Urban Bus Network of Priority Lanes: a Combined Multi-Objective, Multi-Criteria and Group Decision-Making Approach

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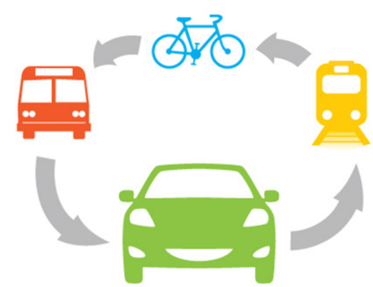
General framework

- Single-objective problem — SOP
- Multi-objective problem — MOP
- Multi-criteria decision making — MCDM
- Group decision making — GDM

Motivation

- Israel's ministry of transport published in 2011 a call for proposals for a sustainable transportation model city (60M USD)
- Proposal's components:
  - **priority lanes (30%)**
  - advanced technologies for PT
  - PT network update
  - improving passengers' infrastructure
  - cycling lanes
  - improving pedestrians' infrastructure
  - sustainable parking policy



Background

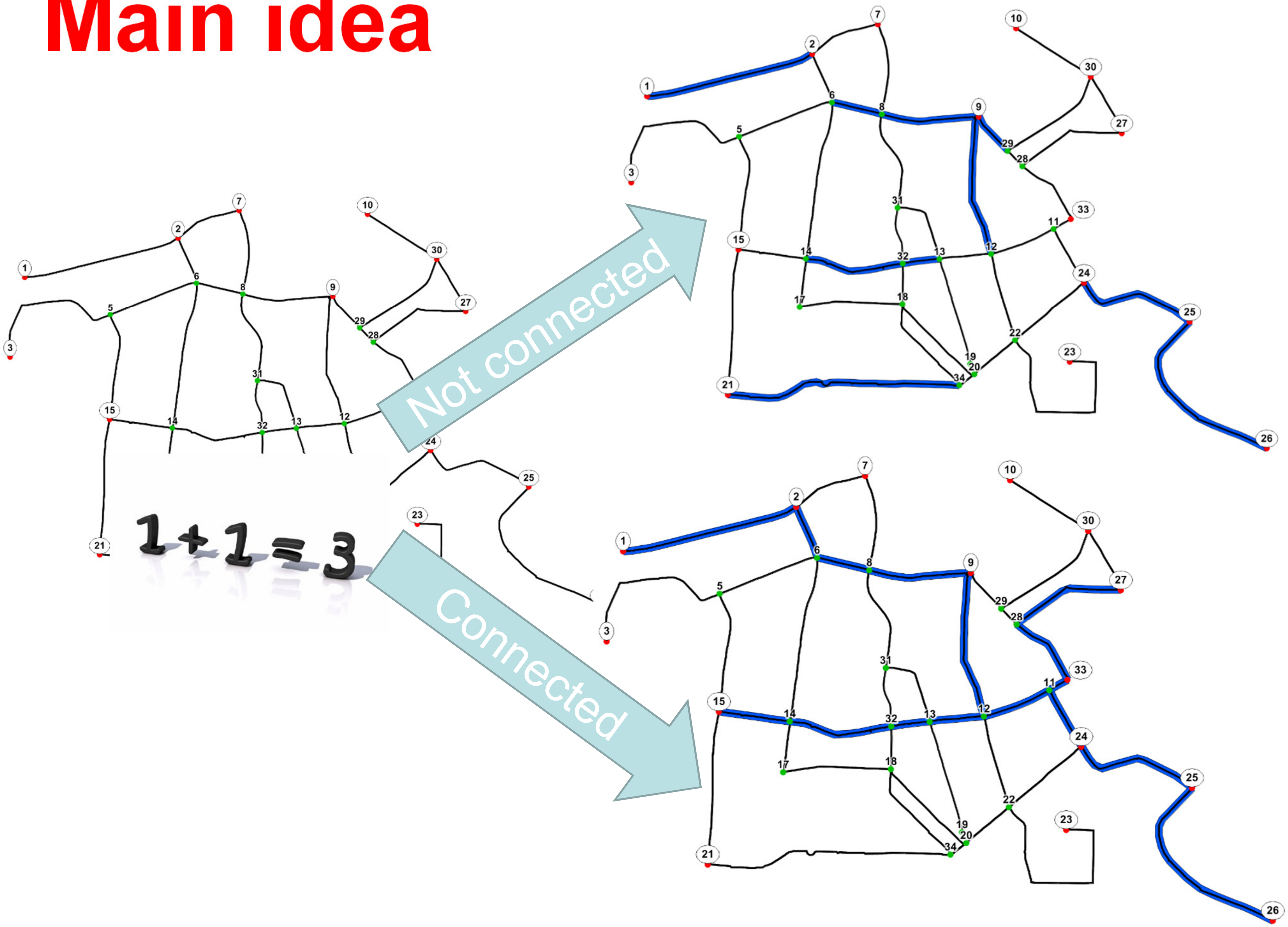
- Bus priority schemes and techniques on urban roads and highways have proven effective

- Bus priority schemes contribute to:
  - Decreased travel time
  - Improved reliability
  - Improved vehicle productivity

