Advanced Modeling Approach for Computing Multicriteria Shortest Paths in Multimodal Transportation Networks

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Abstract— **Nowadays, the human mobility always happens in a multimodal transportation network. However, the transport system has become more complex. Therefore, building Advanced Travelers Information Systems (ATIS) that provide passengers with pre-trip information on navigating through the network has become a certain need. Since passengers do not only seek a short-time travel but they endeavor to optimize several criteria such as comfort and effort, an efficient routing system should incorporate a multiobjective analysis for both routes and transport modes. We aim in this paper at proposing a new formulation for representing a multimodal network. Based on this formulation, we develop a routing algorithm to compute the entire set of nondominated solutions to go from one place to another. As transport modes, we use railway, Bus, Tram, Metro, Pedestrian, Road and Bike. As optimization criteria, we use travel time, number of changes and walking time. Experimental results have been assessed by solving real life itinerary problems defined on the transport network of the city of Paris and its suburbs. Results indicate that the proposed approach is efficient enough to be integrated within a real world journey-planning system.**

Keywords-component; Multimodal Transport Networks, Modeling, Multicriteria shortest paths.

I. INTRODUCTION

For the sake of helping passengers, several companies and transport operators endeavor to build Advanced Travelers Information Systems (ATIS). These systems usually provide passengers with pre-trip information, as well as, real time advice on navigating through the transport network. Although, there are several routing applications used nowadays, however, such systems do not always meet users' expectations. For instance, many car navigators systems have been already established as commodity items and most railway and flight companies offer some kind of route planning facilities through the Internet. However, all these systems have several limitations.

Firstly, actual routing systems do only allow route planning within their respective domains. For example, sat-nav systems only show the way around the road network. If we rather like to use means of public transportation, we are stuck with the task of getting to and from the nearest station. Moreover, routing systems belonging to public transport operators do not usually support some transport modes such as Bike, Car, etc. As a result, there is a real need to develop a seamless routing application that combines both continuous transportation modes (i.e. modes that offer continuous service such as Car, Bike, Car Sharing, etc.) and public modes (modes that offer services according to predefined schedules such as Railway, Bus, Tram).

Besides, passengers in real world do not only look for a feasible multimodal path that minimizes the travel-time. They however tend to optimize several criteria. Therefore, in addition to the incorporating of multimodality into routing systems, we should also consider multiobjective analysis.

Generally, routing applications whether they arise in transportation area or other domains such as communication networks usually refer to solving shortest path problems. While solving some routing problems is usually straightforward, computing shortest paths in certain contexts is not always an easy task.

For instance, solving the one-to-one shortest path problem in static network can be easily done by applying the well-known algorithm of Dijkstra. On the other side, computing multicriteria shortest paths appears to be more difficult especially in large-scale networks.

The difficulty in a multiobjective context stems from the fact that there is not only one single optimal solution, but rather a set of nondominated solutions, denoted Pareto optima, from which the decision maker must select the most preferred one.

Additionally and in contrast to single criteria search, one cannot abort the search after finding a first optimal solution. In fact, even after finding all Pareto-optima, search algorithms require a substantial amount of time to prove that no further solutions exists. The main goal of this paper is to develop a new model for representing a multimodal transportation network that includes both private and public transportation modes.

For the interest of readers, no general model exist into the literature that adequately allows representing a multimodal network, as well as, yields correct results when solving basic and advanced routing issues. We also develop in this paper a routing algorithm to compute Pareto-optimal paths between an origin place and a destination. As optimization criteria, we focus on the total travel time, the number of exchanges and the total walking time.

The rest of this paper is structured as follows: in next section, we present some related works. We introduce in Section 3 the new modeling approach and fix some notations. In Section 4 we apply a routing algorithm over the proposed model to solve the multicriteria shortest path problem. Experimental results are presented in Section 5. Finally, Section 6 gives some comments and outlines future works.

