mobil.TUM 2016
International Scientific Conference on Mobility and Transport
Transforming Urban Mobility
6-7 June, 2016
Munich, Germany

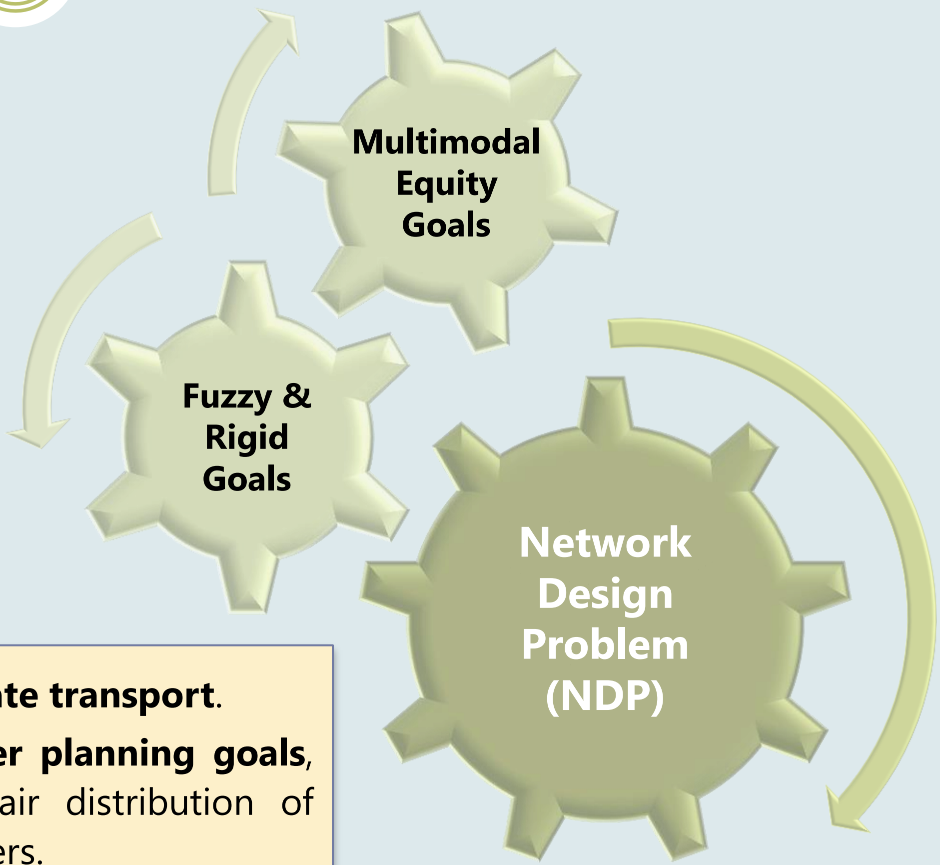
Better for everyone : an approach to multimodal network design considering equity

R.Camporeale, L.Caggiani, A.Fonzone, M.Ottomanelli
rosalia.camporeale@poliba.it

DICATECh – Transportation@Poliba Research Group - Politecnico di Bari - Italy
Transport Research Institute - Edinburgh Napier University - UK

General Overview

We propose a formulation of the **Network Design Problem (NDP)** to support transport planners in dealing with **multimodal networks** in contexts characterized by different (and sometimes conflicting) interests and limited resources in a transparent way.