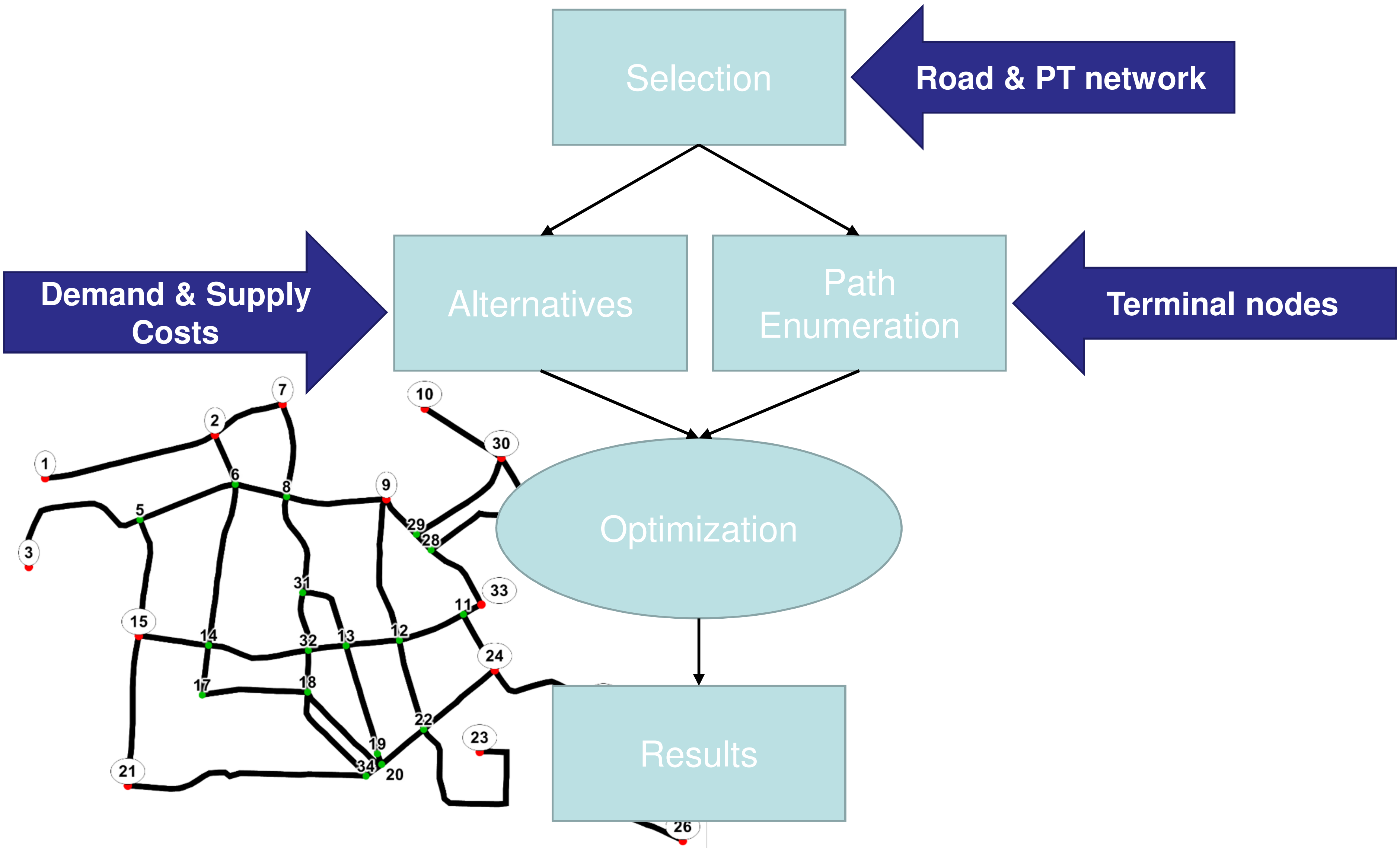
Network approach

- System-wide approach for designing priority lanes [Mesbah, Sarvi, and Currie, IEEE, 2011]
- Optimal Connected Urban Bus Network of Priority Lanes [Hadas and Ceder, TRR, 2014]

Main idea



Model's framework

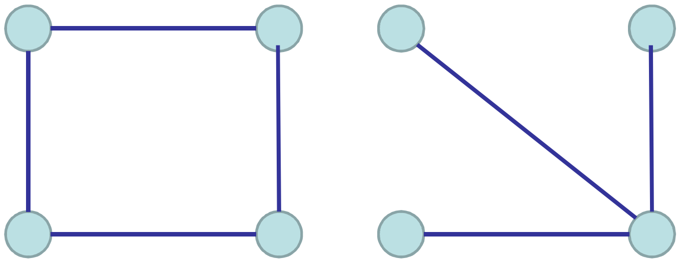


Why Multi-Objective formulation?

Stakeholders / Objectives	Passenger	Authority	Operator
Budget		V	
Connectivity	V	V	
Time saving	V	V	V

Objectives

- To select a set of continuous priority-lanes (paths) that:
  - Maximizes the total travel time saving
  - Maintains a balanced origin and destination nodes



  - Minimizes the required budget

Optimization Model

$$\max \sum_i \sum_j \sum_k x_{i,j}^k \cdot v_{i,j}^k \cdot f_{i,j}$$

$$\max \min_{i \in SL} \left\{ \min_j \left(\sum_t px^{j,t}, \sum_s px^{s,j} \right) \right\}$$

$$\min \sum_i \sum_j \sum_k x_{i,j}^k \cdot c_{i,j}^k$$

s.t.

$$\sum_i \sum_j \sum_k x_{i,j}^k \cdot c_{i,j}^k \le B \ \forall i, j \in n$$

$$\sum_k x_{i,j}^k \le 1 \ \forall i, j \in N$$

$$\sum_k x_{i,j}^k - \left[\sum_s \sum_{t \ne s} \left(p_{i,j}^{s,t} \cdot px^{s,t} \right) \ge 1 \right] = 0 \ \forall i, j \in N$$

$$x_{i,j}^k = \{0,1\}$$

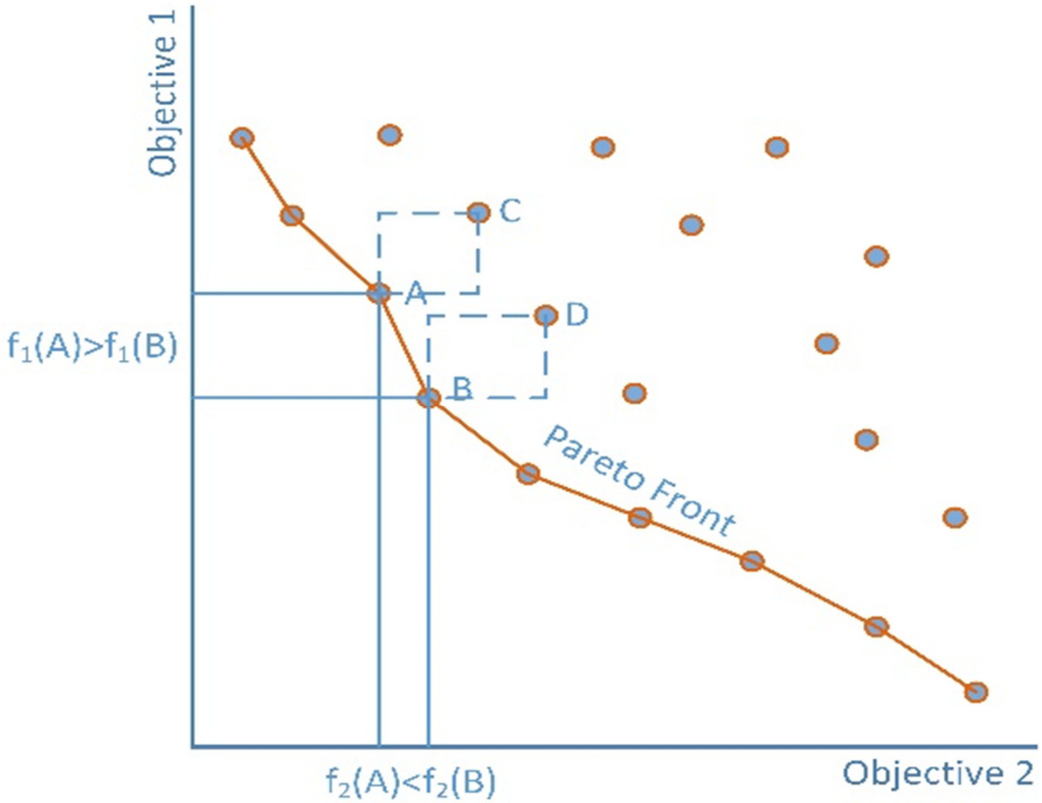
$$px^{s,t} = \{0,1\}$$

$$Dl \le \sum_t px^{s,t} \le Du \ \forall s \in I, s \ne t$$

$$Dl \le \sum_s px^{s,t} \le Du \ \forall t \in I, s \ne t$$

- $x_{i,j}^k$ road section selection
- k alternative
- (i, j) road section
- $c_{i,j}^k$ construction costs
- $v_{i,j}^k$ travel time saving
- $f_{i,j}$ passengers flow
- $p_{i,j}^{s,t}$ is road section part of path
- $px^{s,t}$ path selection
- D_l, D_u node degree bounds

