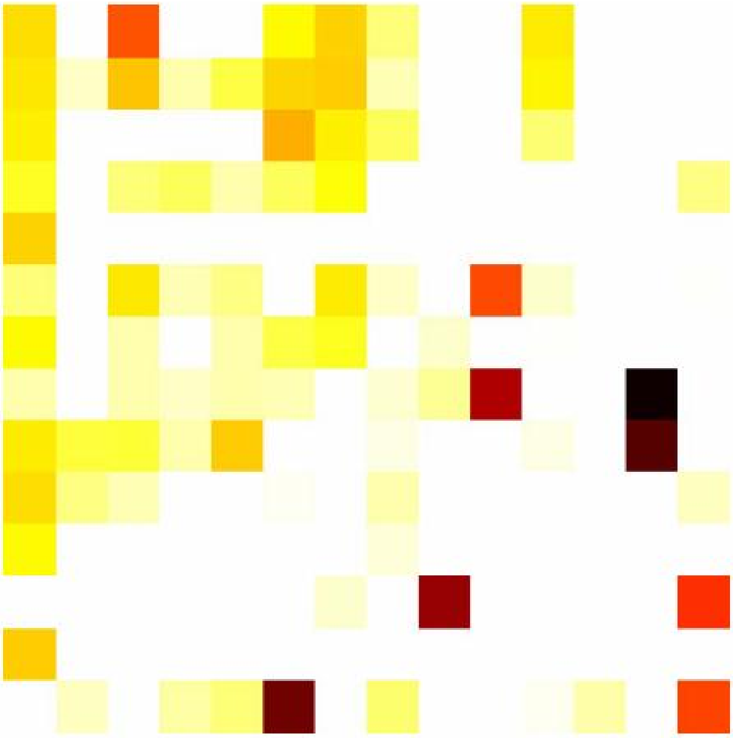

Optimization of Large Transport Networks Using the Ant Colony Heuristic

Basil J. Vitins, Rapp Trans AG
Kay W. Axhausen, IVT, ETH Zürich

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B.J. Vitins
Rapp Trans AG
Hochstr. 100
CH - 4018 Basel

Telephone: +41-61-335 7867
Telefax: +41-61-335 7700
basil.vitins@rapp.ch

KW.Axhausen
IVT
ETH Zürich
CH – 8093 Zürich

Telephone: +41-44-633 3943
Telefax: +41-44-633 1057
axhausen@ivt.baug.ethz.ch

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Abstract

Long-term transportation planning in larger regions encompasses more than the evaluation of individual infrastructure projects; it must also assess synergies and interference among sets of projects. The objective is the maximizing of the overall benefit within specific budget restrictions by finding the most favourable bundle of projects, i.e. solving the network design problem. For large numbers of projects, complete enumeration of all combinations, requiring time consuming equilibrium calculations is not feasible for detailed networks. The ant colony heuristic is suitable for this kind of problem.

According to our knowledge, this paper presents the above-mentioned heuristic's first application to a realistically sized network: a substantial Swiss city and surrounding region. A detailed multimodal network assignment provides the basis for calculations. First, each infrastructure project is assessed using comprehensive cost-benefit analysis. The ant colony heuristic is then successfully executed and evaluated. The paper focuses on problematic calibration details and objective function, and provides new insights into applications of the heuristic to large networks. Suggestions are made for general applications and further research in the conclusions.

Key words

Network design problem, ant colony optimisation, Switzerland, EMME/2

1 Introduction

Congested roads and overcrowded transit lines increase travel time and costs, and lead to economic, social and environmental losses. Today, no one questions the need to expand numerous urban transportation networks. New network infrastructure can result in large societal benefits. The existing network can either be improved through improvement of existing roads and transit lines, or by building additional links and lines to extend the network. In master plans, such expansion can be combined with the removal of existing infrastructure because of spatial, environmental and societal considerations. Network improvement must be carefully considered, especially within heavily used transportation networks. Negative consequences of new infrastructure are often very difficult to predict, so benefit-cost ratios may be smaller than expected.

When evaluating new infrastructure projects, various qualitative and quantitative assessment methodologies can be employed, e.g. Multi-Attribute Utility Theory (Keeney and Raiffa, 1976) or cost-benefit calculation (Stopher and Meyburg, 1976). Most of the existing methodologies focus on already defined projects or project bundles. However, in transportation networks, the best bundle of projects is usually not clear. Often, one has to choose the best alternatives from a very large number of possible bundles. In contrast to other policy areas, evaluations of network change have to consider interdependences between projects. Therefore, when implementing two projects, assessment outcomes cannot be summed up to obtain overall benefit. Instead, the assessment outcome must be recalculated to include both projects simultaneously, producing a different outcome. Moreover, additional links do not automatically increase overall benefit (Braess, 1968). It has been shown that new links can also increase travel time, even though an improvement was expected, e.g. when building a shortcut. The well-known knapsack problem and its methodologies could be applied when assuming independence (or only limited interactions) between the projects (Kellerer, Pferschy and Pisinger, 2004). As this assumption is unrealistic, it would be very useful to have a procedure or algorithm available that could address these interactions appropriately. This paper will present and apply a suitable heuristic algorithm to address network design problem (NDP), i.e. the selection of the optimal bundle of discrete projects from a larger set, while accounting for the interaction of their effects on network flows.

While other papers focus more on methodology of the NDP solution, this paper aims to provide a link between theory and practice. A large bimodal transportation network (350 zones) of the Bern region (Switzerland) and realistic infrastructure projects replicate the real-life situation as far as possible. The region encompasses highly congested streets, occasional parallel routes and short cuts. Complex route choice and secondary effects call for careful, detailed modelling and planning if the current situation is to be improved efficiently.