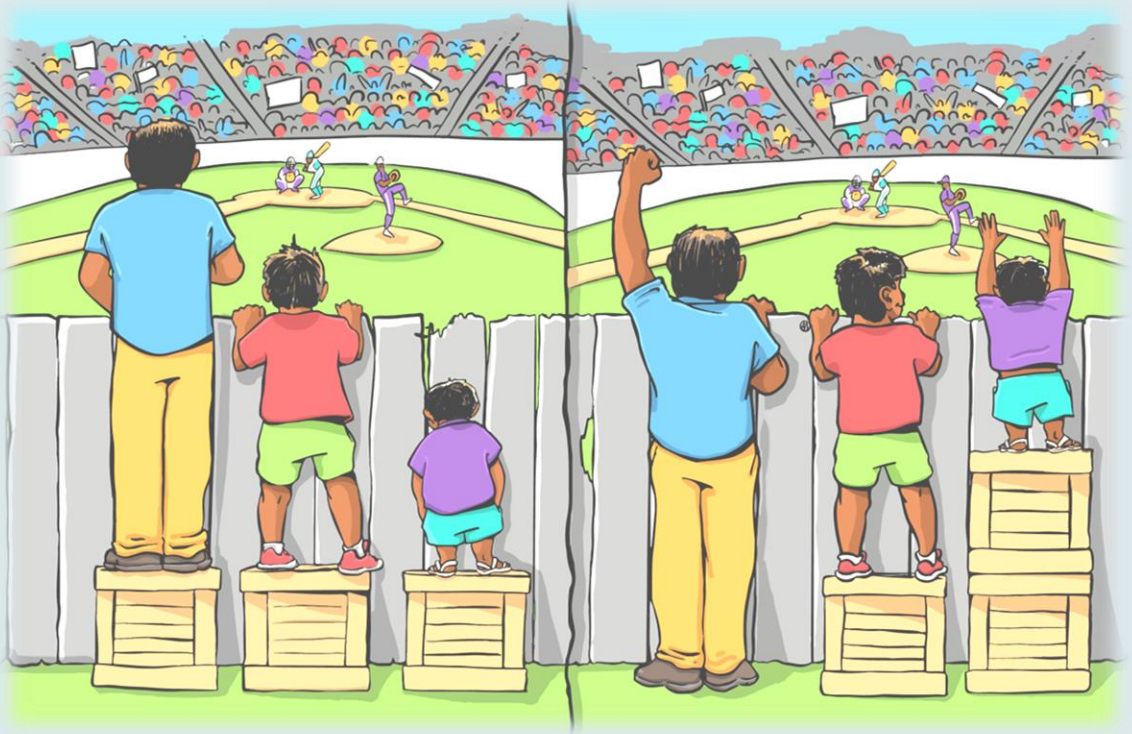


It expands the scope of traditional NDP approaches:

- It takes **public transit** into account **alongside private transport**.
- It considers the relevance of **equity among other planning goals**, enabling the achievement of solutions with a fair distribution of transport impacts (benefits and costs) among the users.
- It proposes the conjoint use of **fuzzy and rigid goals and constraints** to improve the quality of the solutions.

Concept of Equity

Equity refers to the **distribution of impacts** *(benefits and costs)* and whether that distribution is considered fair and appropriate.



HORIZONTAL EQUITY
(egalitarianism)

VERTICAL EQUITY
(social justice)

Horizontal equity concerns the provision of equal resources to individuals or groups considered equal in ability. It means to avoid favoring one individual or group over another, and so to offer services regardless of needs or actual ability.

Vertical equity applies to the distribution of resources among individuals with different abilities and needs, in order to make up for overall societal inequalities.

Transit Equity

*"**Transportation equity** is a civil and human rights priority. Access to affordable and reliable transportation widens opportunity and is essential to addressing poverty, unemployment, and other equal opportunity goals such as access to good schools and health care services.[...] Providing equal access to transportation means providing all individuals with an equal opportunity to succeed" (The Leadership Conference on Civil and Human Rights, 2015).*

Also the implementations of the equity concept in **public transport planning** can be classified in one of the two mentioned perspectives:

- the *horizontal equity framework* has been used in the *"mass transit" approach*, aiming at maximizing the number of served users it encapsulates;
- in the *"social transit" perspective*, a case of *vertical equity*, the goal is to provide public transit service to those who need it most, such as people without private transport means or specific low income groups, youth or ethnic minorities.

We extend the NDP formulation to consider the concept of equity applied to public transit in a quantitative way. **We adopt a mass transit perspective, fostering horizontal equity to ensure the best distribution of the service among users.**

Multimodal equity constraint specification

To improve the equity of the solution, **a constraint can be added to the traditional NDP formulation**:

$$\alpha_w = \frac{z_w(x)}{\bar{z}_w}$$

Meng and Yang (2002) define equity considering the **OD travel costs generated by the modification of a network**. In particular, they consider *the ratio between the equilibrium travel costs after and before changing the network for each OD pair w in the network.*

$$\alpha = \max_w \alpha_w$$

- If $\alpha < 1$ → all users benefit from the network design implementation.
- If $\alpha > 1$ → some users experience an increase of travel costs.

Therefore, we can enforce that the possible equilibrium OD travel cost increases are **below a given threshold**, set by the decision makers.

Multimodal equity constraint specification

However, the formulation of Meng and Yang (2002) **neglects the level of the demand between the OD pairs**. Therefore, the use of an equity constraint based on α may generate solutions with remarkable benefits (in terms of individual costs) for OD pairs with low demand and smaller negative consequences for OD with high demand level.

To avoid this problem, let:

$$\delta_w = \frac{d_w}{\sum d_w}(\alpha_w - 1)$$

In this way the relative variation of OD pair cost brought about by the network modification is weighted by **the ratio of the demand associated to that OD to the total demand.**

$$\delta = \max_w \delta_w$$

We propose **to account for the equity issue in the NDP by adding a constraint on the value of δ** (i.e. an indicator of the variation of the overall mobility cost).