The Pareto front



Multi-Objective Evolutionary Algorithms

- EA algorithms were found to be efficient for solving MOP
- Main advantage – they generate sets of solutions
- SPEA2 – (improved) Strength Pareto Evolutionary Algorithm [Zitzler et al, 2001]
- Uses:
  - strength (number of solutions an individual dominates)
  - Raw fitness (strengths of individual’s dominators)

SPEA2 algorithm

Algorithm – SPEA2

Input: N - Archive size
M - Offspring population size
T - Maximum number of generations

Output: A* - Non-dominated set

1. Initialization: Generate an initial population P_0 and create the empty archive (external set) $A_0=\varnothing$. Set $t=0$.
2. Fitness assignment: Calculate fitness values of individuals in P_t and A_t.
3. Environmental selection: Copy all non-dominated individuals in P_t and A_t to A_{t+1}. If size of A_{t+1} exceeds N then reduce A_{t+1} by means of the truncation operator, otherwise if size of A_{t+1} is less than N then fill A_{t+1} with dominated individuals in P_t and A_t.
4. Termination: If $t \geq T$ or another stopping criterion is satisfied then set $A*$ to the set of decision vectors represented by the non-dominated individuals in A_{t+1}. Stop.
5. Mating selection: Perform binary tournament selection with replacement on A_{t+1} in order to fill the mating pool.
6. Variation: Apply recombination and mutation operators to the mating pool and set P_{t+1} to the resulting population. Increment generation counter ($t=t+1$) and go to Step 2.

Case Study

- Israel's ministry of transport published in 2011 a call for proposals for a sustainable transportation model city (60M USD)
- Proposal's components:
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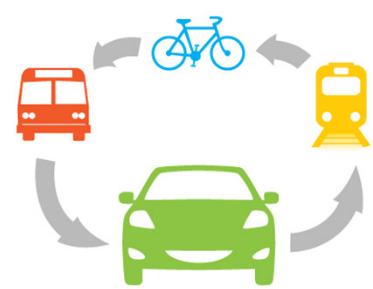
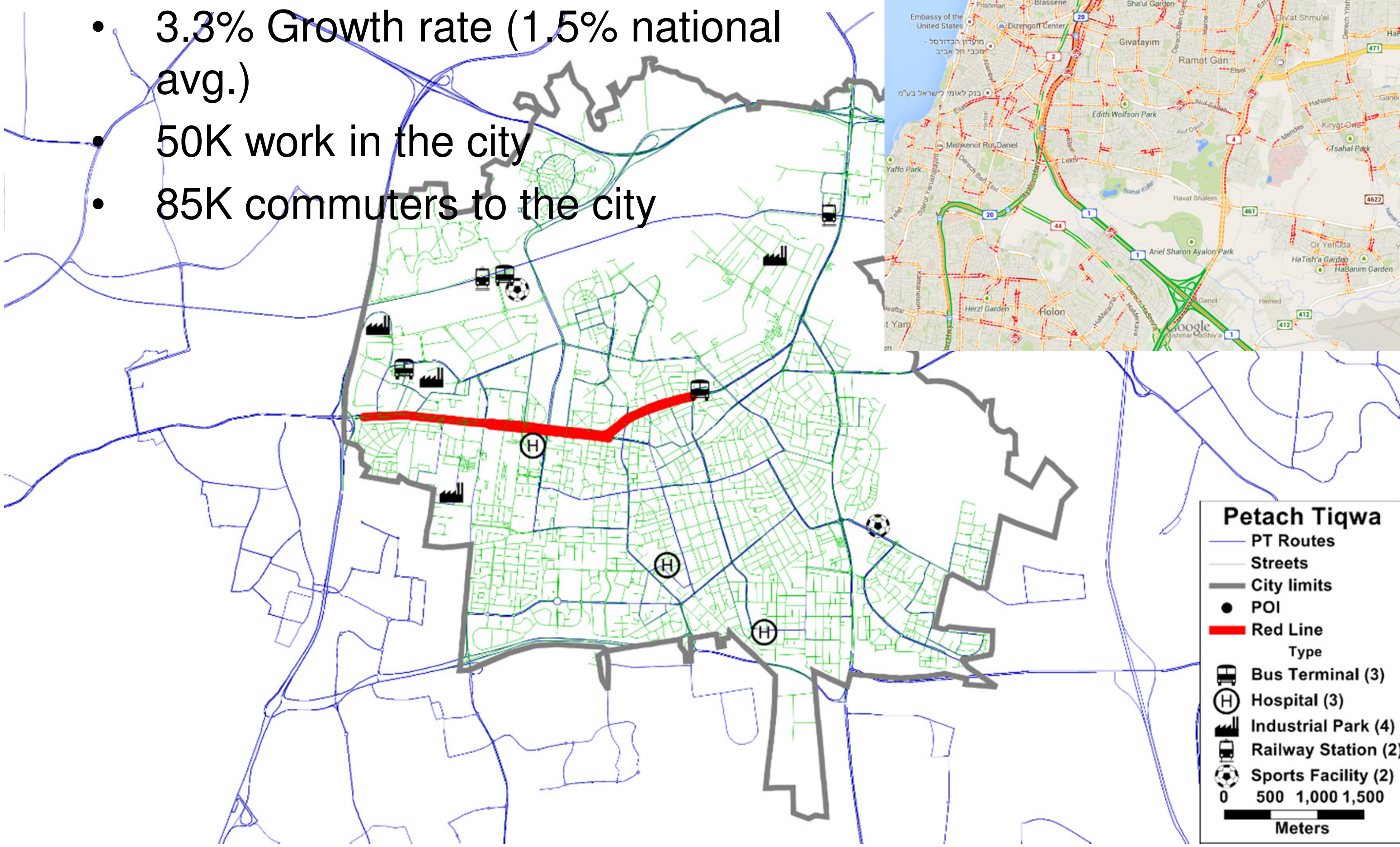
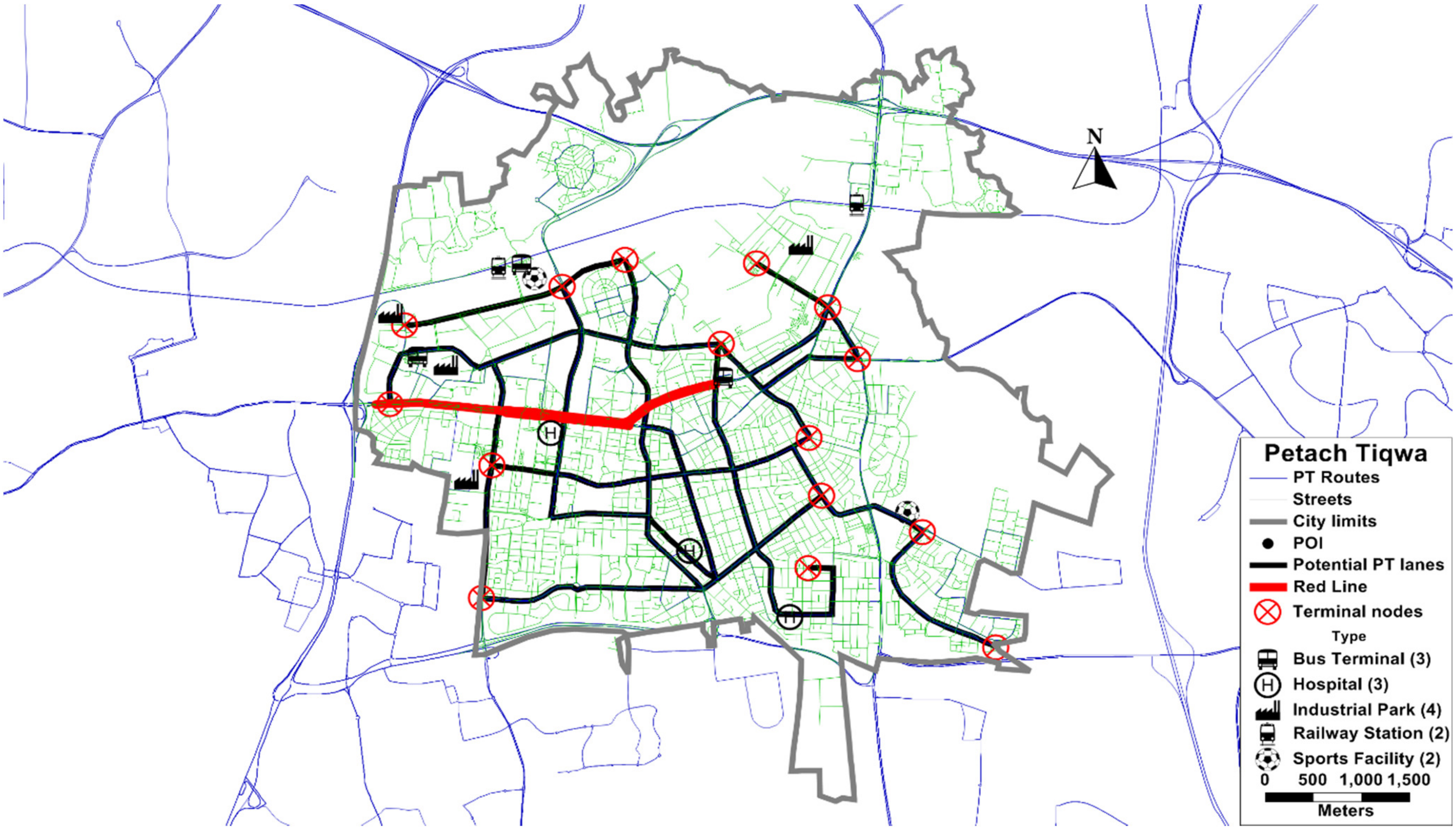


