On the Design of Leisure Devoted Cycling Networks

Alessandro Giovannini[1], Federico Malucelli[2], and Maddalena Nonato[3(✉)]

[1] Dipartimento di Matematica, Università degli Studi di Milano, 20133 Milano, Italy
[2] D.E.I.B., Politecnico di Milano, 20133 Milano, Italy
[3] Dipartimento di Ingegneria, Università di Ferrara, 44121 Ferrara, Italy
maddalena.nonato@unife.it

Abstract. Due to the several benefits associated to cycling, the demand for bicycle devoted infrastructures has considerably raised in the last few years. Public resource investments into infrastructure provision increased to meet demand, despite of the lack of mature design and planning methodologies. Leisure intended cycling networks in particular, which are the topic of this work, are even less addressed. We revise the critical issues in cycling network design, present a design methodology for cycle tourist networks that integrates the specific features of the problem into a combinatorial optimization framework, and test the approach on realistic data comparing with previous contributions on this topic.

Keywords: Cycling network design · Cycle tourism · Combinatorial optimization

1 Designing Cycling Networks: Facts and Challenges

Benefits associated with cycling are many, ranging from transport sustainability and public health improvement to cycle tourism development. In the last few decades, the car-centered dominating culture has been shaping urban development all over the word, yielding cycle-unfriendly cities. Nevertheless, a recent trend rediscovered the advantages related to cycling, which in turn ignited scientific publications on this topic. Functional cycling in particular, i.e., when the bicycle is intended as a mode of transport, has been widely investigated in the transportation literature, and its promotion is central to proposals willing to increase the share of soft mobility, reduce traffic congestion, and lower carbon emissions, as testified by the many European projects on this topic such as BICY [33]. As demand for cycling increases, the debate on assessed and reliable methodologies for infrastructure provision and planning becomes crucial. Positive correlation has been proven between miles of bicycle pathways per residents and percentage of cycling commuters [29]. However, infrastructure provision alone does not guarantee usage will increase as expected. Moreover, options are so many - from bike lanes, either raised or on road, to cycle ways and cycle

tracks - that selecting the highest return infrastructure investment is a complicated task. Guidelines are often sought ex-post by comparing the outcomes of different interventions: see, for example, [3] for relations between cycling facilities and levels of cycling commuting in 90 large American cities, or [16,18,20,38] for travel behavior. Nevertheless, we still miss an abstract representation of the system sufficiently comprehensive to model cyclists behavior and mode choice, so that the provision of functional cycling devoted infrastructures can be guided by a reliable prevision of future usage, thus assessing the impact of potential interventions prior to deployment, as many advocate [36].

The field of infrastructure planning for leisure cycling is even less mature. This study aims at giving a contribution in this direction: first, the key factors leading functional cycling infrastructure design and planning are revised, and similarities and differences with leisure cycling are analyzed; on these bases, we formulate the leisure cycling network design problem as a combinatorial optimization model, propose a heuristic solution approach, present results for a realistic case, discuss them, draw conclusions, and sketch future work.

1.1   Criteria for Planning Cycling Infrastructures: Leisure Versus Functional Cycling

The Safety Concern. Among the several factors influencing the decision of whether or not commuting by bike, safety stands out as the main concern and many are the proposals in the literature aimed at hazard reduction and safety level improvement of cycling facilities to make cyclists feel safe en route [1]. In particular, a highly debated issue concerns the integration of cycling infrastructures into the vehicular road network (a common practice in the U.S., U.K. and Southern Europe) as opposed to its segregation from motorized traffic (a highly valued option in Northern Europe), each having strengths and weaknesses. While a segregated cycle track would guarantee the highest safety, it can be seldom deployed along the shortest route to destination in highly urbanized settings. As a result, the detour on the safest bike track is often too long to be a practical option for commuters who have to choose between longer travel times and higher safety (see [20]). Safety perception, thought, is itself an issue: indeed, the most critical challenge in modeling cyclist behavior is the understanding of risk perception, since perceived safety often substantially differs from objective safety [30]. Moreover, the cycling culture of each country adds to the built environment in affecting cyclist behavior and risk perception (see [17,20,24]). For example, [36] reports a case where even the provision of segregated cycling infrastructure would marginally reduce the car commuting share whereas a monetary reward on cycling could induce a consistent modal shift. In conclusion, while general guidelines can be shared, investigations focused on cyclists' perception and drivers' attitude towards cyclists should be carried out on site, for each specific project, to provide tailored guidance to policy makers for infrastructure provisioning devoted to functional cycling.

Several synergies exist between leisure and functional cycling, and planning methodologies share common challenges. Indeed, the two cycling communities are often mixed, and cycling infrastructures originally designed for leisure often

get used for functional journeys by experienced cyclists as well [29]. Nevertheless, functional cyclists and leisure cyclists have specific user needs. On the one hand, commuters prefer direct routes to destination, allowing constant travel speed and no stop at junctions. On the other hand, since cycling is part of the experience when cycling for leisure, riding the fastest route to destination is not a cycle tourist priority and traveling time is gladly traded for route quality. Moreover, different classes of users exist among leisure cyclists, as later discussed in Sect. 2. Sport oriented recreational cyclists are moved by fitness improvements and value challenging itineraries embedded in healthy environments. On the contrary, family cyclists prefer less engaging trips and appreciate attractions along the way as well as easily accessible service facilities [8,21].