II. RELATED WORKS

Routing is a widely researched topic in transport systems. The major research efforts on this problem relates to two things: modeling a transport network and solving routing issues. While the former consists of defining how to represent a transport system, the latter deals with developing algorithms to support routing issues faced by travelers and transport operators.

In terms of modeling, [1] and [2] have done extensive works to incorporate the multimodality aspect into their models. [3] proposed a switch point approach to model multimodal transport networks. [4] conducted several researches for designing multimodal transport networks. [5] proposed a transfer graph approach for multimodal transport problems. [6] introduced a generic method to construct a multimodal transport network representation by using transfer links, which is inspired by the so-called super-network concept. [7] has also done relevant works to generalize a time-expanded model that deals with realistic transfers. [8] handled multimodal networks by incorporating predefined transfer arcs between nearby stations. Although the previously mentioned works are very interesting, they have many limitations. Firstly, they usually omit important elements presented into the transport system such as platforms where passengers wait, entrance point of stations, transfer inside and outside stations. Therefore, itineraries resulting from applying routing algorithms will not reflect real world situations. Secondly, such representations usually suffer from significant computational efforts and high memory requirements when loading data and applying routing algorithms [9]. Thirdly, most models are not flexible enough to handle additional real-world routing problems such as multicriteria shortest paths, dynamic re-routing, handling vehicles' capacities, etc. To overcome the above-mentioned limitations, we introduce in this paper a new generic model for representing multimodal transport networks.

When it comes to routing algorithms, several approaches have been proposed for solving basic and advanced routing problems. For instance, [10] adapted the algorithm of Dijkstra to take into account the time dependency and the multimodality aspect of the transport system. [11] described an algorithm for itinerary planning based on dynamic programming. [12] did a study on handling times and fares in a routing algorithm for public transport. [13] solved the earliest arrival problem on the time-expanded model in a straightforward manner by using a modified version of the algorithm of Dijkstra. [14] introduced a granular tabu search to solve the Dial-A-Ride problem.

Computing multicriteria shortest paths has been also studied recently as part of solving advanced routing issues. For instance, [15] proposed a backward label-setting algorithm for identifying important solutions for the all to one multiple criteria time-dependent shortest path. [16] also used a linear utility function that incorporates travel time, ticket cost, and "inconvenience" of transfers. Although the above-mentioned contributions are very significant, however, they have many drawbacks. From one side, they have not been evaluated on real world test instances. From the other side, they usually lie on incomplete model for representing multimodal networks. Therefore, it is crucial to study the issue of multicriteria shortest paths using real world data instances, as well as, on a multimodal formulation that adequately represents the transport system.

III. MODELING APPROACH

In this section, we present the novel approach to represent a multimodal network. Each network is modeled as a separate digraph. An additional work is then done to integrate all sub-models into one larger model. In contrast to most models in the literature, the term "multimodal" in this paper refers to a combination between private transport modes that offer continuous services and public transport modes that offer services w.r.t to predefined timetables.

A. Private Modes

We focus in this paper on three private modes: Pedestrian, Bike and Car. Components of those modes are modeled as vertices and edges in a directed weighted graph. More precisely, the pedestrian network comprises pedestrian route segments and intersection points linking those segments. Each intersection point is represented by a vertex in a directed graph G. An edge $e\ (u, v)$ is inserted between u and v if u is linked with v by a footpath. The weight $w(e)$ represents the average travel time along that edge.

Similarly, road junctions in road networks are represented by vertices and road segments by edges. The weight on an edge $e(u,v)$ represents the travel time using the car to go from u to v. Although the travel time on any road segment is stochastic, we simplify this characteristic by assuming fixed travel times. Additionally, we model a car parking by a vertex. We decided with modeling car parkings in the perspective of computing routing issues that require the use of a car during the journey. Modeling Bike network is also quite canonical. A vertex v represents a road junction; an edge $e(u,v)$ is inserted to account for a bike path between u and v. In addition, we assume that the travel time on a bike path is static and represents the travel time along the segment using a bike. Moreover, we model bike rental stations as special type vertices to keep information about the places where people can rent out or return a bicycle.

