Multi-objective optimization of multimodal transportation networks

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1 Introduction

Highly urbanized regions in the world nowadays face well known problems in the traffic system, like congestion, use of scarce space in cities by vehicles and infrastructure and the emission of greenhouse gases. In this research we focus on the integration of transportation networks of cars, public transport (bus, tram, metro, train) and bicycles as a cost effective solution direction to alleviate these problems.

2 Problem definition

In infrastructure planning, current practice is often to design a few alternatives, assess these alternatives by a transportation model and choose the best performing alternative. However, this alternative is still likely to have room for improvement. That is the reason for applying optimization techniques in this context.

2.1 Multi-objective optimization

A multi-objective approach is adopted, because of the complex context of competing sustainability interests, like accessibility, environmental impact, livability and costs. We do not choose to translate multiple objectives into a single objective by using weights for each objective, because the weights as well as the normalization of the different objectives are arbitrary. Furthermore, we are interested in tradeoffs between objectives, which can only be achieved by studying the Pareto optimal set [1].

2.2 Bi-level problem.

The transportation network design problem is often solved as a bi-level optimization problem (for example [2]). In our case the problem is discrete. The upper level represents a network authority that wants to optimize system objectives. In the lower level the travelers minimize their own generalized costs in the multimodal network, which results in a stochastic user equilibrium. This equilibrium is a constraint for the upper level problem.

2.3 Network and demand definition

The network is defined as a directed graph G, consisting of nodes N and links A. Transportation zones Z are a subset of N and act as origins and destinations. Total fixed transportation demand D is stored in a $|Z| \times |Z|$ matrix. Furthermore, transit service lines L are defined as ordered subsets A_l of A and transit stations or stops S are defined as a subset of N.

2.4 Decision variables

Decision variables in this multimodal network design problem are related to transfer facilities or to public transport facilities and are defined in table 1. Candidate locations for these decision variables are defined in advance, taking spatial / physical constraints into account. The car and bicycle networks are assumed to be fixed.

Decision variable	Formulation	Explanation
Park and Ride facility at station *s*	$p_s \in \{0,1\}$	This binary variable indicates whether it is possible to park the car at a station *s*. At existing stations with park and ride facility, this variable is fixed to 1. At candidate locations, this variable can take values 0 and 1.
Existence of station *s*	$t_s \in \{0,1\}$	This binary variable indicates whether transit vehicles call at station *s* or not. At existing stations this variable is fixed to 1, at candidate locations this variable can take values 0 and 1.
Express status of station *s*	$e_s \in \{0,1\}$	This binary variable indicates whether transit vehicles of express lines call at station *s* or not. At existing stations this variable is fixed to 1, at candidate locations this variable can take values 0 and 1.
Frequency of transitline *l*	$f_l \in F_l$	F_l contains possible values for the frequency of transit line l. Existing transit lines can either be fixed (F_l contains only 1 element) or free (F_l contains 2 or more elements). In the latter case 0 may also be included. For candidate transit lines F_l always contains at least 2 elements, including 0.

Table 1: Definition and explanation of decision variables.

2.5 Objective functions

The values of the objective functions are calculated based on loads and costs in the network, which are stored in link characteristics and in $|Z| \times |Z|$ matrices. The objectives are operationalized by total travel time, number of car trips to urban zones (to represent use of urban space for parking), CO_2 emissions and exploitation costs (see table 2). Investment costs are not considered, because the chosen decision variables typically involve higher exploitation costs instead of high investment costs. All four objectives are to be minimized.

Policy objective	***Measured by***	***Formulation***
Accessibility	Total travel time	$\sum_{ijm} T_{ijm} D_{ijm}$
Climate impact	CO$_2$ emissions	$\sum_{abd} q_{ab}\delta_{ad}E_{bd}^{\mathrm{CO2}}(v_a)\ell_a$
Use of urban space	Number car trips to and from urban zones	$\sum_{i:i\in Z_U, j, m:m\in M_O} D_{ijm} + \sum_{i,j:j\in Z_U, m:m\in M_D} D_{ijm}$
Cost efficiency	Exploitation costs	$\sum_{b\in B_{PT}, l} (C_b\Delta_{bl} f_l \sum_{a\in A_l} t_{ab})$

With:	
T_{ijm}	Travel time from origin *i* to destination *j* with mode or mode chain *m*
D_{ijm}	Transportation demand from origin *i* to destination *j* with mode or mode chain *m*
q_{ab}	Flow on link *a* for vehicle type *b*
δ_{ad}	Road type indicator, equals 1 if link *a* is of road type *d*, 0 otherwise
$E_{nb}^{CO_2}(v_{ab})$	CO$_2$ emission factor of vehicle type *b* on road type *d*, depending on average speed of link *a* for vehicle type *b* v_{ab} (grams/(veh*km))
l_a	Length of link *a*
Z_U	Set of highly urban zones
M_O	Set of modes (including mode chains) that start the trip with a car leg
M_D	Set of modes (including mode chains) that end the trip with a car leg
B_{PT}	Set of vehicle types that are part of the public transport system
A_l	Set of links that are traversed by line *l*
C_b	Exploitation costs for vehicle type *b* (euro's per vehicle*hour)
Δ_{bl}	Public transport vehicle type indicator, equals 1 if line *l* is of vehicle type *b*, 0 otherwise
f_l	Frequency of line *l*
t_{ab}	Travel time in link *a* for vehicle type *b*

Table 2: Definition of objective functions and list of symbols

3 Solution method

3.1 Upper level

The problem is hard to solve and is computationally too expensive to be solved exactly, so we rely on heuristics. Literature provides different techniques to approximate the multi-objective optimization problem in the upper level (see for example [3] for theory and [4] for a practical application in transportation science). Examples of these are different forms of genetic algorithms, simulated annealing or tabu search. In this research we use the genetic algorithm NSGA-II algorithm as it was successfully applied by [5].