Case Study at Petah-Tiqwa

- 5^{th} largest city
- 39 KM^2
- 210K residents
- 3.3% Growth rate (1.5% national avg.)
- 50K work in the city
- 85K commuters to the city



PT network with potential road-sections and terminals



Alternatives costs & time saving

- Alternatives
  - – exclusive lanes (grade-separated busways)
  - – semi-exclusive lanes (at-grade busways)
- one-KM cost was estimated according to a given costs break-down

Alternatives time saving

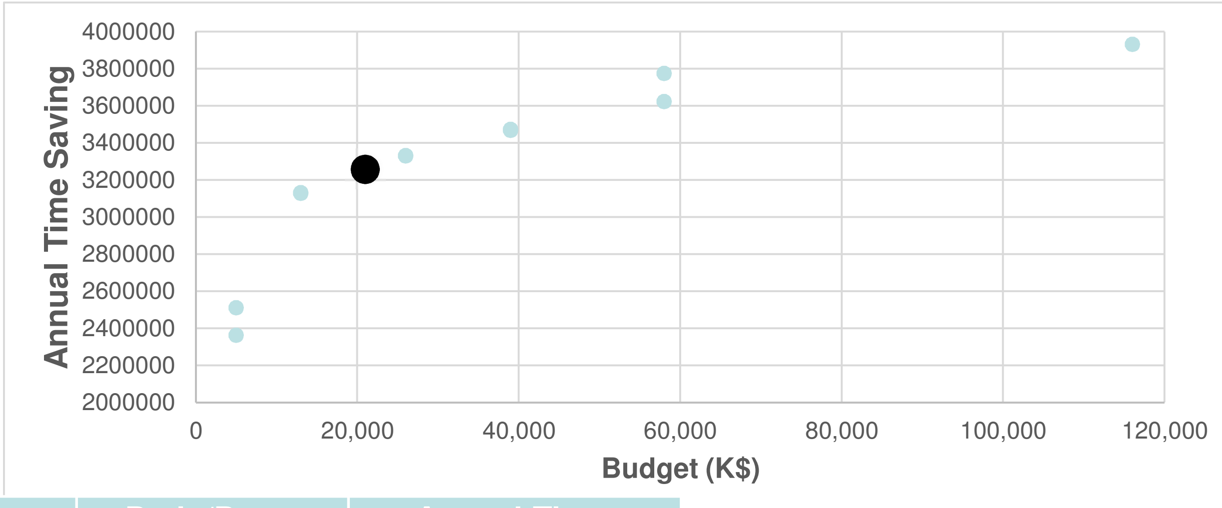
- **annual time saving (ATS) for distance traveled**

$$\text{ATS} = \text{E1} \cdot MAX\ (PTE,\ XE \cdot AE) \cdot PTS \cdot TD \cdot P$$

- – E1 - time saving elasticity of PT
- – PTE - total PT passengers traveling along the road section
- – XE - cross-elasticity of vehicle users to PT
- – AE - number of private vehicle users traveling along the road section
- – PTS - time saving for PT users results from a priority lane
- – TD - road section length
- – P - annual peak factor

			Semi-exclusive		Exclusive	
O	D	L [meters]	ATS	Cost [K$]	ATS	Cost [K$]
1	2	1689	35839	222	46591	3379
2	1	1689	82390	222	107108	3379
2	6	515	18690	68	24297	1031
2	7	727	0	96	0	1454
3	5	1622	112164	213	145814	3244
4	16	2362	39742	311	51665	4725
5	3	1622	53142	213	69084	3244
5	6	979	28996	129	37695	1958
5	15	1140	34582	150	44956	2280
6	2	515	25133	68	32673	1031
6	5	979	37705	129	49017	1958
6	8	506	38960	67	50648	1012
6	14	1566	51998	206	67597	3133