First, the paper formally defines the network design problem. A short overview summarizes existing methodologies, and the next section explains the methodology applied in detail. Then, the study area and its characteristics are introduced. Special attention will be given to the two mode choice models, used alternatively. A results report on the behaviour of the solution algorithm (particularly its convergence) is presented, and finally, the bundles obtained for the study region are discussed. Suggestions for further work conclude the paper.

2 Network Design Problem (NDP)

The network design problem (NDP) has recently been revisited by various authors, both because computation speeds have increased, and the issue has become more important, especially relating to planning for emergencies, evacuations and reliability improvement (Bakuli and Smith, 1996; Bell, 2000; Bonabeau, Dorigo and Theraulaz, 2000; Sumalee, Watling and Nakajama, 2006; Tuydes and Ziliaskopoulos, 2006). This section will briefly review the problem and suggested solutions.

2.1 Definition

NDP is a discrete optimization problem and NP-hard (Garay and Johnson, 1979). It was first defined by LeBlanc (1975). It refers to a transportation network with links, corresponding volume delay functions and nodes. Additional modes, functions and parameters normally used in a transportation model can be included as well. The goal is to choose a bundle **x** among a defined set $x_1 \ldots x_n$ of possible infrastructure projects *i*; while $x_i \in \{0,1\}$ and $x_i=1$ when project *i* belongs to the bundle. The chosen bundle generates maximum benefit **c**, whereas the benefit of project *i* is a function f_i of the other projects chosen. The added costs $\sum a_i$ have to be below a defined resource constraint *A*.

$$\begin{aligned}
&\text{maximize} && \mathbf{c}^T\mathbf{x} \\
&\text{subject to} && \mathbf{a}^T\mathbf{x} \le A \\
& && c_i = f_i(\mathbf{x}) \\
& && \mathbf{x} \in \{0,1\}^n \\
&\text{where as} && \mathbf{c} > \mathbf{0};\ \mathbf{a} > \mathbf{0};\ A > 0;\ \max_{j=1,\dots,n} a_j \le A < \sum_{j=1}^{n} a_j
\end{aligned}$$

2.2 Existing methodologies to solve the NDP

A complete enumeration of all possible combinations is the only way to determine the correct and exact solution of the NDP. In our case, the estimate of computation time for a complete enumeration of all possible bundles of 14 pre-selected projects is 114 days, is not normally practical. All other methodologies are either of heuristic nature or based on relaxations of certain constraints. The well-known knapsack approach and its corresponding solutions (Kellerer *et al.*, 2004) can be applied when ignoring possible interactions between projects. The quadratic knapsack problem and its existing solutions (Kellerer *et al.*, 2004) can just be applied if there are only pair-wise interactions between projects. Hsieh and Liu (2004) propose a genetic algorithm to solve the NDP. Regression analysis is another, less complicated way to calculate a possible solution. May (2003) proposed a step by step regression analysis to find the optimal bundle (Santos, Antunes and Miller, Submitted). The Ant Colony heuristic, used in this work, mirrors ant behaviour, a form of artificial or swarm intelligence (Bonabeau *et al.*, 2000). This methodology has been employed for a variety of Operational Research problem classes and is currently known as the best algorithm for many of them (Bonabeau *et al.*, 2000; Dorigo, DiCaro and Gambardella, 1999; Merkle, Middendorf and Schmeck, 2002).

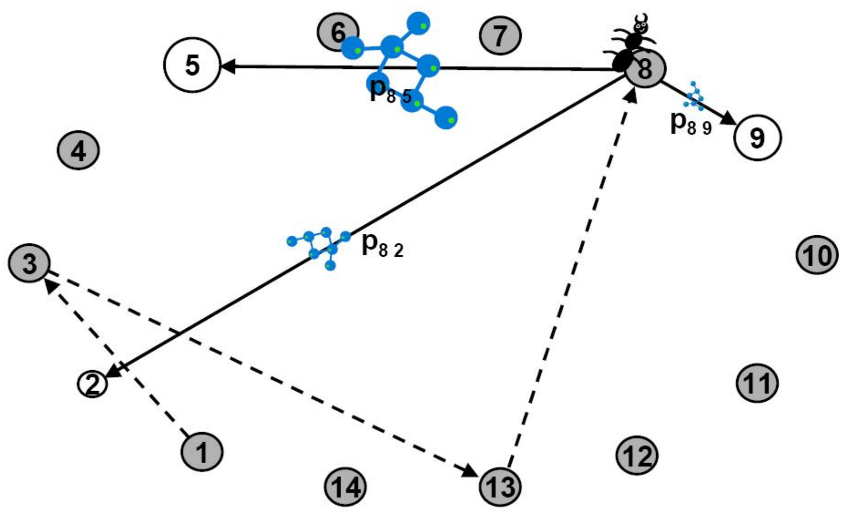
2.3 Ant Colony Heuristic

As a reference, the Ant Colony heuristic can be explained by an analogy with ants' social behaviour. Ants communicate through chemical substances, called pheromones, while looking for food resources. Ants interpret pheromones deposited by previous ants on the trails. The more a trail is used, the more pheromones are dispensed on it, allowing ants to learn from the success or failure of preceding ants. As opposed to ant behaviour, pheromones in the algorithm are only deposited when the entire tour is finished and the overall success is known.

Figure 1 shows schematically as circles different network optimization projects i=1 … 14. The ant has already chosen project 1, 3, 13 and 8 and is now continuing onto one of the projects $j \in \{2,5,9\}$. The last project chosen is called project i. The ants choose additional projects j according to the probability p_{ij}, which depends on the current pheromone density τ_{ij} on the corresponding link $[i\ j]$ and the benefit N of the projects j in isolation, respectively (P1). Projects with large benefits (when assessed separately) and high pheromone density on link $[i\ j]$ are chosen more often. In an extended approach, the benefit of project j would account for the interaction with project i as well. Here, for simplicity and a reduced computational burden, N only includes the benefit of project j ($N_{ij}= N_j$). F_k projects can be taken into consideration at each point of time, depending on the financial resources left. Projects in dark circles in figure 1 do not belong to F_k and therefore cannot be chosen anymore: $F_k = \{2,5,9\}$. α and β are parameters requiring calibration.