B. public Modes

While modeling private transport modes is quite canonical, modeling public modes turns out to be more difficult. A key difference to static networks is that public transit networks are inherently time-dependent, since certain segments of the network can only be traversed at specific, discrete points in time. As such, the first challenge concerns modeling the timetable appropriately in order to enable the computation of journeys. As a first step of modeling, we introduce four types of vertices that correspond to stations, access points, platforms and departure events. As in real life, a station can have one or several entrance area. Therefore, a two-direction edge is inserted between each station node and its entrance points. Note that the weight of such edges is made to 0. As previously mentioned, several models ignore the presence of several entrance points for one station; however, in many real-life situations such as in Paris (e.g. the railway station of Chatelets), taking the wrong exit or entrance in a big station would highly affect the length of an itinerary. Therefore, we decided with modeling stations' access points to provide precise itineraries.

Besides a station comprises a set of platforms where passengers wait for vehicles. An edge *e(p,ap)* is inserted between a platform *p* and an access point node *ap* iif there is a foot path inside the station between *p* and *ap*. The weight of *e(p,ap)* represents the minimal time required for accessing *p* from *ap*. Platforms inside stations are also related via transfer edges to account for the fact that passengers can go from one platform to another. The weight of transfer edges inside stations represents the minimal time required to go from one platform to another.

Furthermore, we assign each platform with a type (Bus, railway, tram...) to differentiate between modes. This information can be used by routing algorithms to support queries that privilege one mode over another.

Since a timetable consists of time-dependent events that happen at discrete points in time, we use the idea of building a space-time graph to unroll time. Roughly speaking, the model creates a vertex for every event in the timetable that consists of vehicle departing from a platform p_1 at departure time *(dt)* and arrives to another platform p_2 at arrival time *(at)*. Timestamps are inserted into event nodes to account for the departure and arrival times. Event nodes are ordered in the way that a higher-level node refers to an earlier event. This ordering is very helpful to reduce the search space of routing algorithms. In addition, waiting, boarding and alighting edges are inserted between event nodes and platforms. More precisely, the edge linking a platform *p* and an event node *e* represents the waiting time at the platform and the minimal time required to board a vehicle. Similarly, the edge between an event node e and a platform *p* represents the minimal time required for alighting from a vehicle to access the platform.

C. *Combining Networks*

To compute multimodal paths, the query algorithm has to use multiple networks simultaneously. For that reason, after modeling each network as a separate digraph, we have to combine the different networks in order to form one larger multimodal network. To do so, we use the pedestrian network to transfer from one mode to another. More precisely, each sub-graph have to be connected to the subgraph corresponding to the pedestrian network.

To link the road network, we use nodes corresponding to car parkings. We link each parking node to the nearest neighbor node in the pedestrian networks. Therefore, to go from the road network to another network, the passenger has to pass through a parking node. Linking the bike network is also done through bike rental stations nodes. Each rental station node is linked through an edge to the nearest neighbor node in the pedestrian network. Finally, linking public networks is done using access points. We link each access point node to the nearest node in the pedestrian network.

IV. COMPUTING PARETO PATHS

After presenting the new modeling approach in the previous section, we apply in this section a modified version of the label-setting algorithm of Dijkstra for solving the multicriteria shortest path problem. Although many algorithms have been proposed in the literature for computing Pareto-optimal paths, however, applying such approaches as they are on the proposed model would not solve the problem. As previously mentioned, the proposed model deals with more realistic issues and computing multicriteria shortest paths requires thereby additional adaptations.

The emerging problem consists of determining the entire set of nondominated paths to go from one place (i.e. station, parking, address) at certain departure time to another place. We focus our work in this paper on the following criteria: i) the total travel time ii) number of transfers iii) the total walking time.

Before presenting the algorithm, it is worth to present how the multicriteria aspect is reflected into our model. More precisely, how the presented model allows solving multicriteria shortest paths w.r.t the predefined mentioned criteria. To do so, we assign each node in the multimodal graph a set of labels representing the criteria to be optimized. Several cases exist for assigning values to those labels while the routing algorithm accomplishes its search process.