Safety en route is a common concern for both communities, although differently perceived. As motorized traffic represents the main source of hazard, both value traffic free or low traffic routes and clear signage. However, a 14.000 people survey in the UK [12] shows a different attitude towards traffic volume, which appears to have greater impact on leisure cyclists than on commuter cyclists, the former being generally less keen mixing with motor traffic. Such behavior is partially explained by the higher average level of experience utility bikers have, with respect to leisure bikers. Actually, there is some positive feedback in providing safe, leisure devoted, cycle routes: since inexperienced cyclists tend to overstate risk perception, offering a friendly and protected environment where they can ride and have fun in complete safety increases their confidence with this mean of transport and decreases their hazard perception, potentially enlarging the community of utility cyclists in the near future. [8] reports such a positive effect regarding the Great Western Greenway in Ireland, a cycle route created to attract visitors and cater to recreational cycling. A few years from its completion, the percentage of sustainable travel patterns of residents, school commuting by bike in particular, remarkably increased.

Safety can be evaluated based on quality indexes such as Bicycle Level of Service (BLOS) and Bicycle Compatibility Index (BCI), thus providing a quantitative methodology to set safety standards. Additional, less measurable, design criteria should be also considered when designing a cycle route, such as continuity, attractiveness, comfort, directness, societal and economical impact.

Additional Criteria. The lack of **continuity**, i.e., the possibility of reaching destination along a seamless itinerary, is often questioned by urban cyclists and it strongly affects the perceived suitability of cycling as a transport mode of choice for commuters. This concept is closely related to network **connectivity**, that is continuity for all origin - destination pairs. In a similar way, a leisure cycling route is appealing only provided that it ensures a certain quality standard throughout its way, from origin to destination; likewise, a leisure cycling network is expected to connect the local attractions in a seamless manner.

Comfort is related to surface quality and number of junctions and stops. For recreational cyclists it is also affected by accessibility of service points en route. Gradient impacts on comfort, although specific challenging itineraries can be a valid alternative to the regular track for sport oriented practitioners.

When commuting by bike, additional **travel duration** with respect to the shortest path must be limited: several studies suggest that only itineraries not longer that 33% of the shortest path are considered as viable alternatives [13]. When cycling for leisure, though, journey ambiance is favored with respect to **directness** to destination, and different classes of users should be considered, each one with its own time limit ranging from few to several hours.

In case of recreational cycling, **attractiveness** refers not only to the particular features of the pathway and to its aesthetic, but it concerns the appeal of the points of interest reachable along the pathways and to the scenery of traversed landscapes, so it varies according to the user profile. Pathway attractiveness, thought, started to be recognized as an asset by academics and city planners also for cycleways catered for commuters within a urban environment [22]. Indeed, attractiveness is among the five criteria suggested in [7] for cycle infrastructure design, and [19] mentions attractiveness as one of the attributes for a functional cycling infrastructures quality index.

Promoting cycling as a mode of transport provides direct and indirect **economic benefits** since it decreases motorized traffic and improves population health and well being. Promoting cycle tourism provides opportunities for sustainable development to many areas featuring natural and cultural attractions concentrated in a small region [23]. Cycle tourists are a particular kind of eco-tourists, who appreciate the journey as well as the destination; segregated infrastructures, scenic landscapes, and Points of Interests (PoIs) en route are a must; quite often, though, areas that would qualify in terms of attractions miss an appropriate infrastructure. This fault affects the satisfaction level, since the cycling activity is an integral part of the tourist experience. Therefore, providing adequate riding facilities is mandatory for cycle tourism development, whose economic benefits are unquestioned: the value of cycle tourism in 2012 was estimated at about 44€ billions, with significant potential to increase [37]. The Great Western Greenway is a representative success case: its creation spurred several tourism related business activities supporting the local economy and the estimated annual economic impact suggests a very short payback period for public investments of this kind.

The development of cycle networks is becoming more and more part of the public agenda at the regional, national, and even international level [33]. Since political and governmental policies shape the development of cycling infrastructures, providing guiding principles and well assessed planning methodologies to support decision makers is fundamental. Consider for example Euro Velo, the European cycle velo network (www.eurovelo.org) now extending for almost 45.000 km, which is a challenging project intended to connect all countries in Europe by an ever growing network of high-quality cycling routes [37]. This planning effort, however, often acts a posteriori, setting quality thresholds and other standards for existing bikeways to be included in the project that marginally influence planning decisions on the territory. Indeed, the planning phase of each single route is often conducted independently by each local administration as a once-off project, being managed as a resource led activity driven by

cost-benefit analysis and responding to local stakeholders expectations [6]. As a result, cycle networks tend to be discontinuously developed, potentially lacking a comprehensive vision and missing the chance of achieving long term targets [28]. On the contrary, the scientific literature advocates user needs evaluation prior to deployment as the key to fulfilling cyclists expectations and exploiting cycling facilities at their best, besides consistency and integration of all decision maker actions [9]. For example, Manton [26] provides guidelines for greenways design, emphasizing their multiobjective purpose (such as natural corridors, commuter cyclists links, and recreational traffic-free sites) while ensuring path quality and providing connection with points of interest and other networks; Weston [37] envisions a network of greenways featuring safe and continuous routes, with point of interests on route through scenic landscapes. On our side, we stress the need for embedding the system representation into an optimization model as the only mean of implicitly considering all the feasible network alternatives and supporting decision makers with reliable quantitative methodologies, rather than narrowing the choices to a limited set of precomputed options [5]. Some recent proposals in this direction are listed in the following.

1.2   Optimization Models for Cycling Network Design

A limited though significant body of literature concerns the application of optimization techniques to the solution of mathematical models for cycling network design, building on the methodologies developed for network design in other fields. This allows to potentially optimize over all the network configurations that correspond to feasible solutions to the mathematical model instead of comparing a limited number of previously designed alternatives. The resulting models, often multi-objective ones, generalize the fixed charge, multicommodity, min cost flow problem, but realistic instances are not solved to optimality.