P1
$$p_{ij} = \begin{cases} \dfrac{e^{\alpha\tau_{ij}} \cdot e^{\beta N_{ij}}}{\sum\limits_{m \in F_k} e^{\alpha\tau_{im}} e^{\beta N_{im}}}, & when\ j \in F_k \\ 0 \quad , & otherwise \end{cases}$$

Figure 1: The decision making process of an ant.



Following Poorzahedy and Abulghasemi (2005), one iteration includes 14 tours of different ants, leading to 14 project bundles, as they report better results when ants start at each project once, instead of starting at a randomly chosen projects.

The pheromone amount, which is distributed on the links, depends on the benefit of the entire bundle created. The larger the benefits, the larger the amount dispensed on the links. Additionally, to improve convergence, an evaporation rate is included in the algorithm (Poorzahedy and Abulghasemi, 2005). The pheromones eventually decay unless more ants follow onto the same links. Generally, accurate evaluation of the evaporation rate increases in importance with the difficulty of the optimization problem (Dorigo and Stützle, 2004). Furthermore, according to Poorzahedy and Abulghasemi (2005), the algorithm obtains better results when pheromone density is not recalculated after each ant tour. We recalculate pheromone density after 14 bundles, or one iteration, respectively. A ratio ρ of the existing pheromone molecules τ_{ij}^{0} evaporates after each iteration, before the new molecules $\Delta\tau_{ij}^{k}$ are added to the links (P2). $\Delta\tau_{ij}^{k}$ is proportional to the benefit of bundle *k*. Link $|i\ j|$ was chosen *m* times before new density is calculated. In this work, ρ is calibrated together with α and β for optimal convergence (see chapter Results).

P2 $$\tau_{ij}^{1} = \rho \cdot \tau_{ij}^{0} + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}$$

In summary, the algorithm proceeds as follows:

Step 1: Benefit-cost ratios are calculated for each project.

Step 2: The first ant starts at project 1 and chooses a second project according to p_{ij} (P1). As soon as the financial resources are depleted $(F_k = \phi)$, the overall benefit is calculated for the evaluated bundle.

Step 3: Step 2 is repeated until a certain number of bundles *k* (*k*=14 in this work) are defined by the ants. The ants start at each project once, instead of choosing the initial project randomly; suggested by Poorzahedy and Abulghasemi (2005).

Step 4: Pheromone density is calculated according to formula P2.

Step 5: As soon as the benefit of the best bundle (of one iteration) does not increase anymore, pheromone densities are slightly changed in order to avoid a local optimum. Pheromones are doubled on links with pheromone density below average, suggested by Poorzahedy and Abulghasemi (2005).

Step 6: When the overall benefit does not change anymore after 3 iterations (Poorzahedy and Abulghasemi, 2005), the algorithm stops, otherwise it proceeds to Step 2.

2.4 Assessment of the bundles

A key advantage of the ant colony heuristic is its independence from assessment methodology. Here the isolated projects and the bundles are assessed using cost benefit analysis (Stopher and Meyburg, 1976). Cost benefit analysis is a popular and widely accepted evaluation tool in Switzerland (VSS, 2006). Other methodologies could also be applied with ant colony heuristic. However, only methods not requiring the analyst’s intervention during an iteration are appropriate. For simplicity, only travel times and distances are considered in the benefit-cost analysis employed here, but account is taken of modal shifts due to network improvements. Additional indicators, such environmental impacts, safety gains etc. can be included, but had to be excluded due to data availability problems; for details see Stopher and Meyburg (1976) and VSS (2006). Travel times savings are valued according to Hess (2006) and VSS (2007), which vary the valuations by distance travelled. Travel distances are used to calculate the operating costs of private transportation. Operating costs of public transportation are not included. No changes in trip generation and distribution are integrated into evaluation. For this reason, the assessment function calculates only the First Year Return (benefit-cost ratio for one year). A time horizon of 40 years is assumed for all calculations. Benefits and costs are discounted (VSS, 2006).

3 Region of Bern

The case study reported here is the first with a realistically sized network. The algorithm was implemented using EMME/2’s macro language (INRO, 1998), interfaced with the existing static EMME/2 transportation network of Bern (RVK4, VRB and Trans, 2004). Because of the on-going work for a new long-range transport master plan, the case study makes use of the slightly out-of-date model for the year 2000.

3.1 Study area

The perimeter of the model surrounds the capital Bern and encompasses 370’000 inhabitants, 235’000 employed (year 2002) and 85 municipalities. The city of Bern has 129’000 inhabitants. The suburban areas and the city of Bern are highly congested during morning and evening peak hours. The main highways around the city are at their capacity limits. Compared to off-peak times, private transport travel times of the entire model increase by 10% during rush hour due to congestion effects. There is a clear need to improve the current situation.

3.2 Multimodal simulation of the Region of Bern

The transportation model used in this work has the characteristics listed in Table 1. Network and demand uses data of the year 1998 or later. For simplicity, only evening rush hour (5pm – 6pm) is considered. Demand includes trips in and out of the perimeter, through trips and local trips. Demand in private and public transportation only changes through mode choice, and no additional trip generation and distribution are calculated for this work. Private transportation route choice depends on link travel times, which are functions of actual traffic flow. Route choice is calculated using the well-known Wardrop Equilibrium (Frank and Wolfe, 1956). Public transportation equilibrium does not account for any congestion effects. Participants are assumed not to know timetables and choose randomly out of a set of possible line combinations.

