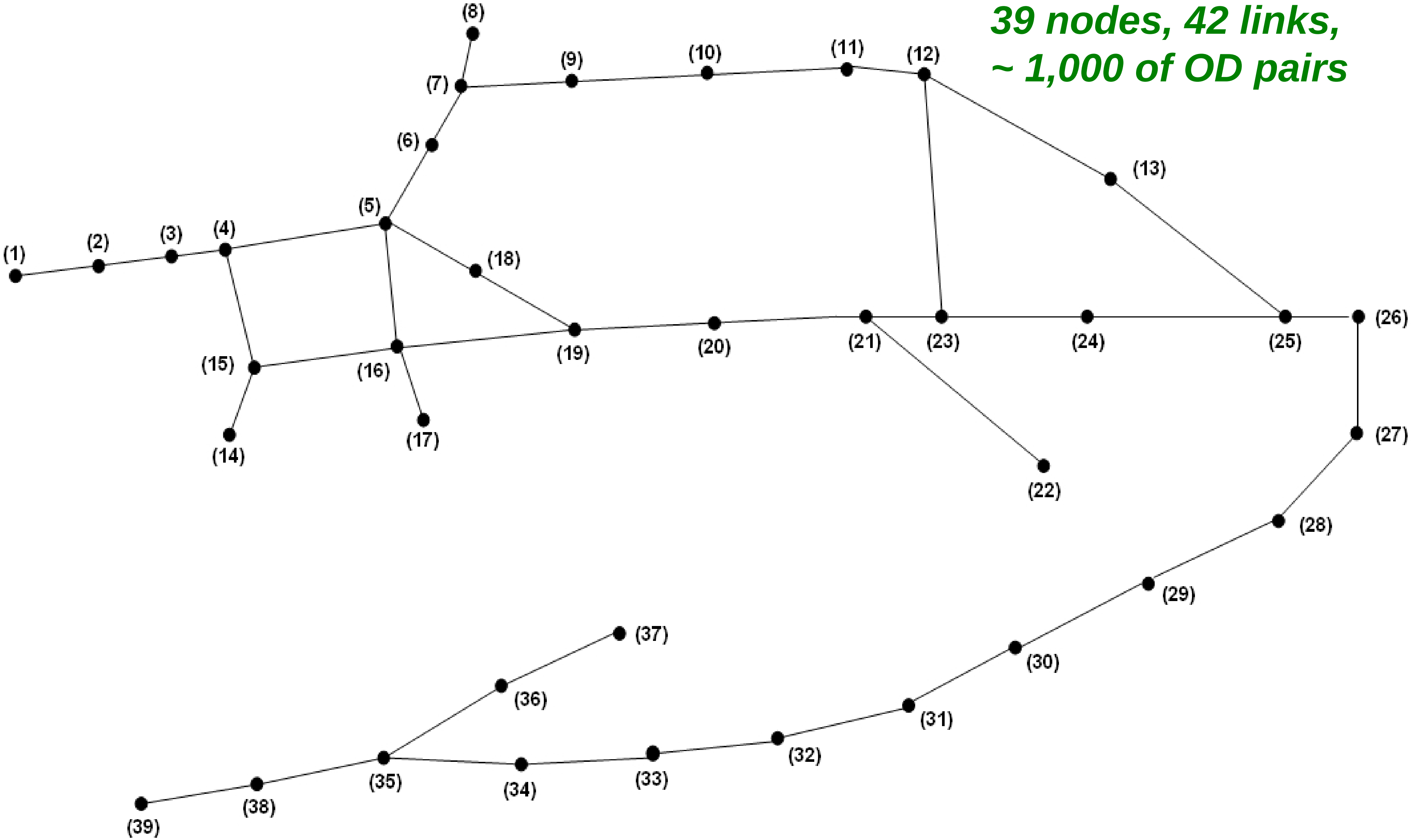
Net Cost from Upgrading Infrastructure **VS** **Delay Cost = Unit Delay Cost x Hours x Trains**