All but one of the following are devoted to functional cycling.

In [22] a multiobjective optimization model is proposed to design a urban cycling network in Taipei. The objectives are minimizing risk and impact on traffic, maximize comfort and residents service coverage. The constraints involve bikeway type, monetary budgets, path continuities, and value ranges of decision variables. Six non dominated solutions are computed and analyzed.

In [21] the same methodology is extended to tackle the design of a recreational cycling network in the north coastal area of the Sanzhi district in Taiwan, currently featuring a fragmented offer of bikeways. The authors consider four types of bikeway retrofitting or construction (reserved or shared use bike paths, bike lanes, and bike routes) and two types of service facilities (rest areas and rental shops); constraints concern (i) connectivity among gates (existing transit stations providing access to the scenic area) and from each network node to a gate, (ii) maximum distance required for service coverage, (iii) limited budget; service demand is assumed known, given by the number of tourists currently using the access transit stations; four criteria (served demand, service station coverage, safety, attractiveness) were optimized in a 0/1 multiobjective linear programming model, solved by the ϵ-method yielding six non dominated alternatives.

In [28] cycle-network planning (CNP) at the local level is solved targeting several objectives including accident reduction, modal shift in favor of cycling, health benefits and strategic network expansion, exploiting a spatio-temporal model embedded within a GIS-based decision-support system; the development of a cycle network in a small town in the UK is used as a case study.

In [10] an optimization model is proposed that designs a minimum cost cycling network interconnecting a set of origin destination (OD) points by retrofitting existing roads such that a given quality is guaranteed (in terms of BCI on segments and LOS on intersections) and each OD path duration is bounded. The aim is to support seamless bicycle trips between all OD pairs, mending fragmented sets of existing cycle paths. Bicycle demand is not considered, as latent demand will be revealed only afterward. The methodology is applied to the county of Austin, Texas, and favorably compares to separately designing individual itineraries. However, only toys instance are solvable. In [31] the authors solve a similar problem aiming at minimizing trips length and maximizing the LOS of selected links. The terms in the objective functions are weighted according to present OD demand, disregarding latent demand.

In [27] the authors propose an optimization framework for the design of a network of bike lanes in a urban road network, aimed at identifying on which links a bike lane should be realized. The lower level of a bilevel model embeds a traffic assignment problem, while the upper level optimizes total travel time for car users and total distance that can be ridden on bike lanes subject to a budget constraint and assuming given bicycle demand. The model is heuristically solved by Genetic Algorithms and tested on an artificial grid network.

Building on top of these experiences, we propose a mathematical optimization model that either integrates as constraints or fulfills by construction the above mentioned criteria and seeks the highest utility for several classes of users. This introduces the issue of *routing for profit*.

1.3 Routing for Profit

Many applications in tourism planning are based on generalizations of the Orienteering Problem (OP) [11,34]: given a graph with travel time on edges and profit on nodes, OP consist of computing the maximum profit tour subject to maximum travel time. In tourism applications nodes represent PoIs and edges model the shortest path between PoIs [14]. They are usually embedded in decision support tools designed for tourists visiting a city and often allow to integrate user preferences [35]. A version devoted to cycle trips planning is described in [32], while the issue of thematic routes building has been recently addressed in the eco-tourism framework [2]. Again, infrastructure provision is not contemplated. In all these applications the physical (road) network providing connection between PoIs is always taken for granted, so that no design cost is taken into account. Moreover, traversed PoIs provide reward only at the first visit, so no optimal solution has multiple traversals.

The problem addressed in this work, i.e., cycle tourist network design, can not be solved by the aforementioned approaches for at least two reasons:

(1) infrastructure provision costs must be handled; (2) since biking is part of the tourist experience, successive traversals of the same edge impact total reward and must be accounted for. Both features were first addressed in [4] where the Most Attractive Cycle Tourist Path Problem (MACTPP) was introduced: it consists in computing the most rewarding itinerary from origin to destination, subject to duration and budget constraints, with decreasing attractiveness at successive traversals of the same edge and node. Due to the strong ties with OP, MACTPP was modeled by a Mixed Integer Linear Programming (MILP) model generalizing the one in [11], and easily solved by commercial solvers for realistic instances. In a later study [25], a multi-commodity version of MACTPP, named MOP-ND, was proposed to jointly handle several classes of users with different attractiveness functions and to design potentially different itineraries going from the same origin to the same destination which must share the same budget. The study experimentally shows that using more information in the planning phase pays off in terms of potential attractiveness of the resulting infrastructure. Both studies designed itineraries connecting a single origin-destination pair. In [15] the design of the whole network is finally tackled. Given a set of network access points (gates), the tools developed for the single origin-destination itineraries were exploited to build an interconnected infrastructure, linking all the gates and providing access to most PoIs. In that work, high quality paths from gate to gate were first built and then a subset was selected and the network was built out of the edges of those paths. In this work we totally revolve the decision flow: we start from selecting a set of budget compliant edges and then build the itineraries from gate to gate based on these edges, as detailed in Sect. 2.