Table 1: Characteristics of the network analysed

Number of zones	350
Modes	Public transportation (train, bus and tramway) Private transportation
Nodes	724
Links	2100
Demand public transportation (evening peak hour):	38’500 [pers.]
Demand private transportation (evening peak hour):	69’500 [veh.]
Travel time public transportation (evening peak hour):	58’500 [h*per.]
Travel time private transportation (evening peak hour):	46’100 [h*veh.]

3.3 Modal split estimation

Two different modal split estimates were tested to assess results sensitivity. The first model implements the parameters of the neighbouring Zürich area mode choice model via a pivot-point-logit formulation (Vrtic, Fröhlich, Schüssler, Axhausen, Schulze, Kern, Perret, Pfisterer, Schultze, Zimmermann and Heidl, 2005). The second model had been calibrated for Bern (RVK4 and Trans, 2002), but has a simpler general cost formulation. Both approaches include travel time and distances, but the Zürich model also considers access time to public transport, public transport service headways and number of transfers.

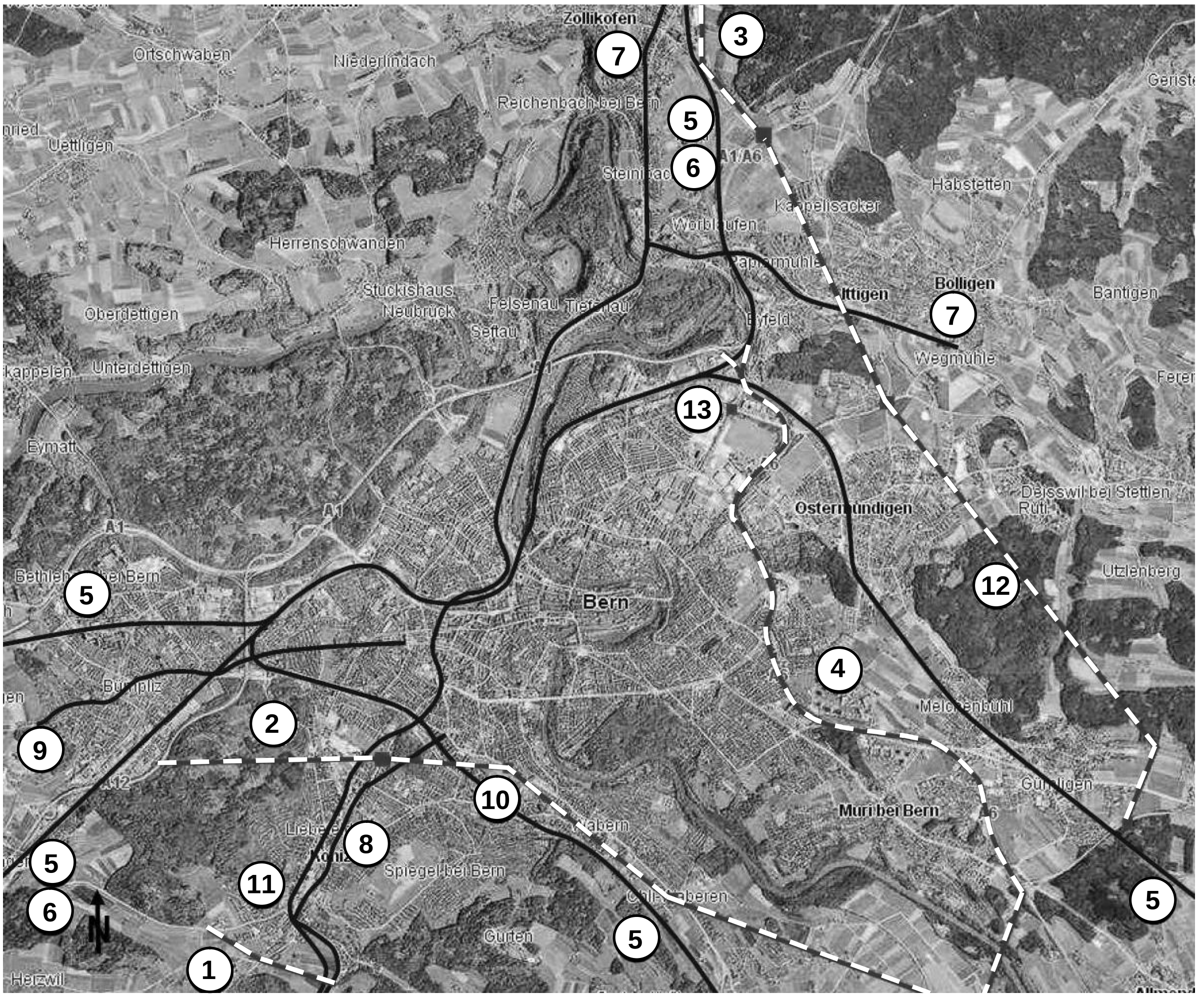
3.4 Potential infrastructure projects

From the set of projects currently discussed in Bern, a set of fourteen was selected. This set includes both small and large projects, as well as public transport and road projects (Table 2 and Figure 2). Descriptions can be found in Vitins (2006), values in Table 2 are estimates and cannot be compared with ongoing assessments of similar projects.

Table 2: Possible infrastructure projects

Public transportation		Invest-ment [Mio sFr]	Private transportation		Invest-ment [Mio sFr]
5	Upgraded commuter railway system	300	4	Removal of existing by-pass	4500
11	Extension of regional train network	270	10	Large by-pass (south)	1200
8	Tramway 1 (Köniz Schliern)	190	12	Large by-pass (east)	950
9	Tramway 2 (Bern West)	160	2	Access road (Morillon)	700
6	Accelerated express trains	130	14	Access road (Münsingen)	90
7	Higher frequency on regional train	130	3	Access road (Zollikofen)	90
			13	Expansion of a major junction	60
			1	Small by-pass	10

Figure 2: The region of Bern and the infrastructure projects.