NDP : General formulation

NDP is an allocation problem. In the mainstream approach to NDP resources are deployed so as **to minimize the total system cost under a set of constraints** and taking into account the user behavior.

$$x^* = \arg\underset{x}{\operatorname{opt}} z(x, f^*)$$

$$s.t.$$

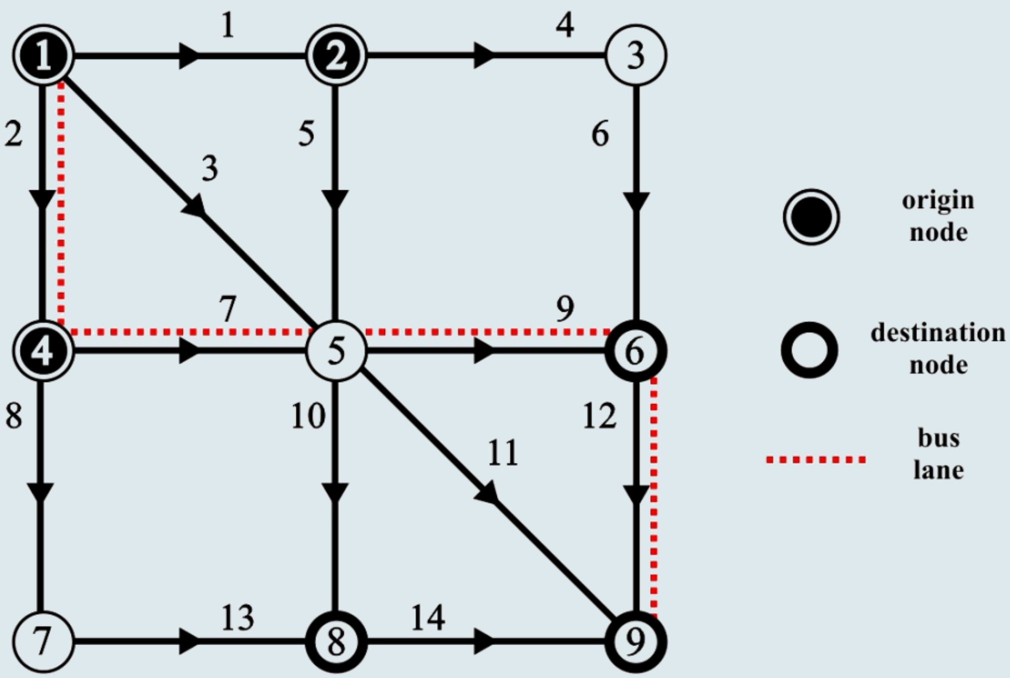
$$f^* = \Delta(x) P(x, C(f^*, x)) d(C(f^*, x))$$

$$x, f^* \in E, T$$

Our formulation is a case of a **Multi-Modal Network Design Problem (MMNDP)** with two modes (**private transport and buses**). We note that a multimodal problem arises when at least two modes are considered and simulated, even if design decisions are related to only one of the modes. In our car-bus problem, buses move in dedicated lanes, and therefore public transit flows are physically separated from private transport ones. Consequently, **z** (the function of the total cost of the network) **is the sum of the costs of private and public transport.**

Comparison of two specifications of NDP with equity constraints

We study two different specifications of the problem: **one based on crisp optimization, the other on fuzzy optimization.** We illustrate them by an application to the network of Yang and Zhang (2002). We compare the performance of the two approaches in terms of equity of the suggested solutions.