2 Solving the Cycle Tourist Network Design Problem

2.1 Problem Statement

As discussed, the problem consists of selecting the tracks to be retrofitted, taking into account budget constraints and user preferences, in order to design a network of bike trails spanning over a restricted but compact area where several visitor attractions are located, which the network should provide access to and mutually connect along itineraries that are fit for casual, recreational, day cyclists. In our proposal, as in [21], the access to the cycling network is given through a set of gates that provide connection to other means of transport, i.e., gates are locations on the main road network or stops of the local public transport system, whether bus or train, and are equipped with parking lots and renting facilities. The cycling network should connect gates to each other and to the most attractive spots by way of scenic pathways providing maximum satisfaction to potential users, according to their preferences. While exploiting existing tracks already fit for cyclists, our planning methodology tries to consider each of them as an additional asset rather than taking all of them for granted from the beginning as *Cost for Benefit* approaches would suggest.

Note that we comply with the design criteria and recommendations discussed above. Indeed, we guarantee continuity and completeness by construction, since the resulting network connects all gates and selected routes have limited duration. Safety and comfort are ensured thanks to either selecting links already fit or retrofitting those unfit, so that all routes, from origin to destination, meet quality standards. User needs are taken into account by modeling the utility function of different user classes, and thematic itineraries will be designed between the given network gates. Directness intended as providing routes with different maximum travel durations, is guaranteed as well. The required investment is an input parameter, so that public stakeholders can set it and vary it according to availability. The model can be used as well to compute the lowest amount required to build a complete, compliant network.

More formally, we face the following combinatorial optimization problem.

We assume to be given: (i) the most sought after locations (PoIs) present in the area and the edges that connect them: the latter are the potential links of the cycle network; (ii) the locations acting as gates, giving access to the cycle network from the outside; (iii) the utility functions of a predefined set of user classes, quantifying the reward experienced by the user when biking along a link or visiting a PoI; (iv) the time required to traverse each link, in both directions; (v) the cost of upgrading each potential link in order to reach a minimum BCI threshold (0 if the link is already fit).

The problem consists of selecting the optimal set of links to be retrofitted to form a network so that: (a) each origin-destination pair of gates is connected along at least one itinerary not longer than a given duration, (b) the total budget available for upgrading is not exceeded, (c) the sum of the attractiveness of the thematic itineraries over the different user classes is maximized.

Building on the experience gained in modeling and solving MACTPP and its multi-commodity version MOP-ND, in [15] we proposed a network design methodology structured into five steps: (1) compute a set of promising paths by solving MACTPP for different time durations and total budget shares; (2) select one path for each pair of gates and user class; (3) build the network made of all the edges in the selected paths; (4) solve a MACTPP on that set of edges for each pair of gates and user class, and eventually (5) get rid of redundant edges (those never used by the computed itineraries). We call this approach *Path-First-Network-Second* (PFNS).

Despite PFNS can solve the problem, several MACTPP instances for the same origin destination pair - differing for time limit and budget share - have to be solved at step (1) to produce a sufficient variety of paths for step (2). The major drawback, however, is that PFNS is not robust with respect to budget. First, it provides no clue about the minimum budget required for a feasible solution. Second, it may fail to find a solution for a given budget even when such a solution exists, due to the fact that some paths part of that solution have not been generated at step (1). Therefore, a trial and error approach is necessary with respect to budget calibration, which is a serious pitfall for practical applications. Finally, the resulting networks are rather dense, which is not desirable. In fact,

beside being intrinsically a bi-objective problem, i.e., minimizing budget and maximizing attractiveness, a third network quality criterion concerning edge number is also present. These objectives are all conflicting, and we aim at finding Pareto (sub-)Optimal solutions; in particular we aim at being able to compute solutions with low budget whenever they exist.

The drawbacks of the PFNS approach come at no surprise since PFNS starts from individual paths, each of which is selected while unaware of its share of budget and of the set of edges used to connect the other gates. In the present work we try to overcome this weaknesses and propose an approach that reverses the previous decision flow: instead of starting from the paths and building the network out of them, here we start from a set of budget compliant edges and build the itineraries on them. We shall name this approach *Network-First-Path-Second* (NFPS) as opposed to PFNS. Since budget and total attractiveness are conflicting objectives, we do not expect NFPS to increase attractiveness at lower cost with respect to PFNS; our aim is rather to set up a methodology able to explicitly manage the budget level from the start, as an exogenous parameter. The NFPS solution algorithm is detailed in Subsect. 2.2.

2.2   NFPS: An Iterative Algorithm for Cycle Network Design

NFPS stems from an observation: the cycle tourist network design problem can be modeled by generalizing the MOP-ND model [25] so as to encompass all origin destination pairs. In detail, the resulting *complete model* consists of two parts, regarding design and routing. Design, modeled by binary variables z, concerns edge selection subject to a budget constraint; the routing part, modeled by integer variables x, is decomposable by commodity since it concerns computing the most attractive duration-constrained route for each origin-destination pair, user class, and duration. Design and routing are linked by logical constraints $z = 0 \Rightarrow x = 0$. The objective is to maximize the thematic itineraries attractiveness and depends on flow variables x. However, the number of commodities typical of realistic instances makes the automatic solution of the complete model out of reach of state of the art solvers.

This evidence leads to addressing the problem heuristically, exploiting the ability to solve a core problem, that we call the *Simplified Model* (SM) as opposed to the complete one. SM retains budget, connectivity, and the strictest time constraints requirements; the objective is to maximize first traversal attractiveness of selected edges. Its formulation is reported in (1–8). Given a graph G, SM either returns a subset of edges $E^*(G)$ admitting a feasible solution, or certifies G's infeasibility. In the first case, the value of $E^*(G)$ is computed by solving the routing part, which is now decomposable by commodity. The core procedure made of **SM + routing** is the building block of our algorithm, and it is iteratively called on different subgraphs $G' \subseteq G$ obtained by pruning different edge sets.