Private transportation projects are in dashed lines; numbers refer to Table 2.

4 Results

4.1 Modal split calculations

Aggregated travel time changes are central elements of any transport project benefits. In a congested urban environment, it is necessary to assess the intermodal competition as well. In advance of the optimisation, the size of these interactions was assessed by calculating the impacts of modal shifts on public and private transport travel times using the two models described above, iterating once between assignment and mode choice. To check for the stability of the results, calculations with the first model were iterated three times using the method of successive averages to smooth the matrices. Table 5 presents travel times calculated independently for each infrastructure project.

Table 3 Travel time change due to the projects in isolation with and without modal choice effects

#	Project		After assignment	One iteration (2^{nd} model)	One iteration (1^{st} model)	Three iterations (1^{st} model)
Change in public transport travel times [h]						
1	Small by-pass	Private	0	-180	-310	-299
2	Access road (Morillon)	Private	0	-34	-262	-253
3	Access road (Zollikofen)	Private	0	-146	-295	-291
4	Deconstruction of existing by-pass	Private	0	143	-32	-30
5	Upgraded commuter railway system	Public	-311	85	311	289
6	Accelerated express trains	Public	-683	-995	1'637	1'585
7	Higher frequency on regional trains	Public	-206	40	-281	-261
8	Tramway 1 (Köniz Schliern)	Public	-28	10	-229	-227
9	Tramway 2 (Bern West)	Public	-14	8	-254	-248
10	Large by-pass (south)	Private	0	-649	-543	-524
11	Extension of regional train network	Public	-209	24	117	110
12	Large by-pass (east)	Private	0	-154	-396	-388
13	Extension of main junction	Private	0	-110	-275	-266
14	Access road (Münsingen)	Private	0	-30	-275	-274
Change in private transport travel times [h]						
1	Small by-pass	Private	-144	-89	-229	-235
2	Access road (Morillon)	Private	-33	-32	-161	-145
3	Access road (Zollikofen)	Private	-98	-89	-193	-199
4	Deconstruction of existing by-pass	Private	504	423	339	267
5	Upgraded commuter railway system	Public	0	-125	-339	-349
6	Accelerated express trains	Public	0	-86	-650	-648
7	Higher frequency on regional trains	Public	0	-79	-151	-113
8	Tramway 1 (Köniz Schliern)	Public	0	-12	-155	-127
9	Tramway 2 (Bern West)	Public	0	-19	-147	-111
10	Large by-pass (south)	Private	-867	-737	-903	-891
11	Extension of regional train network	Public	0	-87	-252	-250
12	Large by-pass (east)	Private	-305	-302	-400	-381
13	Extension of main junction	Private	-93	-51	-182	-181
14	Access road (Münsingen)	Private	-57	-78	-191	-171

The second mode choice model implies less change, partly because it does not capture all relevant changes in generalised costs (Note that travel time increases can be due to reduced capacities (e.g. Project 4) or increased demand (e.g. Project 5)). Changes due to additional iterations are generally small and do not justify the computational effort during the optimisation.

4.2 Convergence of the ant colony heuristic

The convergence of the ant colony heuristic is the precondition for its success in application. Setting the parameters α, β and ρ (P1 and P2) within a neutral range does not guarantee convergence. It depends to a certain extent on the values range of the objective function. Notably, the pheromone markers' influence ($\alpha \cdot \tau$) cannot be captured with the suggested standard values. Few related papers take notice of this crucial topic (Merkle *et al.*, 2002). We found no consideration of this issue for the network design problem in existing literature.

A general problem, also for the calibration issue, is the assessment of the results quality obtained by the ant colony algorithm, as a complete enumeration is infeasible. The relative position vis-à-vis the true optimum bundle cannot be known because of the heuristic nature of the algorithm. However, a manual analysis of iterations indicates the quality of the obtained result.

According to Poorzahedy and Abulghasemi (2005), results improve when the ants start at each project once, before pheromone markers are recalculated. As our specific case study contains 14 different infrastructure projects, the pheromone markers are updated only after 14 bundles. This seems to be the general rule for the pheromone update: for more complex combinatorial problems, better results are obtained with less frequent pheromone updates (Dorigo and Stützle, 2004). Results also improve when ants start in strict rotation, instead of choosing the initial project randomly (Poorzahedy and Abulghasemi, 2005).

The benefits (mean and variance) of bundles tested during a run are similar for various runs. Below, a single run is used for illustration. Its convergence behaviour is shown in figure 3. The pheromone amounts of each link are proportional to the grey value of the squares. Most of the squares diminish while a few stay stable or even get darker. It is possible to recognize relevant links after the 7th iteration. The squares belonging to the selected bundle never appear in black because of the constant evaporation rate. Convergence has to take place continuously. If convergence were reached in one of the first iterations, a local maximum can be assumed, making it possible to identify misleading parameters sets and early convergence with graphics like figure 3.

Figure 4 shows the benefit-cost ratio of the evaluated bundles for a complete run. The average benefit-cost ratio increases at the beginning and remains stable towards the end. The heuristic finds the most favourable bundle first during the third iteration. After that, the most favourable bundle is chosen more and more frequently. However, there are always bundles with lower benefit-cost ratios, even when the algorithm has already converged. They occur particularly when ants have to start at projects with low benefit-cost ratios. At first, the random choice of the next project is the reason for the unfavourable solutions. Later, the algorithm always finds the most favourable bundle as long as the ant starts at a project belonging to the best bundle. In Figure 4, oscillation of mean benefit can be seen until the end of the run. This is due to remaining variance of the bundles tested in each iteration.