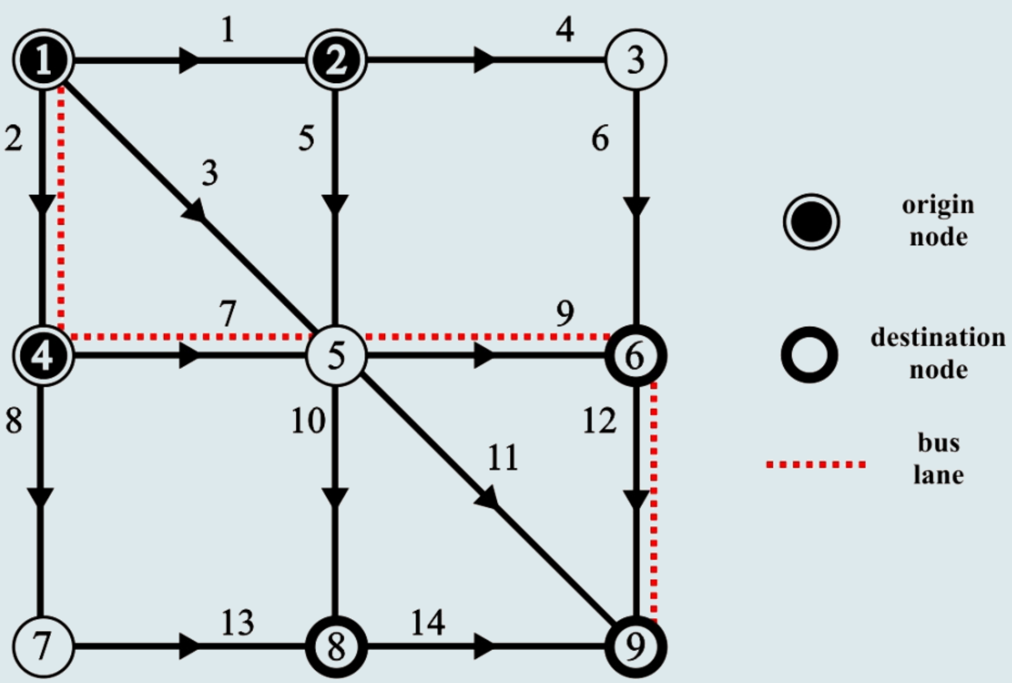


In our test, **the supply design variables are signal settings parameters.**

We adopt a global optimization approach, in which we search for the vector of optimal effective green times (**x***) for all signalized intersections. These values are obtained minimizing the network total cost **z** depending on signal settings (**x**), on equilibrium flows (**f***) and on equity constraints.

Comparison of two specifications of NDP with equity constraints

O-D	1-6	1-8	1-9	2-6	2-8	2-9	4-6	4-8	4-9
Demand	120	150	100	130	200	90	80	180	110



- 9 nodes (3 origins, 3 destinations)
- 5,6,8 = signalized intersections
- Fixed cycle time of 90 seconds

- 1,4,5,6,9 = bus stops
- Fixed dwell time of 10 seconds
- 30% of the demand generated by the OD pairs 1-6 and 1-9 is served by public transport.

Performed optimizations

We solve the optimization problems using **genetic algorithm (GA) metaheuristic**. The analysis entails two steps: in the first one we generate **600 starting configurations, i.e. vectors of design variables.**; in the second step, we apply GA using each of these starting configuration as **starting point of different runs**.

		Equity Crisp Specification (ECS)	**Equity Fuzzy Specification (EFS)**
Objective Functions	Satisfaction	-[(1)]	max $(g_1 h_1 + g_2 h_2 + g_3 h_3)$
	Network total cost	min z ($\mathbf{x}$, $\mathbf{f^*}$)	-[(1)]
Problem Constraints	Network total cost	-[(1)]	$z\ (\mathbf{x}(h_1), \mathbf{f}^*) \leq (1 - h_1)$
	Car equity	$\delta_{car,\ ECS} \leq \delta_{car,\ max}$	$\delta_{car,\ EFS} \leq \delta_{l\_car} + (\delta_{u\_car} - \delta_{l\_car}) \cdot (1-h_2)$
	Bus equity	$\delta_{bus,\ ECS} \leq \delta_{bus,\ max}$	$\delta_{bus,\ EFS} \leq \delta_{l\_bus} + (\delta_{u\_bus} - \delta_{l\_bus}) \cdot (1-h_3)$
	Demand – flows Consistency	$\mathbf{f^*} = \Delta(\mathbf{x})\mathbf{P}(\mathbf{x}, \mathbf{C}(\mathbf{f}^*, \mathbf{x}))\mathbf{d}(\mathbf{C}(\mathbf{f}^*, \mathbf{x}))$	
	Cycle time consistency	$\sum g_{nd,ph} = c_t \ \forall \ nd \in \{5,6,8\}$	

Performed optimizations

We solve the optimization problems using **genetic algorithm (GA) metaheuristic**. The analysis entails two steps: in the first one we generate **600 starting configurations, i.e. vectors of design variables.**; in the second step, we apply GA using each of these starting configuration as **starting point of different runs**.