Let us introduce some notations to formally describe NFPS. Given the graph $G^0 = (N, A \cup E)$ where N includes PoIs, gates and junctions, E is the set of all potential links and A represents their traversal in one or the other direction,

let $\Gamma = \{1, .., n_\Gamma\} \subseteq N$ denote the set of gates and let Γ^2, indexed by $k \in \{1, .., n_\Gamma(n_\Gamma - 1)\}$, be the set of ordered pairs (γ, ν) s.t. $\gamma, \nu \in \Gamma$, $\gamma \neq \nu$. Denote by $u \in U = \{1, .., n_u\}$ a user class for which a utility function on first and second traversal on nodes and edges of G is known. For each $u \in U$ and for each pair $k = (\gamma, \nu) \in \Gamma^2$ we consider the pair $c = (u, k)$ as a commodity in the set $C = U \times \Gamma^2$. To provide the chance to choose among routes of different durations, for each commodity c we consider a set of values $T(c) = \{\tau\}$ to be used as maximum travel time, which are function of the duration of the shortest path from γ to ν.

Any set of budget compliant edges $E^* \subseteq E$ such that for each c and $\tau \in T(c)$ there is a time feasible route defined on E^* is a solution to our problem. We search for sub-optimal solutions by running the core procedure on several subgraphs $G^i \subseteq G^0$ obtained by edge pruning. The aim is to iteratively search the feasible region of the complete model laying in the vicinity of the current solution by locally modifying the most characterizing attributes. The search can be described in terms of a layered graph, whose nodes at the same layer are subgraphs generated during the same iteration by setting to 0 one edge in the solution of the father node at the previous layer. Graph G^0 is at the root of the search graph; the edges to be pruned are positive cost edges in $E^*(G^0)$, i.e., the SM solution on G^0. Indeed, since budget is the only global constraint of the complete model, what fully characterizes a solution are its unfit edges. In fact, any 0-cost edge can be added to the solution for routing purposes without affecting feasibility, as opposed to unfit edges that require retrofitting spending: in particular, the optimal solution usually corresponds to some maximal (with respect to budget) set of unfit edges. In the specific case, given $E^*(G^0)$, the n_e unfit edges with lowest positive flow are selected and as many new problems are generated by pruning (setting to 0) each one of those n_e edges, each yielding a child node at level two of the search graph together with a subgraph G' on which the core procedure will be run again to produce a different solution from the father node. In the second iteration the procedure is repeated on each of the n_e subgraphs. For each subgraph G' two cases are possible: either G' admits no feasible solutions and the search node is discarded, or SM returns a feasible set of edges $E^*(G')$ based on which, after the evaluation-routing step, n_e additional problems will be generated by the edge-pruning procedure.

From iteration three onwards, instances with the same set of pruned edges may occur; as they coincide, a single occurrence is kept, that is, more than one path from the root may lead to the same node of the search graph. Moreover, a cache mechanism records the routing solution for each subnetwork so that whenever SM returns a set of edges which has been already evaluated its reward is retrieved at no cost. To keep bearable the number of problems to be solved at each iteration, two filters are applied at different steps of the procedure. The first filter applies right after the SM solution and keeps the best n_{f1} problems based on the SM objective function value. The second filter applies once the routing part is solved, to keep the n_{f2} nodes with the best actual solution cost.

This yields at most $n_e \cdot n_{f2}$ nodes at each layer of the search graph. The values of n_e, n_{f1} and n_{f2} should be calibrated according to the specific instance size.

Basically, SM picks heuristically a maximal set of unfit edges that is feasible for routing and compliant with the current pruning. As pruning advances, the number of feasible maximal sets lowers and the process converges. However, since search is filtered, optimality is not guaranteed.

Note that SM is considerably easier than the complete model and it is quickly solved. With respect to the complete model, the following differences exist: the objective function is defined on the design variable and not on the flow variables, and the flow part reduces to a pseudo-polynomial problem for each commodity. Even the MATCP problems solved for solution evaluation purpose on the selected edges E^* are computationally less demanding than the instances solved in [4] - actually they are MACTP relaxations since design variables are set. Finally, the cache mechanism prevents solving the routing problem twice on the same subnetwork. Together with filtering, all this allows to keep the computational burden reasonable. The number of iterations depends on the average cardinality of maximal edge sets with respect to the total number of unfit edges. Stopping conditions are reached when each active node yields to the next level only nodes whose simplified model is infeasible.

The MACTP and MOP-ND formulations can be found in [4,25], respectively. For the sake of completeness, in (1–8) we report the SM formulation for a generic time limit $\tau \in T(c)$ at iteration 1, where no edge is pruned.

$$\max \sum_{[i,j]\in E} w_{ij}^h z_{ij} \qquad \text{subject to:} \qquad (1)$$

$$\sum_{(i,j)\in FS(i)} x_{ij}^c - \sum_{(h,i)\in BS(i)} x_{hi}^c = b_i \qquad \forall i \in N, \forall c \in C \qquad (2)$$

$$\sum_{(i,j)\in A} t_{ij} x_{cij}^c \le \tau \qquad \forall c \in C \qquad (3)$$

$$\sum_{[i,j]\in E} c_{ij} z_{ij} \le B \qquad (4)$$

$$x_{ij}^c \le z_{ij} \qquad \forall [i,j] \in E \qquad (5)$$

$$x_{ji}^c \le z_{ij} \qquad \forall [i,j] \in E \qquad (6)$$

$$z_{ij} \in \{0,1\} \qquad \forall [i,j] \in E \qquad (7)$$

$$x_{ij}^c \in \{0,1\} \qquad \forall (i,j) \in A, \forall c \in C \qquad (8)$$

The objective function (1) maximizes the weight of the selected edges. Selected edges must be budget compliant (4) and allow flow in both directions (5–6). For each commodity $c = (u,k)$, for $k = (\gamma, \nu)$, the flow goes from γ to ν (2) where $b_\gamma = 1$, $b_\nu = -1$ and $b_i = 0 \,\forall i \in N$, along a path taking no more than τ time units (3). Note that SM is not a relaxation of the complete model so its optimal solution value does not provide a bound and cannot be used for pruning search nodes.