Using figure 3, 4 and the list of bundles selected and benefits calculated, one can identify when convergence has been reached. Distinct squares (in figure 3) have to match the convergence approach (figure 4) and the largest benefits.

Figure 3: Pheromone marker density during a complete optimisation run.

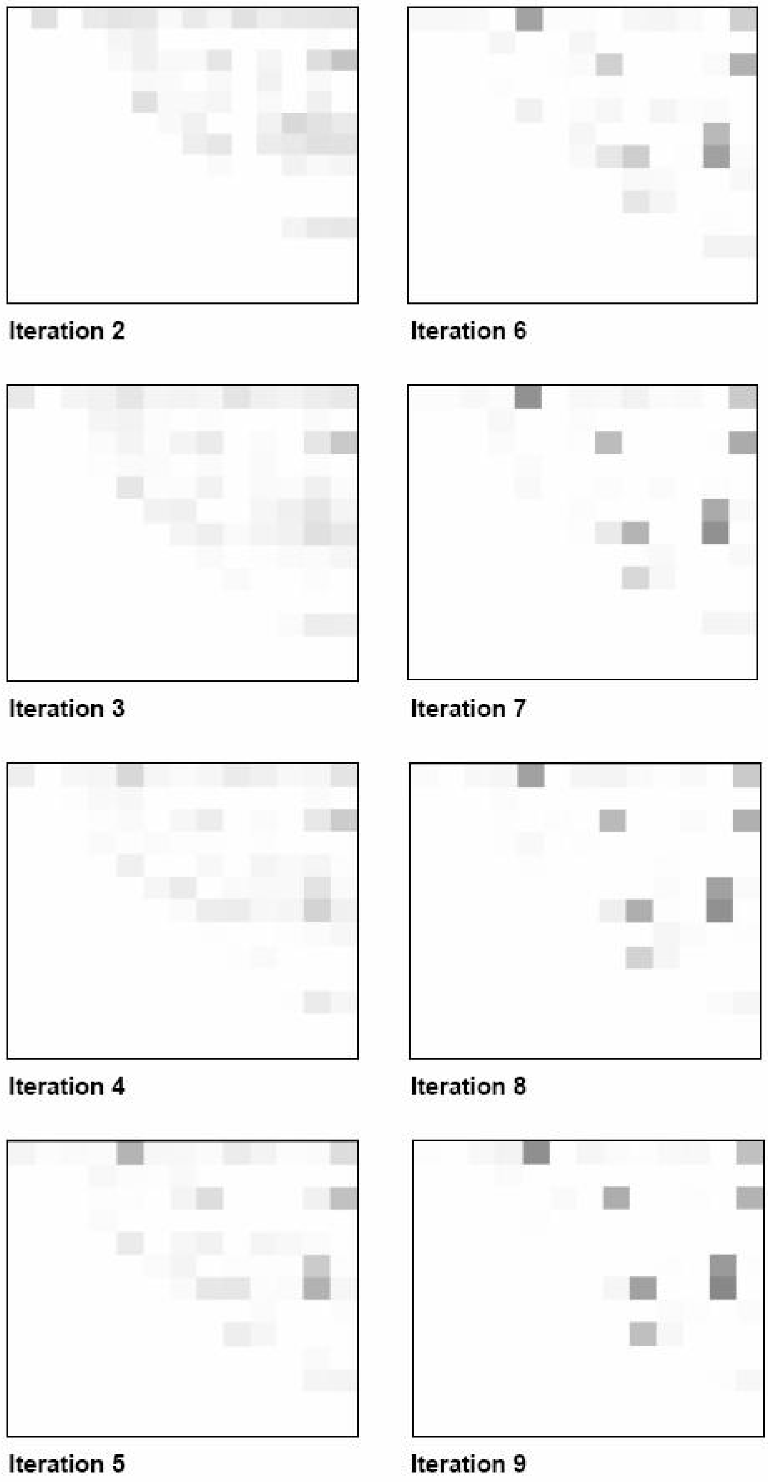
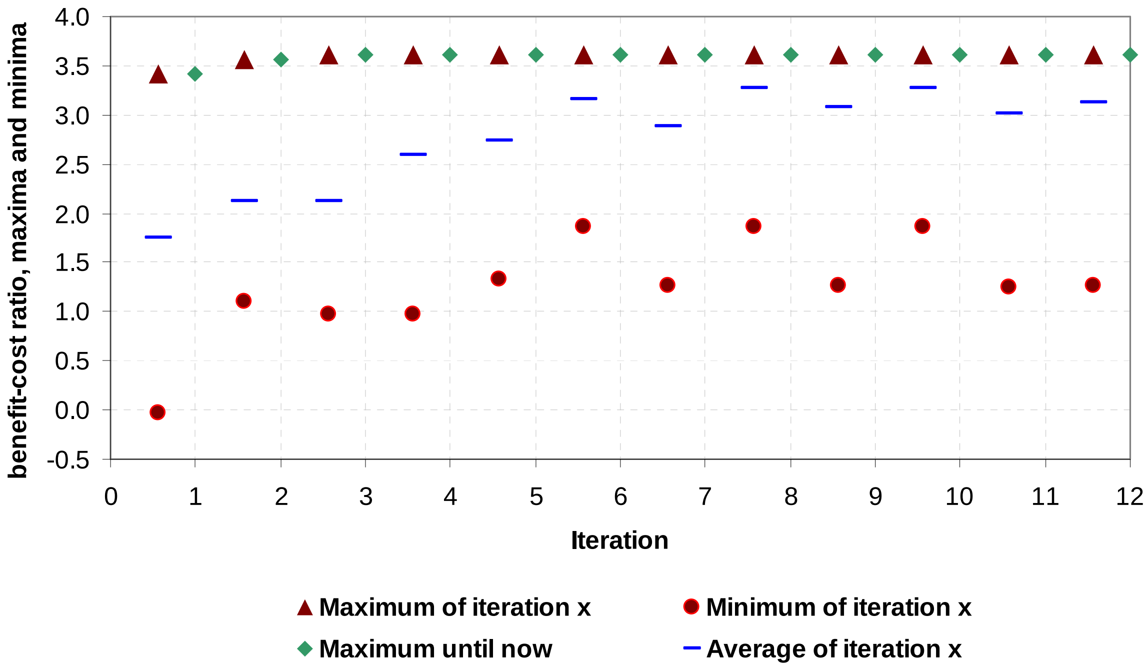