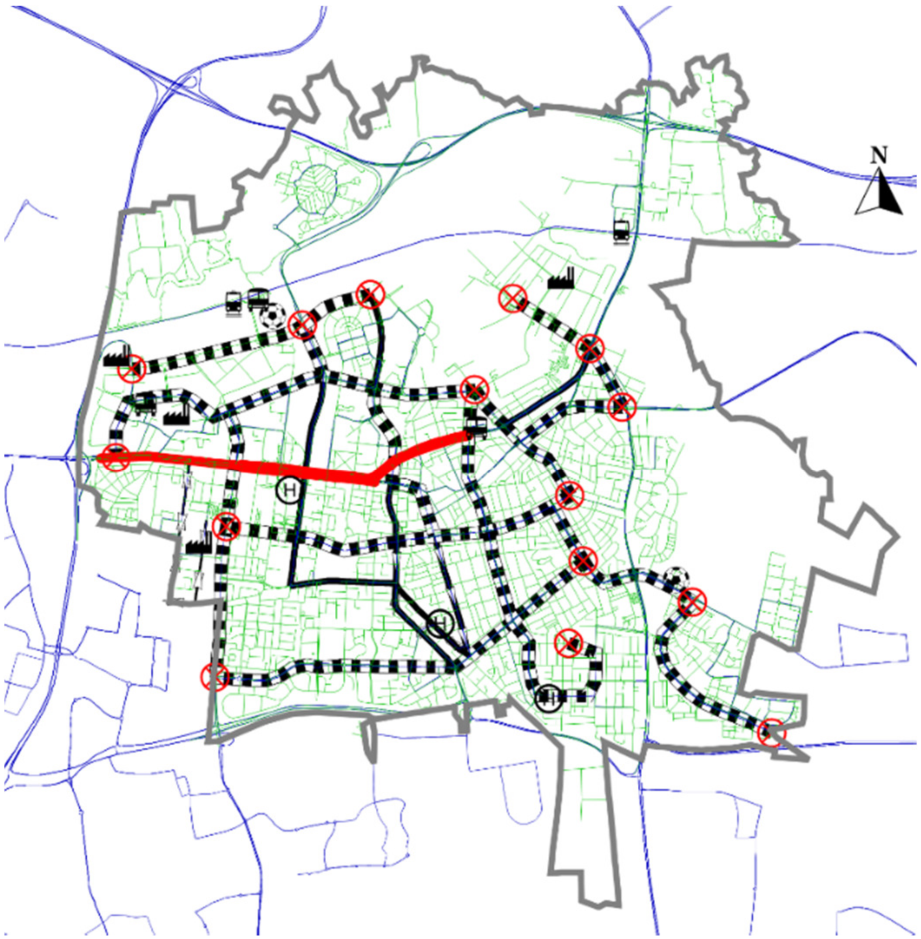
Single-Objective Problem Results



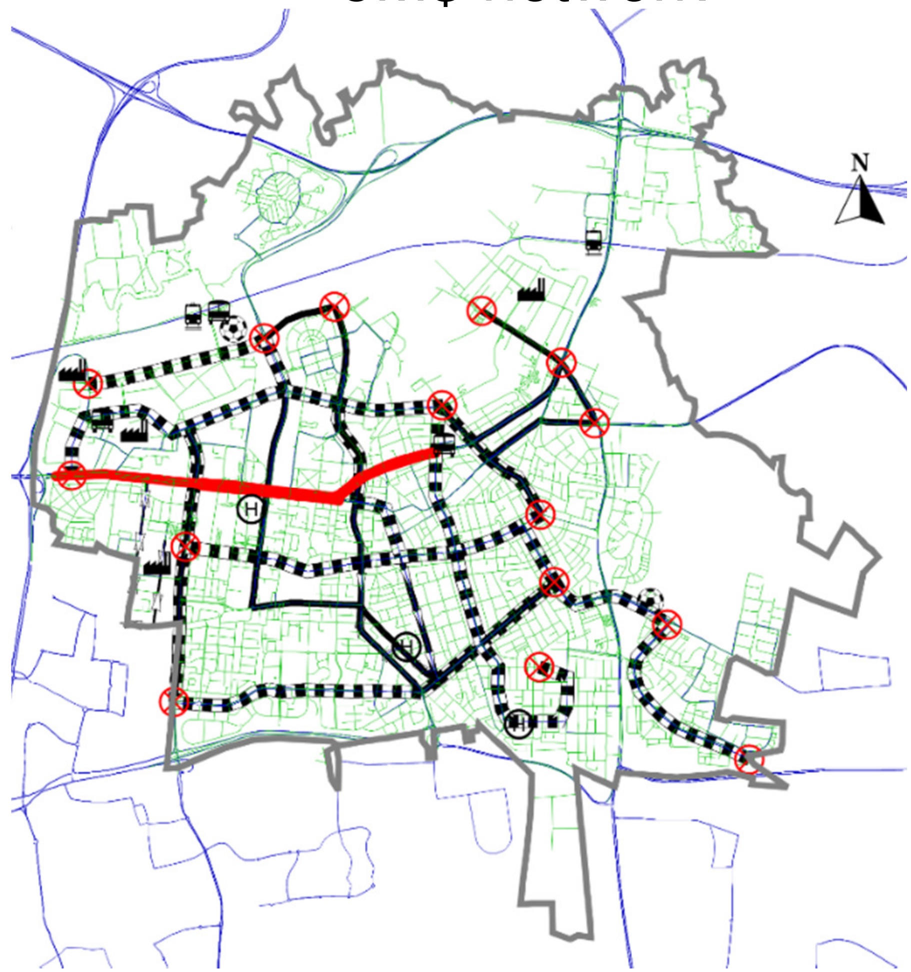
Budget (K$)	Dl/Du	Dmin/Dmax	Annual Time Saving (Pax x KM)
116,000 (Unlimited)	0/14	14/14	3932159
58,000 (max. budget)	0/14	0/14 (3 nodes)	3774525
58,000 (max. budget)	3/14	3/7	3623332
39,000	0/14	0/3 (3 nodes) *	3473065
39,000	1/14	1/12	3468331
26,000	0/14	0/11 (3 nodes)	3332067
26,000	1/14	1/4	3328767
21,000	0/14	0/11 (3 nodes)	3260146
21,000	**1/14**	**1/3**	**3256846**
13,000	0/14	0/1 (3 nodes)	3130844
13,000	1/14	1/3	3127544
5,000	0/14	0/5 (7 nodes)	2510285
5,000	0/1	0/1 (6 nodes)	2362232