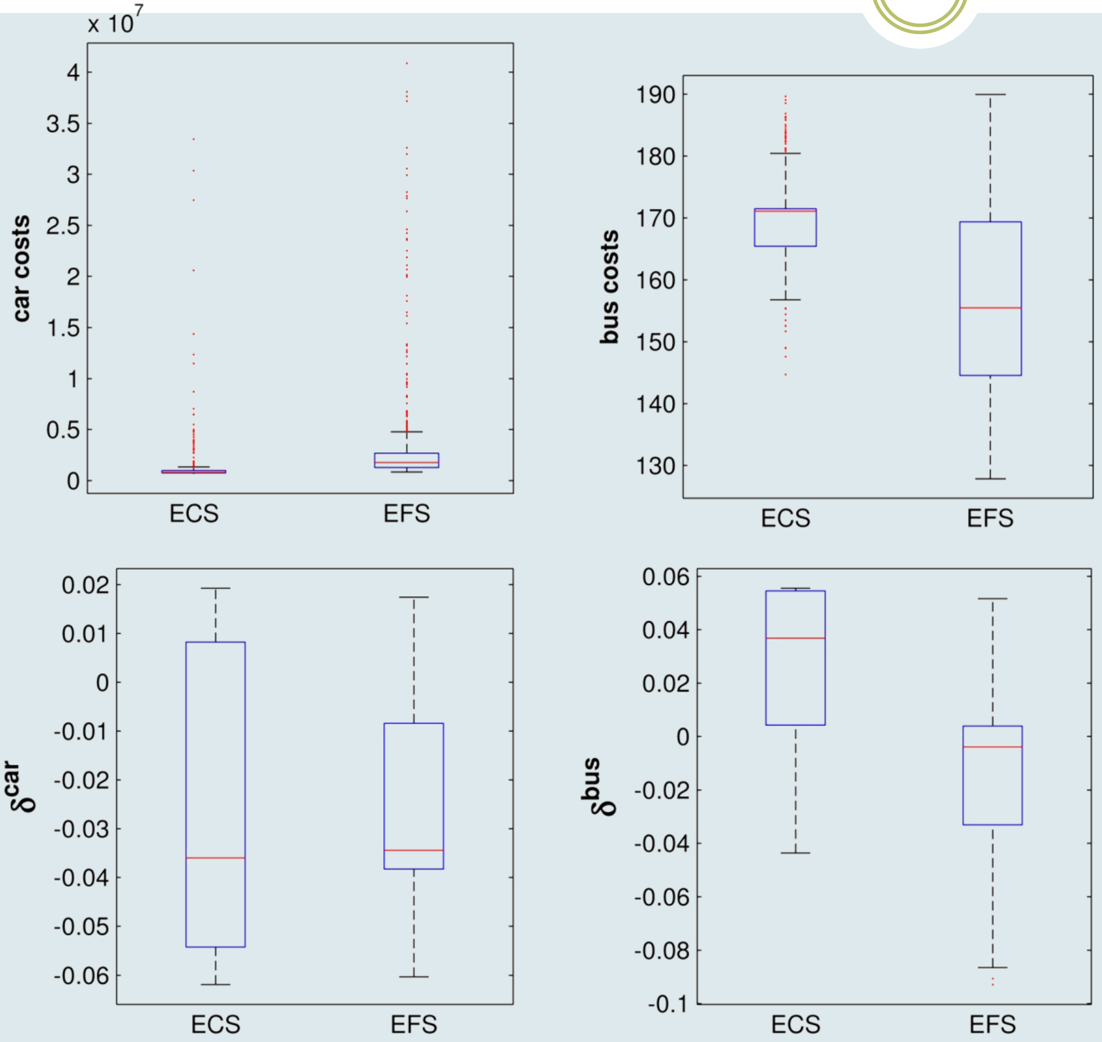
		Equity Crisp Specification (ECS)	Equity Fuzzy Specification (EFS)
Objective Functions	Satisfaction	-(1)	$\max\,(g_1h_1 + g_2h_2 + g_3h_3)$
	Network total cost	$\min z\,(\mathbf{x}, \mathbf{f^*})$	-(1)
Problem Constraints	Network total cost	-(1)	$z\,(\mathbf{x}(h_1), \mathbf{f}^*) \leq (1 - h_1)$
	Car equity	$\delta_{car,\,ECS} \leq \delta_{car,\,max}$	$\delta_{car,\,EFS} \leq \delta_{l\_car} + (\delta_{u\_car} - \delta_{l\_car})\cdot(1\text{-}h_2)$
	Bus equity	$\delta_{bus,\,ECS} \leq \delta_{bus,\,max}$	$\delta_{bus,\,EFS} \leq \delta_{l\_bus} + (\delta_{u\_bus} - \delta_{l\_bus})\cdot(1\text{-}h_3)$
	Demand – flows Consistency	$\mathbf{f^*} = \Delta(\mathbf{x})\mathbf{P}(\mathbf{x}, \mathbf{C}(\mathbf{f}^*, \mathbf{x}))\mathbf{d}(\mathbf{C}(\mathbf{f}^*, \mathbf{x}))$	
	Cycle time consistency	$\sum g_{nd,ph} = c_t \;\forall\; nd \in \{5,6,8\}$	

Performed optimizations

We solve the optimization problems using **genetic algorithm (GA) metaheuristic**. The analysis entails two steps: in the first one we generate **600 starting configurations, i.e. vectors of design variables.**; in the second step, we apply GA using each of these starting configuration as **starting point of different runs**.