Figure 4: Benefit-cost ratios during a complete run.



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4.3 Calibration

Calibration has to be carefully accomplished, employing a systematic approach to reduce the number of equilibria calculated and computation time. The following methodology is straightforward and considers only the three most important parameters (Table 4). They all manipulate the influence of pheromone markers during the ants' decision-making process.

Table 4: Three parameters to be calibrated.

Parameter	Explanation of parameter	Corresponding formula
α	Weight of pheromone concentration	(P1)
β	Weight of an individual infrastructure project	(P1)
γ	Evaporation rate	(P2)

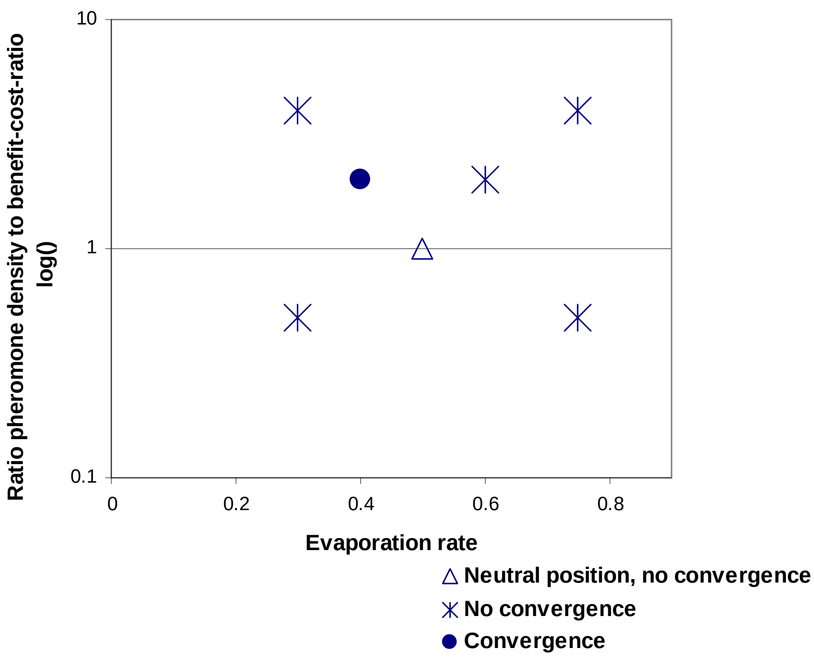
At least one complete run has to be performed for each parameter set. It is desirable to have as few runs as possible to minimize computing times. The parameter sets are displayed in Figure 5, and the first four are arranged in a rectangle. A neutral position is adopted in the centre of the rectangle with $\alpha/\beta = 1$ and $\rho = 0.5$, as proposed by Poorzahedy and Abulghasemi (2005). The corners of the rectangle efficiently show the effect of the parameters. When no set delivered convergence, the search was extended using combinations inside the box defined by the first four sets.

The lower and upper bound of α/β were chosen - on one hand - to limit the influence of the pheromones (small alpha), so that no "learning effect" will occur. On the other hand, when alpha is too large, only the first bundle with a good result will be chosen by the following ants and convergence will occur too quickly in a local optimum. Calibration of the evaporation rate ρ is less sensitive, but important as well. A higher evaporation rate focuses more on recent results and shortens the feedback loop. We started at $\rho = 0.5$ and improved the results as we applied higher evaporation rates. The ability to lose information gained after a certain period of time is equivalent to 'forgetting' in artificial intelligence research.

Additionally, properties of the exponential function have to be considered for enhanced convergence. The smaller the value of alpha and beta, the larger the random effect of the probability function. Results of the calibration run, especially the values of each bundle, have to be considered very carefully to identify convergence behaviour. In this case, the ratio α/β cannot be lower than 1 because no convergence was recognized. However, calculations with a ratio of 4 ended up in a local optimum, recognized by analyzing bundles and the corresponding benefit-cost ratios.

The selected parameter set could be improved with additional calibration runs, but there is a trade-off between additional calibration effort and final results obtained. Nonetheless, the discrete nature of the problem and the relatively small number of projects make this improvement unlikely. In addition to the calibration above, it is possible to change parameter values during an optimisation run to obtain better convergence performance (see below). It is essential to recalibrate the parameters whenever changes are made in the modal split or objective function. Here, such a recalibration was performed after a change in the modal split function.

Figure 5: Different parameter sets tested.



4.4 Comparison between the projects and the evaluated bundle

The two modal choice approaches have a surprisingly large impact on the chosen bundle. The private car oriented projects do not vary between the two optimal bundles, but the transit projects are almost entirely different (Table 5).

Table 5: The applied modal split functions and the corresponding, selected bundles.