Network's Comparison

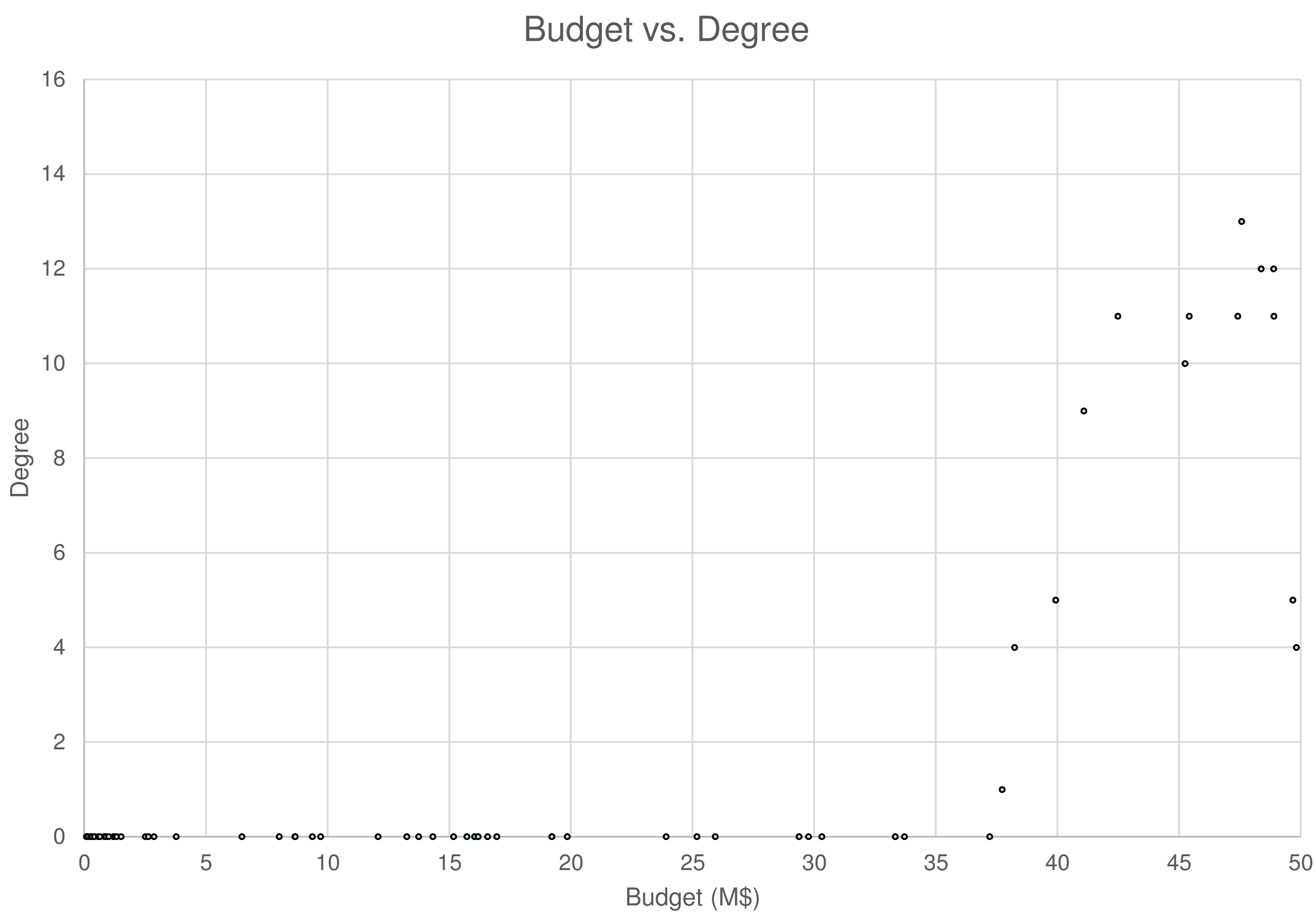
Selected (21M$) **network**



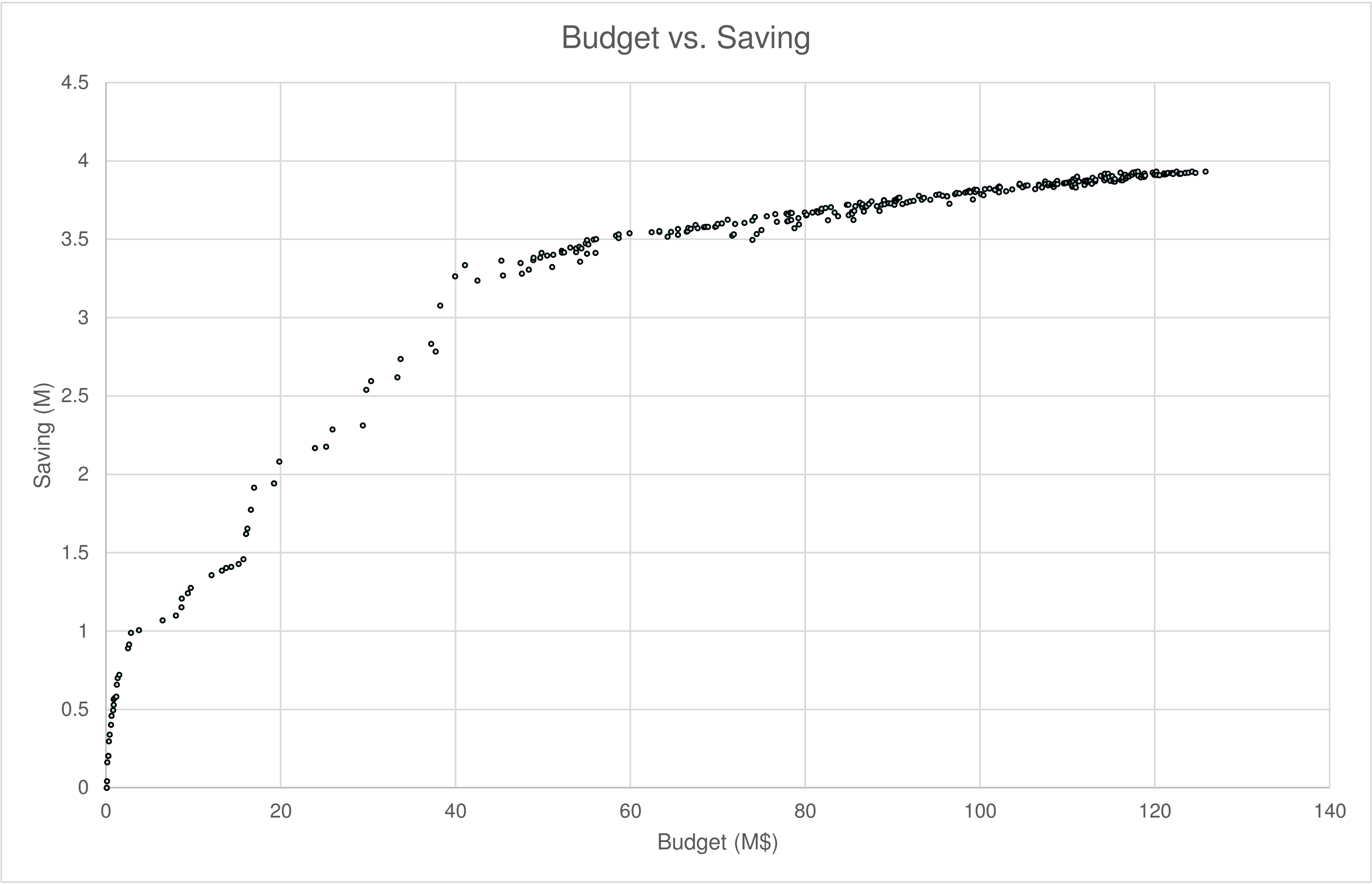
5M$ network



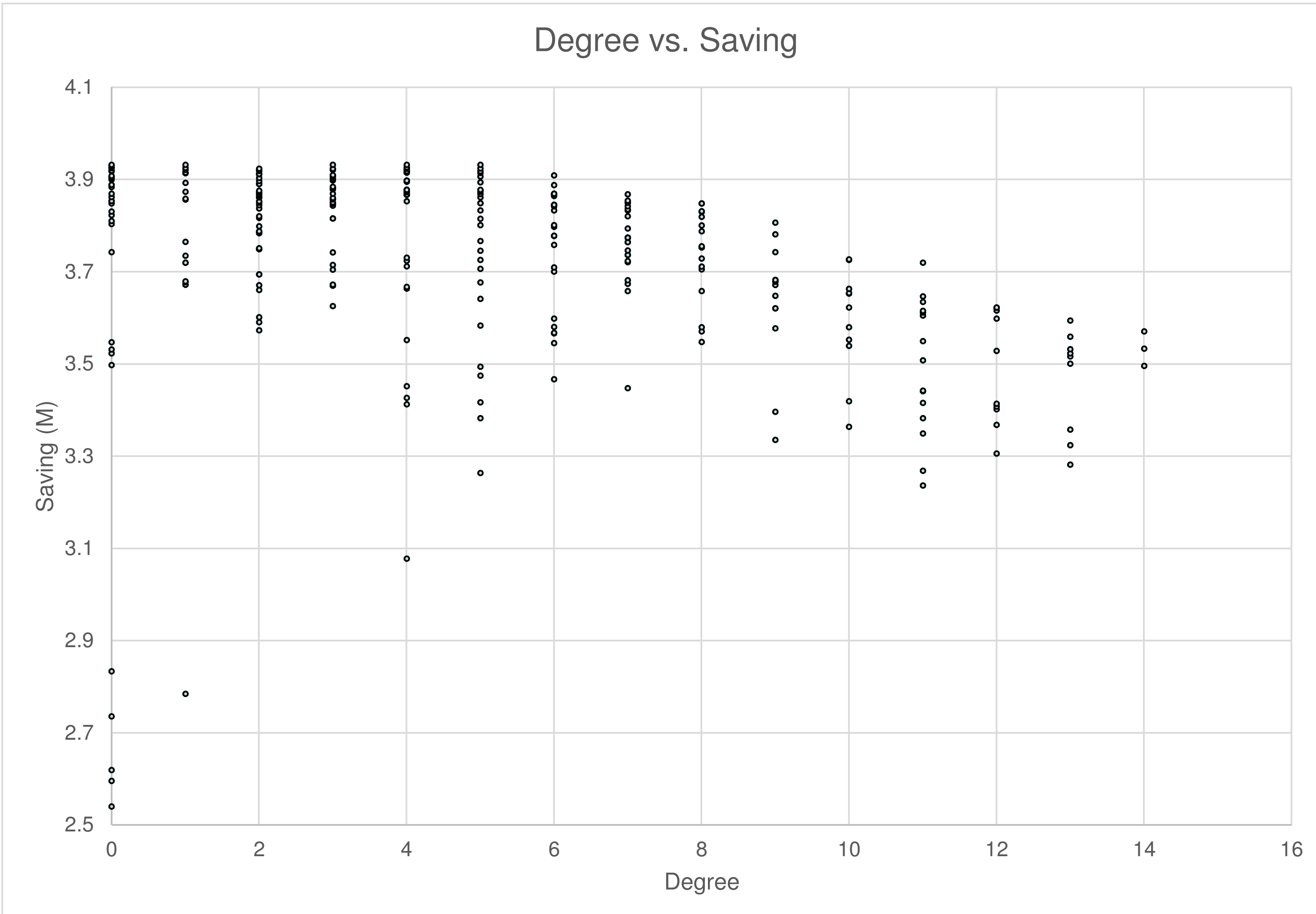
Multi-Objective GA – Results (1)



Multi-Objective GA – Results (2)



Multi-Objective GA – Results (3)



Why Multi-Criteria Decision Making ?

Stakeholders / Objectives	Solution 1	Solution 2	Solution n
Budget	v	v	v
Connectivity	V	V	V
Time saving	V	V	V

Multi-Criteria Decision Making

- In most cases, when solving a multi-objective optimization problem, the result is a set of non-dominated solution from which the decision maker (DM) has to choose his preferred alternative

- Multi-criteria decision making (MCDM) methods are automated methods for selecting a preferred solution

Multi-Criteria Decision Making

- Max-Min method - used when the DM wants to maximize the achievement in the weakest criterion
- Min-Max method - used when the DM wants to minimize the maximum opportunity loss
- ELECTRE Method (Roy, 1991) compares two alternatives at a time and attempts to eliminate alternatives that are dominated using the outranking relationship
- The TOPSIS method (Hwang & Yoon, 1981) - the preferred solution should simultaneously be closest to the ideal solution and farthest from the negative-ideal solution
- Multi-Attribute Utility Theory (MAUT) (Keeney, Raiffa, & Rajala, 1979) is based upon the assumption that every DM tries to optimize a utility function, based on the marginal utility scores of each criteria