3   Computational Results and Conclusions

We apply the described methodology to the benchmark data used in our previous experiments. In the Trebon region, located in Southern Bohemia, Czech Republic, local authorities aim to promote sustainable economic development by facilitating the Trebon region as a cycle tourist destination. While Euro Velo route number 7 traverses Czech Republic, it does not cross the Trebon region but skims its west southern border, as route 13 does on the southern border. Both provide great hooks for visiting the Trebon region, which so far remains untouched and out of the beaten trails. The opportunities offered by cycle tourism in terms of sustainable economic growth motivated this line of research, the current step in particular where emphasis is on budget.

Hereafter we briefly recall the data description provided in [15]. We work on an abstract network, i.e., graph $G^0 = (N, A \cup E)$, made of the set of candidate links: some require an investment to be retrofitted and reconditioned into cycle tracks while others are already fitting and can be used almost at zero cost. The former are unpaved roads, canal towpath, or natural trails that are presently being used for off road cycling or hiking. The latter are minor rural paved roads with low vehicular traffic and fit for cycling. Former military roads once used to patrol the Austrian border add to this set. Indeed, the experience reported in [6] supports the choice of retrofitting and exploiting for tourist use the vast supply of rural roads currently underutilized rather than constructing new facilities, thus substantially reducing both infrastructure provision investment and environmental impact. Nodes N are PoIs or cross-roads, where usually service facilities are present. The resulting graph has 84 nodes and 146 edges, 86 of which are 0-cost edges. Arc traveling time is computed with respect to an average speed of 18 km/h and adjusted according to the gradient. The edge cost for reconditioning depends on present condition and edge length: the estimated cost of a 3 m wide path is 115 € per meter to turn it into an asphalt surface if starting from dirt road, 75 € per meter from gravel one. When an edge is made of several sections in different conditions, the total retrofitting cost is the sum of reconditioning each section to asphalt. The cost of retrofitting all edges is about $13700 \cdot 10^3$ €.

Based on the opinion of local bikers, 8 locations have been selected to operate as gates; since link gradients are low (the area is basically plain), travel direction does not affect travel time and we considered only pairs $k = (\gamma, \nu) \in \Gamma^2 : \gamma < \nu$, thus yielding 28 origin and destination pairs. The map on the left of Fig. 1 depicts the abstract graph overlapping the physical map of the region [15]. Nodes 37, 46, 49, 53, 68, 75 are railway stops, nodes 1, 18, 49, 57, 60 are bus stops: the former are blue circles, the latter orange ones. Both bus and train provide for bike transport. Gateways are marked as green squares and correspond to nodes 1, 18, 49, 57, 60, 70, 75, 80. Nodes 70 and 80, shown in red on the map on the right on Fig. 1, have been chosen as gateways since they are main locations on the road network. Node 70 lays on EuroVelo route 7 and 60 is along the Iron Curtain Trail which is part of EuroVelo 13. Edges distance (km) and travel time (minutes) are reported.

The corresponding abstract graph G is depicted in the middle of Fig. 1, unfit edges marked in red. Note that on the subgraph induced by discarding unfit edges - the 0-budget scenario - some gateways are not connected while others are only by routes circuitous and long, violating the planning requirement regarding directness and continuity.
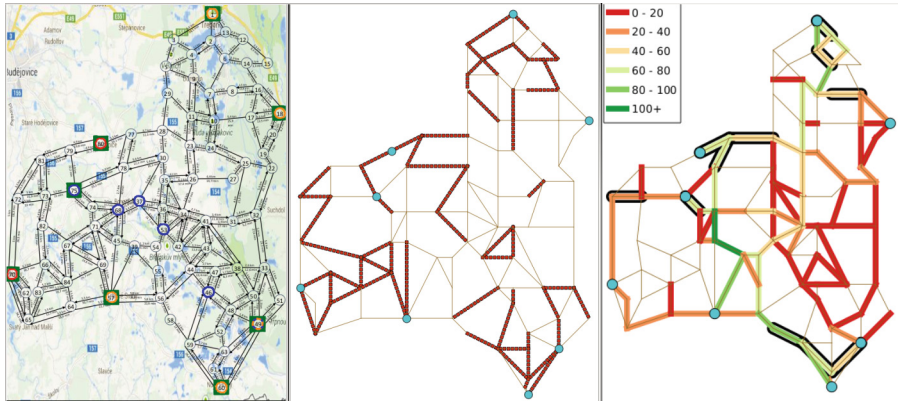

Fig. 1. Graph G overlapping the physical map of Trebon (on the left): gates are marked with colored circles. In the center, the abstract graph induced by the input data (unfit edges in red). The solution network is depicted on the right.

Concerning attractiveness, the three user classes $U = \{1..3\}$ of the previous studies (users fond of culture, of local food and traditions, and of nature and sports) have been modeled, yielding $n_C = 84$ commodities (u, k) if disregarding path orientation. In this work we are not concerned about the process according to which attractiveness has been computed, as we take these values as parametric inputs to our approach. In brief, users' point of view has been taken into account by listing all PoIs in the area that are relevant for each user class, and then by collecting and averaging the evaluation of teams of local bikers. In this way, scores for first and second traversal of each PoI have been assigned, and the attractiveness of edges and nodes was computed based on the PoIs located there and on the category of interest. The objective function is the sum of the attractiveness of the thematic itineraries selected for the three user classes. The different solutions computed along the search can be analyzed to reveal non dominated points in the three dimensional space of each user class attractiveness and provide alternative solutions to the decision maker.