3.2 Lower level

To be able to assess a multimodal network in a suitable way, a multimodal traffic assignment model is applied in the lower level (see fig. 1). This includes a nested logit mode choice model [6] which has the car mode in one nest and mode chains with public transport as a main mode in the other nest. The latter nest contains the mode chains that include walking, bicycle and car as access mode as well as the mode chains that contain walking, bicycle and car as egress mode. The car-only trips are assigned to the network using a standard capacity dependent user equilibrium assignment. The public transport assignment method (including various access and egress modes) includes multiple routing based on the principles of optimal strategies, as developed by [7], without capacity restrictions.

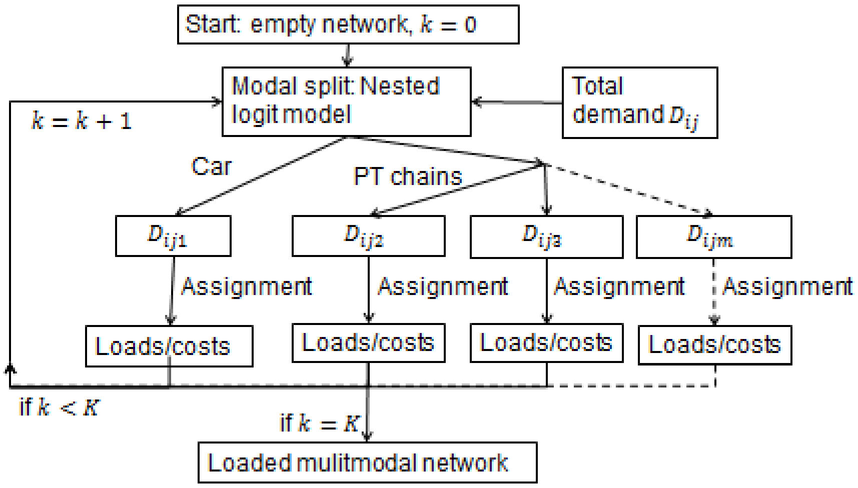

Fig. 1: Multimodal traffic assignment model used in the lower level with K iterations

4 Case study

The optimization framework is applied to a case study in the Amsterdam metropolitan area, which covers a large part of the Randstad (fig. 2). It contains a detailed multimodal network, including bicycle links, car links, transit lines (including distinction between local services and express services). This enables a detailed modeling of the trip chain. On the other hand, the number of zones is limited, to ensure fast calculation times.

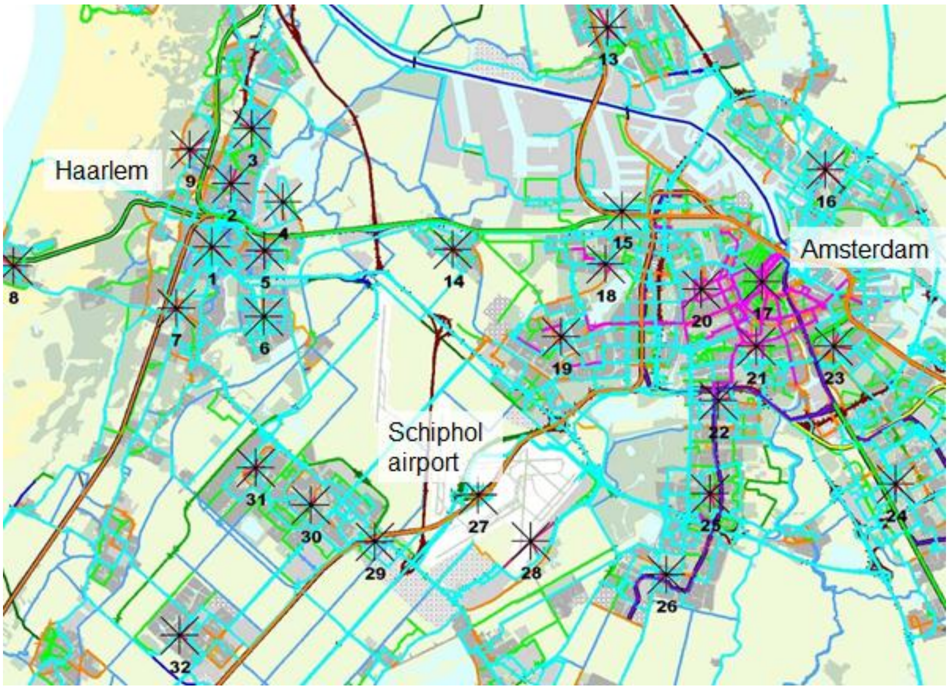

Fig 2: the area of the case study

5 Results

The resulting Pareto set gives insight in the interdependencies and tradeoffs between objectives. Furthermore, design variables can be identified which satisfy one or more objectives.

The results indicate that an additional stop for express trains on multimodal nodes in the network is a cost effective decision variable, with a good tradeoff between travel time and CO_2 emissions. New public transport lines are not cost effective to reduce travel time. New stations are a cost effective way, especially if combined with a park and ride facility, to reduce the number of car trips in urban areas maintaining acceptable travel times.

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