- Analytic Hierarchy Process (AHP, Saaty 1977, 2008) - Information is decomposed into a hierarchy of alternatives and criteria, with pairwise comparison

Utilizing MCDM

- It is difficult, to assign a relative weight for each objective while assessing the complete objective set altogether and maintaining a consistent ranking process
- A better approach is to use multi-criteria methodology for assigning weights for the objectives
  - alternatives=solutions
  - attributes=objectives
- AHP derives ratio scales from paired comparison of criteria
- This approach eliminates the need to compare the whole set, but rather iteratively compare two criteria at a time
- It is also possible to assess the ranking’s quality (CR – consistency ratio)

A>B
A<C ➡ B<A<C

B>C

AHP example

- Three attributes to compare: a, b, c
- Based on the pairwise comparison:
  - **b** 3 time more important than **a**
  - **a** is 5 time more important than **c**
  - **b** is 7 times more important than **c**

	a	b	c							
a	1	1/3	5		0.3928			0.2790		(28%)
b	3	1	7		0.9140			0.6491		(65%)
c	1/5	1/7	1		0.1013			0.0719		(7%)
										(100%)
	Pairwise matrix (A)			Principal Eigen vector (λ)			Normalized principal Eigen vector (λ')			

The Eigen vector is a vector that satisfies :

$AX = \lambda X, X \in R^n \neq 0$

and the solution is given by :

$det(A - \lambda I) = 0$

where I is the identity matrix.