		Equity Crisp Specification (ECS)	Equity Fuzzy Specification (EFS)
Objective Functions	Satisfaction	-(1)	$\max\,(g_1h_1 + g_2h_2 + g_3h_3)$
	Network total cost	$\min z\,(\mathbf{x}, \mathbf{f^*})$	-(1)
Problem Constraints	Network total cost	-(1)	$z\,(\mathbf{x}(h_1), \mathbf{f}^*) \leq (1 - h_1)$
	Car equity	$\delta_{car,\,ECS} \leq \delta_{car,\,max}$	$\delta_{car,\,EFS} \leq \delta_{l\_car} + (\delta_{u\_car} - \delta_{l\_car})\cdot(1\text{-}h_2)$
	Bus equity	$\delta_{bus,\,ECS} \leq \delta_{bus,\,max}$	$\delta_{bus,\,EFS} \leq \delta_{l\_bus} + (\delta_{u\_bus} - \delta_{l\_bus})\cdot(1\text{-}h_3)$
	Demand – flows Consistency	$\mathbf{f^*} = \Delta(\mathbf{x})\mathbf{P}(\mathbf{x}, \mathbf{C}(\mathbf{f}^*, \mathbf{x}))\mathbf{d}(\mathbf{C}(\mathbf{f}^*, \mathbf{x}))$	
	Cycle time consistency	$\sum g_{nd,ph} = c_t\,\forall\, nd \in \{5,6,8\}$	