Firstly, we start by public networks. Accessing a platform *p* from an access point node *ap* will only affect the label related to the travel time. Therefore, the new value of the travel time label will be its current value added to the time required for traversing *(p, ap)*. Other labels will remain unchanged. A second scenario arises when accessing a platform from another platform via an event node. This is a typical example of a vehicle departing from a platform that belongs to one station to arriving at another platform belonging to another station. In this case, the travel time at the arrival platform will be the travel time at the departure platform added to the time required to go from the departure platform to the arrival. Other labels will remain unchanged.

A third scenario arises when accessing a platform via an inter station transfer edge. In this case, the travel time label at the accessed platform will be the travel time at the upstream platform added to the transfer time. In addition, the number of transfers label will be added by one since on transfer has been made. The walking time will also change to be the walking time at the upstream platform added to the transfer time. Moreover, when the algorithm is about to visit a node in the pedestrian network from a node belonging to another network, the travel time on the arrival node will change to be the travel time on the upstream node added to the travel time of the transfer edge. In this case, the number of changes will also be added by 1 since a transfer has been made. The walking time will also change to be added by the time required to walk through the transfer edge. Other scenarios may also arise; however, we do not express them by writing although we consider them into practice.

After emphasizing on the ability of the proposed model in handling multicriteria shortest paths, we present now the multicriteria shortest path algorithm itself. As most shortest path algorithms, the reference is usually the algorithm of Dijkstra. Adaptations are then done according to the routing problem itself. In our case, we use a modified version of Dijkstra's algorithm based on a multilabel setting other than only one single criterion. To illustrate how the algorithm works, we assume that a passenger wants to go from a public transport station at certain departure time to another station. The passenger only wants to use public transport modes. Then, the proposed algorithm works as follows:

At the first step, labels corresponding to criteria are initialized with a big integer value except for the access point nodes belonging to the departure stations. They however initialized to zero. Each node is also assigned a vector for keeping a history about the search. We use a vector instead of a simple label since there may have several nondominated paths. The history vector plays an important role when the algorithm is about to retrieve the paths found.

The algorithm proceeds with the departure station; it updates labels on the access point nodes belonging to the current station. Further, the algorithm maintains a priority queue containing nondominated nodes. The queue is initialized with the access points belonging to the departure station. While the priority queue is not empty, the first element in the priority queue is examined. Labels on its adjacent nodes are updated according to the types of nodes (platforms, events, etc). If labels of the current nodes are better than those belonging to an adjacent node, this means that it is better to go from the departure station to the adjacent node using this link. We update in this case labels on the adjacent node and we add it to the queue. We do nothing on the other case since a better path is already found between the adjacent node and the departure station. It may happen that labels are note comparable (they are nondominated). In this case, we also add the visited node to the queue after updating its history vector.

After that, the first element on the queue is removed. We repeat the previous iterations while the queue is not empty.

The last step is to retrieve paths found. As at each step the algorithm maintain a history vector about the search process, we accomplish a backward search for retrieving nondominated paths. We start with the target station and we go backward until we reach the departure station.

V. Experimental Results

To assess the performance of this work, we developed an advanced web-based routing application based on the real data of the French region Ile-de-France that includes the city of Paris and its suburbs. The transport organization authority that controls the public transport network in Paris provides data for public transport modes. Data comprise geographical information, and timetable information for four public transport modes (Bus, Metro, Railway, and Tram). More precisely, data encompass 60000 platforms and stations; 195000 transfers; 303000 trips and 6800000 events for one day. Another set of data deals with private modes. We focus our experimentations on pedestrian and bike networks. While the former includes 275606 nodes and 751144 edges, the latter encompasses 250206 nodes and 583186 edges. The proposed model and routing algorithms have been implemented using Java/Eclipse. The associated runs for solving test problems were performed on an Intel core I5 of 8 GB of RAM. Google Maps API has been used for visualizing itineraries.