Mode	1st Model with three iterations	2nd Model with one iteration
Public transportation:		
	Tramway 1 (Köniz Schliern)	Accelerated express trains
	Tramway 2 (Bern West)	Tramway 2 (Bern West)
		Higher frequency of regional trains
Road projects:		
	Access road (Münsingen)	Access road (Münsingen)
	Access road (Zollikofen)	Access road (Zollikofen)
	Expansion of main junction	Expansion of main junction
	Large by-pass (south)	Large by-pass (south)
	Small by-pass (Köniz)	Small by-pass (Köniz)

Please take notice of the assessment and the small number of indicators. Current evaluations of projects within the region of Bern could lead to different results.

Table 6 shows the benefit-cost ratios of all infrastructure projects, calculated individually. The small by-pass (Köniz) has the highest benefit-cost ratio due to very low building costs. The reconstruction (actually removal) of the existing by-pass reduces capacity of the eastern highway and results in a negative cost-benefit ratio because its emission reduction objectives are not fully valued here. Generally, public transportation projects show lower ratios. There are several possible reasons for this outcome. First, projects could, in fact, be less efficient than private transportation projects. Second, the benefit-cost function could be incomplete, due to considering only travel times and operation costs and lack of other impacts, such as environmental and social benefits. Neither modal split function covers all aspects of mode choice fully, for example, comfort of vehicles or reliability. Substituting a tramway for a bus line (like the two tramway projects considered) can result in low travel time savings and therefore a low benefit-cost ratio, even though total benefit may be higher.

Table 6: Benefit-cost ratios of the isolated projects (1st modal split function)

Projects	Mode	Costs/year (Mio. sFr./a.)	Travel time savings/year (Mio. sFr./a.)	Benefit-cost ratio (first year return)
Small by-pass	Private	0.4	68	169
Extention of main junction	Private	2.3	57	25.2
Access road (Zollikofen)	Private	3.5	68	19.4
Access road (Münsingen)	Private	3.5	59	16.8
Higher frequency on regional train	Public	5.0	44	8.8
Tramway 2 (Bern West)	Public	6.3	47	7.5
Tramway 1 (Köniz Schliern)	Public	7.5	50	6.7
Extension of regional train network	Public	10.8	51	4.7
Upgraded commuter railway system	Public	13.9	52	3.7
Large by-pass (south)	Private	45.0	175	3.7
large by-pass (east)	Private	37.5	98	2.6
Access road (Morillon)	Private	27.5	48	1.7
Accelerated express trains	Public	5.0	7	1.4
Removal of existing by-pass	Private	17.3	-46	-4.6

Please take notice of the assessment and the small number of indicators. Current evaluations of projects within the region of Bern could lead to different results.

Among private transportation projects, the algorithm chose the project with the highest benefit-cost ratio when considered independently. The algorithm chose public transportation projects slightly differently. When employing the first modal split function, the two tramway projects are selected despite the fact that a higher frequency on regional trains has a higher benefit-cost ratio. Synergies within the tramway network are the explanation. Regarding the second modal split calculation, the tramway's independent performance is poorer compared to other projects. Nevertheless it is selected as well; synergies could be a factor again.

4.5 Network consequences

All included projects operate at full capacity. Applying the ant colony heuristic, possible interactions between projects are taken into consideration. Traffic decreases are remarkable on notoriously congested links such as motorway sections west and east of the city. Referring to detailed network analysis, traffic decreases are due to the new by-pass, and the expansion of the major junction, respectively. Traffic also decreases on permanently congested streets in the centre of the city.

Table 7 shows total travel times when comparing the evaluated bundles with the sum of the isolated projects, separately for the two selected bundles. One sees that cumulated travel times of single projects are substantially greater than travel times of bundles, because the projects compete for the same users. The method employed ensures that these interactions are identified and properly accounted for.

Table 7: Comparison of the isolated projects and the evaluated bundles (both evaluated with the 1st modal split model)

	Reference scenario	Optimal bundle	Sum of isolated projects
Bundle of 1st modal split model	Total travel time	Savings	Savings
Public transport [Passenger.h]	58’483	2’000	2’129
Private transport [veh.h]	46’151	999	2’000
Value [Mio. sFr/a]		226	524
Bundle of 2nd modal split model			
Public transport [Passenger.h]	58’483	555	844
Private transport [veh.h]	46’151	1153	1228
Value [Mio. sFr/a]		218	351

4.6 Conclusions

The paper has demonstrated that a substantial NDP for a large network can be solved with a reasonable effort employing the ant colony heuristic. The results discussed show how dangerous it is to add projects naïvely to a bundle. The results also show the sensitivity of the final results to the overall modelling framework, here exemplified by the different modal split models. It is clear that the incorporation of both destination choice and trip generation, for example in the Swiss National model (Vrtic, Lohse, Fröhlich, Schiller, Schüssler, Teichert and Axhausen, In press), might change the bundles again.

The computation times implied in such a complete equilibration require a faster approach. It will also be necessary to remove or reduce the need for the parameter calibration, or at least to automate it. The integration of the benefit-cost calculation (naturally a richer one than implemented here), into the overall software environment would be highly desirable.

Fixed values of α, β and ρ could be adjusted during the run to improve both speed and quality of the solution. The parameters could be increased or scaled down during the course of a run. For example, at the beginning, α could be smaller, so that the ants choose projects more at random; evaporation would also be small. After a few iterations, α would grow, so that the influence of the pheromone markers would increase during the decision-making process. The ants would start to benefit more intensively from the preceding experiences.

Another important issue is the fixed budget restriction. It is possible to achieve higher cost-benefit ratios when, e.g., not using the entire budget. The algorithm should be adapted so it is possible to stop before the budget is fully committed.

Finally, the staging of the projects should be addressed in conjunction with an appropriate modelling of the changes in travel demand and population and work place distribution. It is clear that the complexity of this programme is still beyond current computing capabilities, but research into this issue should start immediately.

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Any errors are our own.

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