The parameters and settings used in this experimental campaign are the following. The maximum number of iterations depends on n_e, n_{f2}, and on the number of edges in budget maximal sets (about 10) and on the number of unfit edges (about 60): n_e, i.e., the number of brother nodes from the same father in the search graph, is set to 5, while $n_{f1} = 20$ and $n_{f2} = 10$, which keeps the number of nodes at each iteration within $5 \cdot 10 = 50$. Figure 2 depicts a sketch

of the search graph for the first 9 levels, to give a taste of how its size evolves. In particular, the maximum size is immediately reached, that is 5 nodes at level 2, 25 at level 3 and 50 onwards to termination. Stopping conditions are reached when each active node yields to the next level only nodes whose simplified model is infeasible. On the other hand, infeasible nodes are found as early as level 3 (red nodes), meaning that there are very small subsets of edges which can not be altogether discarded. Each such set either identifies a cut separating two gateways in the topological term, or they cut all time feasible routes between origin and destination. While the first kind of sets could be identified by looking at the graph (think of gateways 60, 70 or 80), the second is not as it involves the routing part. Figure 2 also reports the number of duplicated subproblems in the search graph (blue nodes), i.e. subproblems with the same set of pruned edges. This number decreases while the solutions in the same level diversify from each other. It also shows the incidence of filtering, before and after routing, which is crucial to keep the size manageable. Note that the search does not deploy along a decision tree as a standard *branch and bound*; indeed, edge pruning may lead to duplicate nodes that are spotted and discarded.

In the simplified model the maximum path duration for commodity $c = (u, k)$ is set to $\tau = 1.5 \cdot \tau_k$ where $k = (\gamma, \nu)$ and τ_k denotes the length of the shortest path from γ to ν. When solving MACTPP to evaluate the quality of the network, the maximum duration of the itineraries is set to $\tau_1 = 1.5 \cdot \tau_k$, $\tau_2 = 1.6 \cdot \tau_k$, and $\tau_3 = 1.7 \cdot \tau_k$, to cater for different options. This yields a total of 252 MACTPP instances to be solved when evaluating the quality of the network made of the edges selected by the simplified model. However, as discussed, such MACTPP instances tend to be *easy* and each takes few milliseconds. Finally, budget level is set to $2000 \cdot 10^3$ €.

We report the results obtained by applying NFPS to the Trebon data. The simplified model and the MILP model of MACTPP have been coded in AMPL and solved by ILOG Cplex 12.5 on a quad core laptop with i7 processor.

The shape of the resulting network (reward 59849.5) is depicted on the right side on Fig. 1: it is rather sparse and itineraries tend to share the same edges, according to the colors in the legend, in particular in the middle of the network (gates are at the borders). The simplified model selects 97 edges which go down to 91 after the routing phase. Of these, 11 are unfit and use most of the available budget (1982 over 2000) as expected for a budget-maximal edge set.

Now consider the reward of the best each solution of each iteration as compared to the reward of the father node, as sketched in Fig. 3. The positive trend of the best solution reward shows that the search strategy is able to find better solutions in the proximity of good quality available ones. At the same time though, it can be observed that the father of a starring solution node is not the highest reward node of its own iteration at most layers. This fact is a point in favor of keeping a large number of active nodes and setting pretty loose thresholds for filtering (parameters n_{f1} and n_{f2}). Diversity enhances the search.

The cheapest network. NFPS was motivated by the need for keeping budget under control. Indeed, SM provides a feasible solution whenever it exists for a
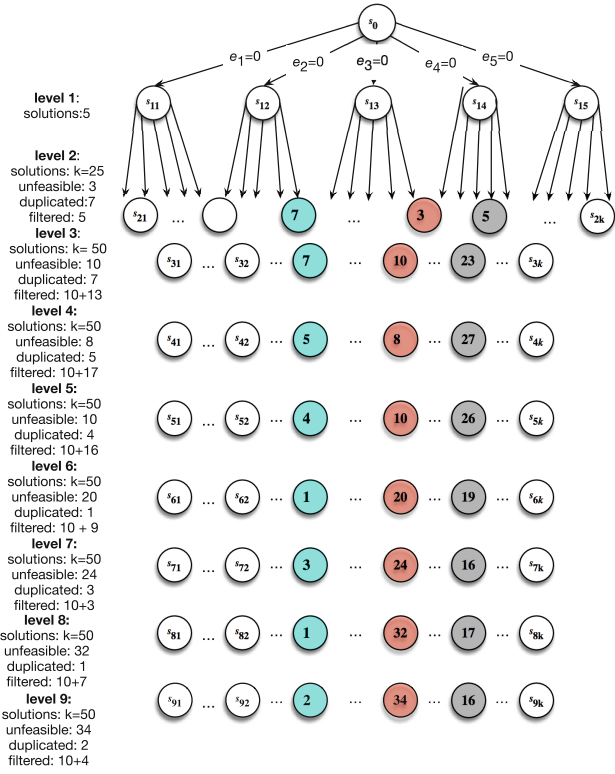
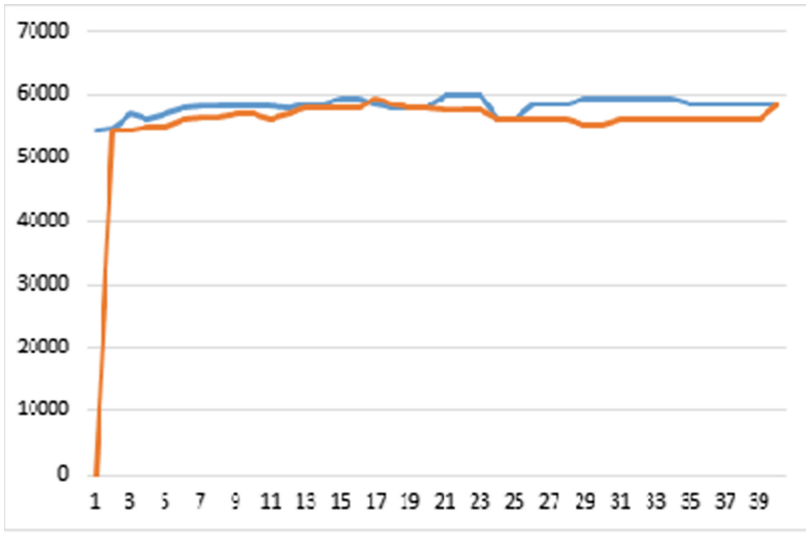**Fig. 2.** The subproblems induced by edge pruning.