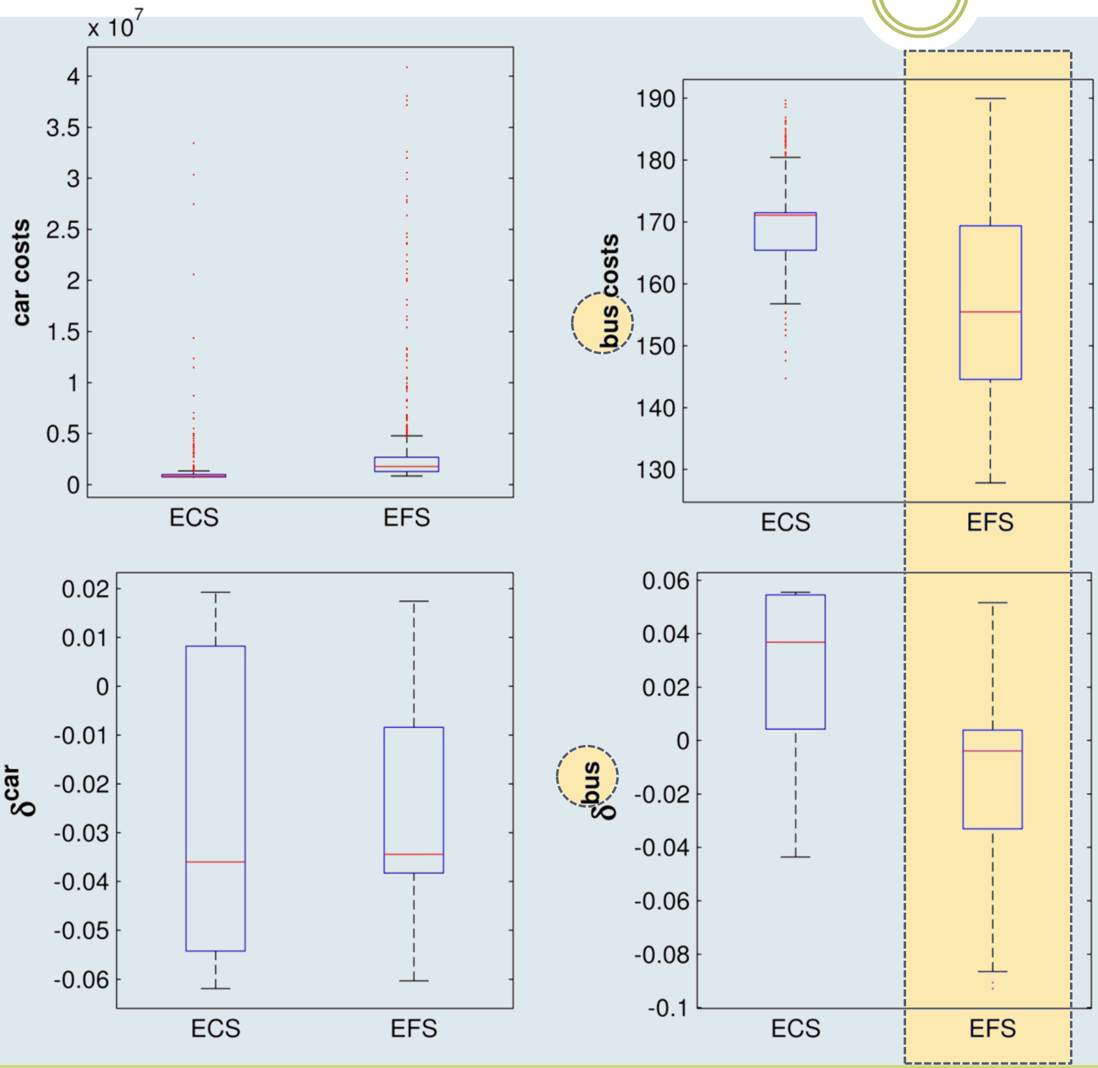
Optimizations results



Using different starting configuration, each GA run (potentially) generates a different solution.

The results of our experiments are summarized in by means of box plots. In each box, the central mark indicates the median value, the edges are the 25th and 75th percentiles, the whiskers extend to the most extreme non-outlier values, and outliers are plotted individually.

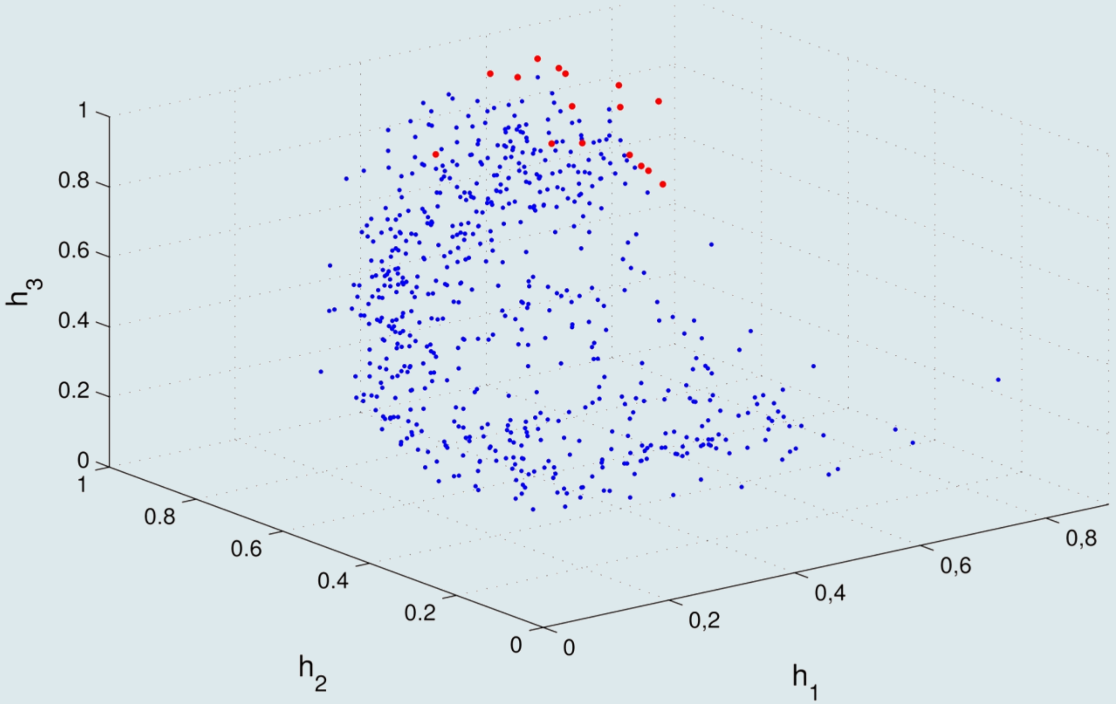
Optimizations results



Overall, the test suggests that **EFS should be preferred to ECS to promote the use of public transport**, because it generates more convenient and equitable solutions for bus users.

Multi criteria decision in EFS

Metaheuristic methods like GA are not always able to identify global maxima and, in general, each run finds a different solution (in our test, we have 600 runs, each with a different starting configuration). Therefore, the problem arises of **selecting one of the detected local optima as solution to the problem**. Consequently, we propose the analysis of the **Pareto front** of the local optima in the space of the specific satisfactions.