Back to the case study

DM	Criteria	Weights	Pairwise comparison			CR	Range (M$)	Solution set size
			Budget	Saving	Degree			
1 (authority)	Budget	3	1	5	3	0.4%	30-50	14
	Saving	10	0.2	1	0.5		>0	
	Degree	8	0.333	2	1		>0	
2 (user)	Budget	7	1	5	8	0.6%	40-60	31
	Saving	8	0.2	1	2		>0	
	Degree	10	0.125	0.5	1		>0	
3 (authority)	Budget	3	1	5	5	0%	30-50	14
	Saving	10	0.125	1	1		>0	
	Degree	10	0.125	1	1		>0	
4 (user)	Budget	1	1	9	7	8.4%	45-60	29
	Saving	10	0.111	1	0.333		>0	
	Degree	7	0.142	3	1		>0	

DM #1 - Solutions ranking

No.	Cost	Degree	Saving	AHP	TOPSIS	AHP-TOPSIS
9	47560	13	3281674	1	1	1
5	42479	11	3236502	2	4	2
4	41071	9	3335523	3	9	9
7	45406	11	3268631	4	6	6
11	48880	12	3367782	5	2	3
10	48366	12	3305832	6	3	5
8	47405	11	3349103	7	5	4
6	45242	10	3363844	8	8	7
12	48894	11	3382294	9	7	8
3	39924	5	3263791	10	11	10
2	38224	4	3077972	11	14	13
13	49668	5	3382540	12	10	11
1	37721	1	2784613	13	13	14
14	49817	4	3412336	14	12	12

DM #4 - Solutions ranking

No.	Budget	Degree	Saving	AHP	TOPSIS	AHP-TOPSIS	USER
13	59879	10	3539263	1	7	25	1
5	58637	11	3508101	2	4	5	3
24	55025	5	3494307	3	17	17	4
17	54865	5	3474573	4	13	16	5
26	54134	4	3451799	5	12	18	10
3	55175	6	3466875	6	10	8	6
9	52134	4	3426225	7	6	13	12
28	52411	5	3416734	8	9	9	15
20	55985	12	3413562	9	23	1	14
11	53120	7	3447309	10	8	20	7
21	56070	13	3500749	11	11	11	2
22	55023	12	3407849	12	3	24	17
14	54397	11	3442082	13	27	19	8
15	53775	10	3419026	14	15	15	11
8	53788	11	3441195	15	2	27	9
19	54235	13	3357861	16	29	23	24
18	49817	4	3412336	17	15	6	16
12	49668	5	3382540	18	14	29	20
7	52164	11	3415455	19	20	2	13
23	50445	9	3396230	20	24	3	19
4	51173	12	3401525	21	16	14	18
10	51028	13	3324070	22	5	22	26
27	48894	11	3382294	23	26	28	21
2	48880	12	3367782	24	19	4	22
6	48366	12	3305832	25	22	7	27
25	47405	11	3349103	26	28	26	25
16	47560	13	3281674	27	1	10	28
1	45406	11	3268631	28	21	21	29
29	45242	10	3363844	29	18	12	23

Why Group Decision Making ?

Stakeholders / Objectives	DM 1	DM 2	DM 3
Budget	V	V	V
Connectivity	V	V	V
Time saving	V	V	V

Group Decision Making

- One of the main obstacles for implementing a transportation plan is the different objectives set by the stakeholders, specifically both the local and national authorities as well as users
- This can lead to disagreement concerning the recommended plan (or solution). As a consequence decisions might not be made or stakeholders might be dissatisfied
- The problem is intensified if multiple available solutions are all feasible and non-dominated
- On the other hand, it is possible to utilize group decision-making (GDM) in order to select a compromise solution

GDM classification

- Social choice theory: each decision-maker casts a vote to select an alternative. Each alternative is analyzed by each voter based on multiple criteria and the selection is based on the group voting process.
- Expert judgment: (or group participation) is characterized by the suggestion of solutions by experts; the consideration of different points of view; and the selection of a solution based on a joint agreement, polling, surveys, brainstorming, etc. When a conflict of interest arises.
- Game theory: is useful as the players deploy strategies in order to address the payoff function of the game.

Voting mechanism (social choice)

- Why?
  - It combines the final decision of each of the DMs, not his judgment
  - Each DM previously ranked an optimal solution set based on his or her preferences
  - The present approach seeks a solution that will be easily accepted by all DM's
- How?
  - Rather than choosing an alternative preferred by a majority, a consensus-based alternative is chosen

Borda Count Method

- The Borda Count (BC) method defines consensus functions by mapping a set of individual rankings to a combined ranking, called *Risk Rank* (RR).
- For every voter $j \in N$, each alternative solution $i \in M$ is given a ranked value, R_{ij}, such that the most important alternative is given the value of one, the second important alternative is given the value of two and so on.
- After all alternative solutions are ranked by all votes, the *Risk Rank* of each alternative $i \in M$ can be calculated such that $RR = \sum_{j=1}^{N} M - R_{ij}$. The most preferred alternative is the alternative with the highest value of RR. Similarly, the least preferred alternative is the alternative with the lowest value of RR.

Borda Count Method advantages

- Easy to implement
- Does not require any training
- Treats all classifiers equally
- It is possible to apply different weights for every classifier

GDM results

No.	Budget	Degree	Saving	AHP-TOPSIS				BC Score
				DM 1	DM 2	DM 3	DM 4	
1	47560	13	3281674	1	3	1	4	27
2	48880	12	3367782	2	6	3	1	24
3	48366	12	3305832	4	5	2	3	22
4	45406	11	3268631	5	1	4	6	20
5	47405	11	3349103	3	4	5	7	17
6	45242	10	3363844	6	2	7	5	16
7	48894	11	3382294	7	7	6	8	8
8	49817	4	3412336	9	9	9	2	7
9	49668	5	3382540	8	8	8	9	3

Concluding Remarks

- This study presents a novel, multi-objective and multi-criteria approach for finding a compromise solution in selecting priority lanes for a public transport network.
- It provides a multi-objective model that incorporates several objective functions representing the different perspectives of relevant stakeholders. Moreover, based AHP or TOPSIS it is possible to easily rank the solution set, based on the DM preferences.
- It introduces an original AHP-TOPSIS ranking methodology which can easily rank a solution set based on the stakeholder's multi-criteria preferences, while assessing the stakeholder's consistency in prioritizing the objectives.
- It provides a GDM tool for selecting a solution that will be acceptable to all parties involved.

Thanks!

Any questions or comments ?

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