Fig. 3. Best solution reward and reward of the father node at each iteration.

given budget. By a slight change SM can be used to compute the minimum required budget, i.e., by using the retrofitting edge costs instead of edge attractiveness as objective function coefficients and getting rid of constraint 4. For our benchmark the minimum budget is $1.474 \cdot 10^3$ and reward is 54.353. Note that for this budget PFNS fails to provide a feasible solution.

Non dominated solutions. The proposed approach may also provide decision makers with appealing alternatives made of the non dominated solutions with respect to users attractiveness which are collected along the search. Since attractiveness is computed out of subjective ratings, it may be worth to consider alternative high quality solutions. As an example, consider the results for budget $1.600 \cdot 10^3$ (again, PFNS fails for this budget). NFPS takes 7 iterations and returns a reward of 55370.8.

Table 1 reports the data for the 5 best solutions, ranked according to total reward. If we disaggregate the reward components and show the contribution of each user class, it can be seen that these solutions are not dominated, and provide different thematic itineraries. Therefore, our approach can also be used to retrieve alternative solutions which are very close to the best one concerning total reward, but offer a better choice for at least one user class with respect to the other networks.

Table 1. Disaggregated and total reward for the best 5 solutions (budget 1600)

Sol	U1	U2	U3	Network reward
1	16001,63	21278,43	18090,75	55370,8
2	16264,12	21557,39	17536,42	55357,9
3	16264,52	21256,76	17774,85	55296,1
4	16249,55	21669,89	17322,96	55242,4
5	16171,97	21831,21	17187,17	55190,3

Conclusions. This paper addresses the design of cycle tourists devoted cycling networks. It provides a short review of the recent literature on cycling network design in order to retrieve the most common planning criteria and compare common practice in the design of infrastructures devoted to functional cycling versus leisure cycling. Based on these premises, we propose a mathematical optimization model which incorporates such planning criteria. These are embedded either as model constraints or in the objective function formulation, or by meeting planning requirements by construction. In particular, the model's objective function is the maximization of the network attractiveness for several classes of users, while the budget available for retrofitting or building the links of the network is formulated as a global constraint. Connection among the network access points is ensured by the flow reformulation, in which users are seen as flow units traveling from an origin gate to a destination gate, for each pair of gates. Several thresholds for route maximum duration are also formalized in the model.

Since the complete model is computationally demanding, it can not be solved by commercial solvers and a heuristic approach is proposed. The method exploits the solution of a simplified model yielding a feasible network, if any, for a given input graph. The simplified model acts as the core of an iterative algorithm due to explore (part of) the feasible region of the problem. It is run on different graphs obtained by increasingly pruning different sets of edges as long as feasibility holds. Optimality can not be guaranteed but computational results show the search capability of improving the initial solution to a large degree. The same simplified model can be used to determine the minimum budget necessary to build a network while guaranteeing all the required network quality standards that have been previously discussed. The approach has been tested for a real network, located in the Trebon region, Southern Bohemia, Czech Republic. Data regarding distances, retrofitting costs according to links status at present, and travel duration are real. Data modeling users utility functions that were previously calibrated with the contribution of local bikers, have been retrieved from previous works. The resulting case study is challenging and quite representative. Indeed, several links are already fit for cycling but either two gateways are not connected on the current infrastructure or the existing routes are too long, whereas retrofitting few links provides a much greater and better choice of itineraries. Since several mending options are possible (a combinatorial number), the only chance to scrutinize them is to implicitly consider them as the feasible solutions of a network design model, as we propose. The computational time amounts to a few hours on a regular personal computer, which is adequate when addressing a design problem. Data analysis shows that the utility function of several classes of users can be handled, providing high quality solutions that meet users needs. Indeed, the thematic routes selected for each user class and connecting the same pair of gates are based on the same network but can be rather different from each other. At the same time, our approach allows to collect the non dominated solutions computed during the search and to make them available to the decision makers to enlarge their set of options. This option can be useful when designing corridors in case of conflicting user preferences. Finally, this method allows for an incremental deployment of the network infrastructure, building some routes before others and prioritizing according to estimated demand. However, even if the implementation is carried out a step at a time, each route would still be part of a comprehensive project that guarantees the best use of the financial investment. We thus believe that this approach could lay at the heart of quantitative based tools to support local administrators in decision making.

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