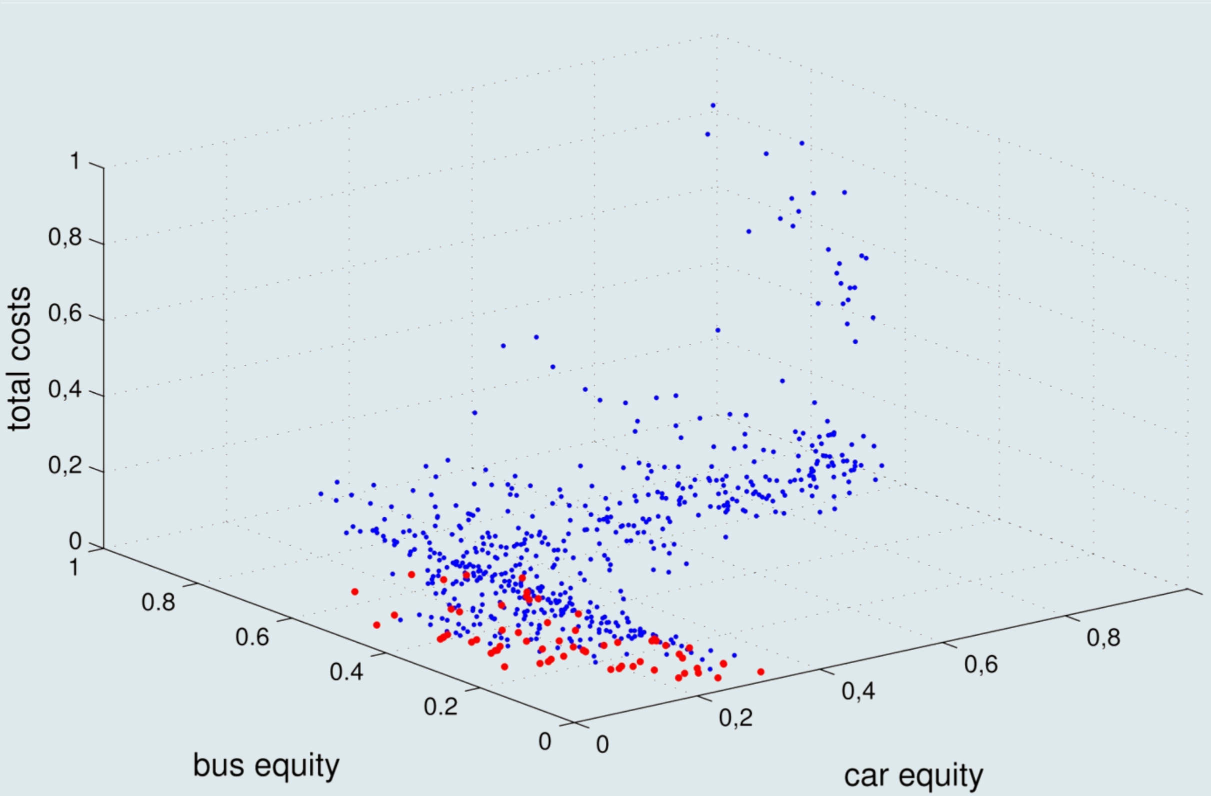
Each point represents the solution found by one run of GA (corresponding to a specific starting condition).

The Pareto front is made up of the 16 non-dominated solutions in red, that reach the highest level of satisfaction.

This is indicative of *how the optimization is able to improve the status of the corresponding starting configuration.*

Multi criteria decision in EFS

Nevertheless, objectively there is no clue about **the factual level of equity and the actual costs to be incurred**. These are shown in the following figure:



Costs and equity values are **normalized in the range between 0 and 1**; the lowest overall cost scored at the end of the 600 runs is assumed to be the zero, the uppermost is set equal to 1.

The Pareto front is made up of the 63 non-dominated solutions in red, the ones able to achieve the lowest overall costs and the greater level of car and bus equity (the closest to 0).

Conclusions

- We present **two specifications of the equitable NDP**, one formulated as crisp minimization problem (ECS), the other as fuzzy maximization problem (EFS). The test reveals that the two methods can lead to different results. In the case we analyze, EFS is more favorable to public transport.

- We solve EFS and ECS by GA. The application of GA does not guarantee the identification of the global optimum and different implementations may identify different local optima. Using the Pareto front, we at first test the ability of the optimization to improve the overall satisfaction starting from different initial configurations. Secondarily we display the Pareto front related to the final values assumed by costs and equity at the end of each optimization run. **This would make the decision-making process more transparent, allowing the decision maker to identify, among all the optimal solutions, that with the set of goal-specific values which suits best his/her priorities.**

Specifications of constraints considering in quantitative way **vertical as well as horizontal aspects of equity** would allow designing transport networks to respond to the needs of disadvantaged population groups.

Thank you for your attention!

Edinburgh Napier
UNIVERSITY

Politecnico di Bari

T@P
TRANSPORTATION AT POLIBA
research group