Before applying routing algorithms, we have to ensure that the generation time of the different subnetworks does not constitute a bottleneck for the performance of the proposed model. Generating networks corresponding to public modes only takes 15 seconds. Moreover generating private modes takes less than 5 seconds. However, linking all networks takes around 30 minutes since for every access point, bike rental and car parking nodes, we have to solve the nearest neighbor problem w.r.t the pedestrian network. To overcome that, we have done a preprocessing operation. That is, we compute nearest neighbors one time and we load them when generating networks. By doing so, we ensure a fast generation step for our multimodal graph.

Since the increased time in computing optimal itineraries decreases the utility of the journey planning services, the computational efforts of the proposed approach constitutes a critical success factor for their integration within an online journey planning decision support system. To assess the computational effort, we have solved 10000 routing queries that have been uniformly generated at random. Each query contains a departure and arrival stations and a departure time.

We start evaluating the proposed approach by limiting the routing query to only one criterion (i.e. we start by travel time). That is, we want to ensure that the proposed model allows computing multimodal routes in a single criterion context. Analyzing and comparing results with real-world routing applications have verified the ability of the proposed model in providing correct results. When it comes to assessing the computational performance, results indicate that the algorithm does not exceed the ratio of 0.2 seconds to answer a routing query. That is, the algorithm is efficient enough to be integrated within an online routing system when considering one criterion. That also remains true even when we change the criteria to be the number of changes or the walking time. We have also noticed that the computational time increases with the number of networks used. For instance, when we deactivate one mode (e.g. bus), the running time for answering a routing query decreases. This can be explained by the fact that the search space of the routing algorithm increases with the size of the final generated graph. More networks means more components in the graph and thus more works for the search algorithm.

After proving the efficiency of the proposed approach when dealing with one criterion, we analyze now its behavior in a multicriteria context. While computing routes in a single criteria context was done without any limitations, computing multicriteria routes tends to be more challenging.

Results have indicated that the average size of the Pareto-front in some cases may grow very rapidly even when we only consider two criteria. However, in other cases, the Pareto-front only consists of few routes. When it comes to the computational performance, the running time of the algorithm is usually inacceptable (> 2 minutes). Thus, it cannot be used in its actual version to support online users' queries. After analyzing results, we have found that in some cases, the algorithm might result in nondominated paths with many exchanges (>10) or a lot of walking time (> 30 minutes). Therefore, we have proposed to introduce into routing queries other parameters to bound the number of exchanges and the total walking time. That is, we ask passengers to express their preference in terms of fixing the maximum number of transfers allowed and the maximum walking time. To have clearer ideas about the impact of such strategy, we reapplied the proposed work and we put 5 as a maximum number of exchanges and 30 minutes as a maximum walking time. Results indicate that when dealing with two criteria (travel time and number of transfers), the average size of Pareto optima is a finite small number. It does not exceed 5 for all queries. Moreover, the average computational time decreases to 12 seconds. It does not exceed 20 seconds in the worst case. When dealing with 3 criteria, results indicate that the average size of Pareto-front is still high (~25) and the average running time is around 75 seconds. As can be remarqued, after putting bounds, the algorithm can be integrated within an online routing system when dealing with two criteria or less. In contrast, it is not possible to use it as it is to deal with three criteria. One limitation stems from the huge number of alternative solutions provided for passengers. The other limitation originates from the inacceptable amount of time required to solve multicriteria query. Finally, only one enhancement strategy has been applied to reduce the search space of the routing algorithm; however, other accelerating techniques can be applied to the proposed model. One can easily, preprocess some data in an offline mode and reuse it when answering users' queries. One of our future works is to adapt existing or invent new accelerating techniques to enhance the performance of the multicriteria routing algorithm applied over the proposed modeling approach.