Benefit = Delay Cost / Net Cost

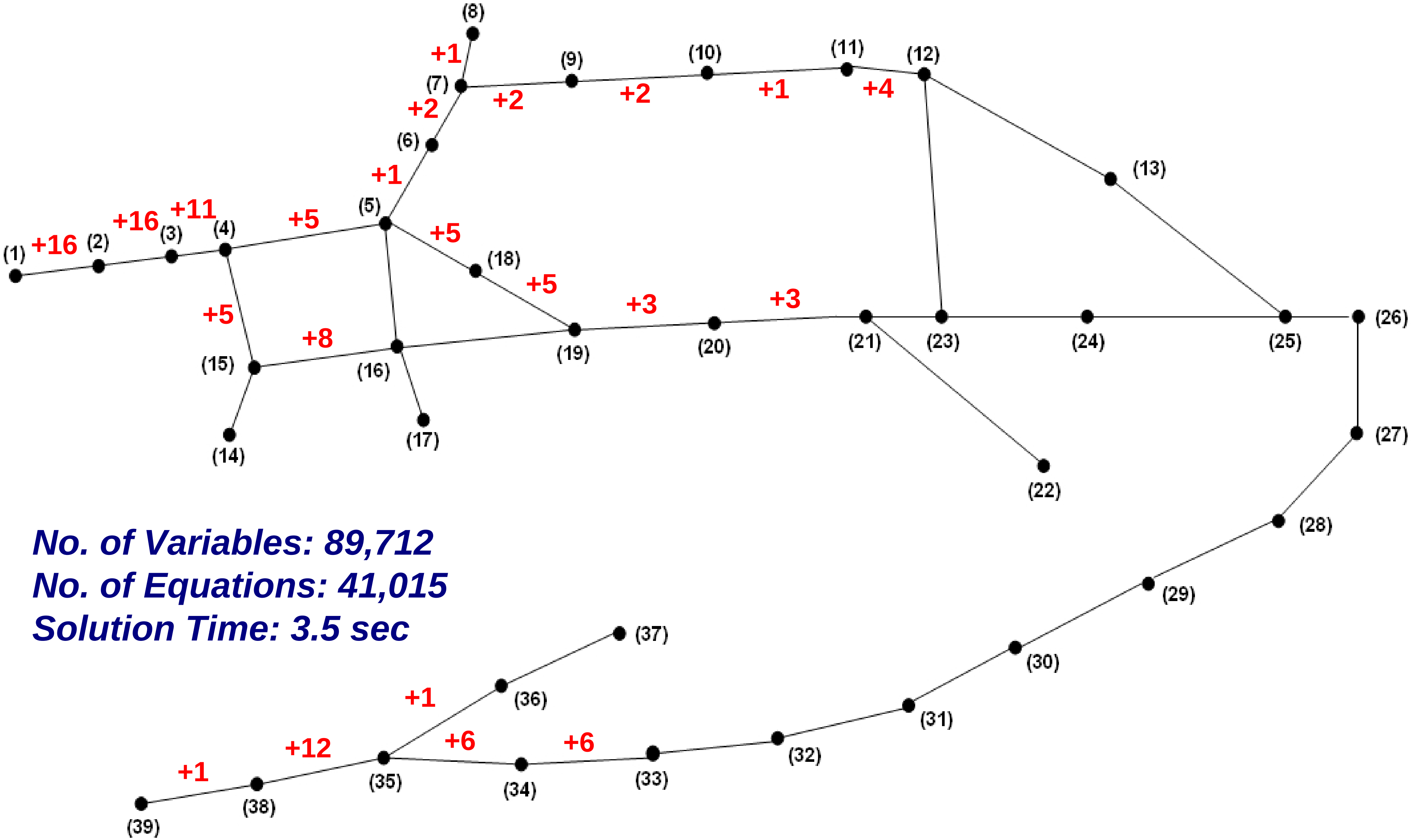
(return on investment)