VI. CONCLUSIONS

We have proposed in this paper a new formulation for representing a multimodal transportation network. Both public and private transport modes are considered in the modeling approach. Based on the proposed model, we solve the multicriteria shortest path problem. We consider the travel time, number of changes and the total walking time. Experimental results accomplished over the real world transport network that includes the city of Paris and its suburbs indicate that the proposed model adequately represents a multimodal network and yields correct results when applying routing algorithms. Moreover, the proposed algorithm allows determining the entire set of nondominated paths between two places. From a computational point of view, results have validated that the proposed algorithm is efficient and fast enough to be integrated within an online routing system. Currently we are working on the solutions mentioned above to make the proposed approach more realistic. We have also planned to integrate train delays and other stochastic parameters in future works.

ACKNOWLEDGMENT

This research work has been carried out in the framework of the Technological Research Institute SystemX, and therefore granted with public funds within the scope of the French Program "Investissements d'Avenir".

REFERENCES

[1] E. Pyrga, F. Schulz, D. Wagner, C. Zaroliagis Efficient Models for Timetable Information in Public Transportation Systems ACM Journal on Experimental Algorithms, 12 (2.4) (2007), p. 39.

[2] Delling, D., Pajor T. & Wagner. D. (2009) Accelerating Multi-Modal Route Planning by Access-Nodes. 17th Annual European Symposium on Algorithms (ESA'09), Copenhagen, Denmark.

[3] Liu, Lu, and Liqiu Meng. "Algorithms of multi-modal route planning based on the concept of switch point." Photogrammetrie-Fernerkundung-Geoinformation 2009.5 (2009): 431-444.

[4] van Nes, R. (2002) Design of multimod-al transport networks: a hierarchical approach. Ph.D thesis of Delft University of Technology.

[5] Ayed, H., & Khadraoui, D. (2008). Transfer graph approach for multimodal transport problems. Second International Conference MCO, Metz, France – Luxembourg.

[6] Zhang, L., Li, J.Q., & Zhou, K. (2011). Design and implementation of a traveler in-formation tool with integrated real-time transit infor-mation and multi-modal trip planning. Transportation Research Board 2011 Annual Meeting, Washington, D.C.

[7] Pyrga, E., Schulz, F., Wagner, D., & Zaroliagis, C. (2004). Towards realistic modeling of time-table information through the time-dependent approach. Electronic Notes in Theoretical Computer Science, 92, 85-103.

[8] Bast, H., Carlsson, E., Eigenwillig, A., Geisberger, R., Harrelson, C., Raychev, V., & Viger, F. (2010). Fast routing in very large public transporta-tion networks using transfer patterns. In Algorithms–ESA 2010 (pp. 290-301). Springer Berlin Heidelberg.

[9] Bast, Hannah, et al. "Route planning in transportation networks." arXiv preprint arXiv:1504.05140 (2015).

[10] Pajor, T. (2009). Multi-modal route plan-ning. Master thesis of Karlsruhe Institute of Technol-ogy.

[11] Zografos, Konstantinos G.; An-droutsopoulos, Konstantinos N.; Spitadakis, Vassilis "Design and Assessment of an Online Passenger In-formation System for Integrated Multimodal Trip Planning", IEEE Transactions on Intelligent Transportation Systems, Volume.10, Issue.2, pp.311, 2009, ISSN: 15249050.

[12] Wang, M..Optimal paths based on Time and fare in transit network. Master thesis of National Cheng Kung University. 2008.

[13] Evangelia Pyrga, Frank Schulz, Dor-othea Wagner, and Christos Zaroliagis. Efficient models for timetable information in public transpor-tation systems. ACM Journal of Experimental Algo-rithmics, 12(2.4):1–39, 2008.

[14] Kirchler, Dominik. Efficient rout-ing on multi-modal transportation networks. Diss. Ecole Polytechnique X, 2013.

[15] Hamacher, Horst W., Stefan Ruzika, and Stevanus A. Tjandra. "Algorithms for time-dependent bicriteria shortest path problems." Discrete optimization 3.3 (2006): 238-254.

[16] Modesti, Paola, and Anna Scioma-chen. "A utility measure for finding multiobjective shortest paths in urban multimodal transportation networks." European Journal of Operational Research 111.3 (1998): 495-508.