Empirical Case Study

39 nodes, 42 links,
~ 1,000 of OD pairs

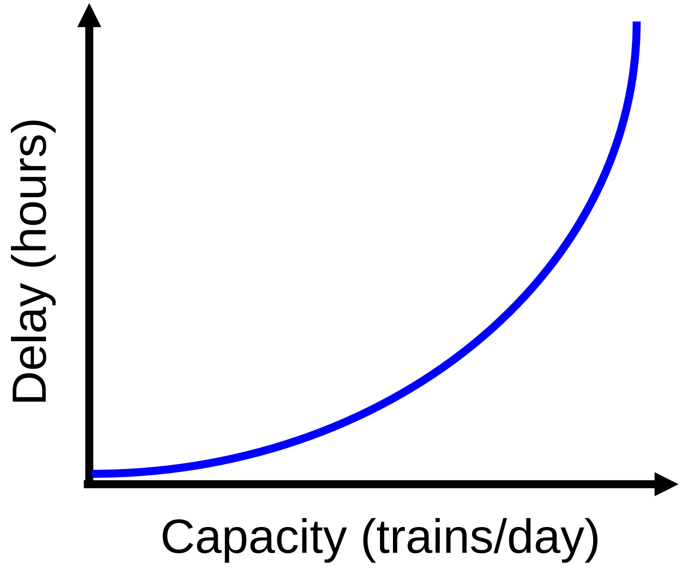


Capacity improvement for 50% demand increase



No. of Variables: 89,712
No. of Equations: 41,015
Solution Time: 3.5 sec

Impact analysis module compares capital investment with train delay cost



i	j	Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	2	16	15	16	16	16	16	16
2	3	14	15	15	16	15	16	13
3	4	9	10	10	11	10	11	8
4	5	4	4	5	4	5	4	5
5	6	1	0	0	0	0	0	1
6	7	1	2	2	1	2	0	2
7	8	1	0	1	1	1	0	0
7	9	1	2	0	1	0	1	1
9	10	1	2	0	1	0	1	1
10	11	0	1	0	1	0	1	1
11	12	2	0	4	0	4	0	3
4	15	3	5	5	5	5	5	4
15	16	7	7	6	7	6	7	8
5	18	4	5	5	5	5	5	5
18	19	4	5	5	5	5	5	5
19	20	1	3	3	3	3	3	3
20	21	1	3	3	3	3	3	3
33	34	6	4	5	5	6	5	6
34	35	5	4	2	6	5	6	6
35	36	0	0	1	0	1	0	0
35	38	2	7	9	11	12	12	10
38	39	0	0	0	1	0	1	0

- ISM determines required upgrade with the premise “LOS is unchanged”
- It is possible to gain a little bit capacity by increasing delay (reduce LOS)
- Train Delay Cost = $ 261 per train-hour

Net Cost vs. Train Delay Cost

Link		Capacity		Cost ($,k)		Difference ($,k)	Benefit
i	j	Current	Max	Train Delay	Net Cost	Delay - Net Cost	
35	38	24	36	31,107	2,289	28,818	13.59
5	18	34	39	18,200	1,643	16,558	11.08
3	4	40	51	135,720	13,169	122,551	10.31
18	19	34	39	12,663	2,735	9,928	4.63
20	21	36	39	5,015	1,393	3,622	3.60
15	16	14	22	7,953	2,435	5,518	3.27
2	3						3.14
19	20						2.96
4	5						1.90
1	2						1.55
33	34						1.31
34	35						1.20
4	15						0.82
6	7						0.70
38	39	23	24	326	1,218	(892)	0.27
11	12	6	10	584	2,435	(1,851)	0.24
35	36	32	33	224	1,218	(994)	0.18
5	6	15	16	217	1,218	(1,000)	0.18
7	8	15	16	217	1,218	(1,000)	0.18
9	10	5	7	258	2,435	(2,177)	0.11
10	11	6	7	95	1,218	(1,122)	0.08
7	9	5	7	153	2,435	(2,282)	0.06
Sum				506,697	185,852	320,845	

$$\min \ Delay\ (no\ upgrade) - \sum_l x_l d_l$$

$$s.t. \ \sum_l x_l c_l \le Budget$$

A decision support framework is developed to assist railway capacity planning projects

- AG can enumerate possible expansion options with their cost and additional capacity
- ISM successfully and efficiently solved the problem regarding where to upgrade and what kind of engineering options should be conducted
- IAM can further explore the trade-off between capital investment and train delay cost
- This process will help RRs ***maximize their benefit*** from expansion projects and thus be better able to provide ***reliable service*** to their customers, and ***return on shareholder investment***
- Future work:
  - Enable demand rejection scenario for insufficient budget
  - Develop a multi-period decision making model with stochastic future demand