Abstract—The environmental impact of the steadily increasing demand for mobility of people and goods, especially in urban environments, raises public concern and presents challenges that need to be addressed in the interest of long-term sustainability. Along this line, the inherently eco-friendly human mobility which involves the use of urban public transit networks must be encouraged and eased. This necessitates the development of context-aware services that hide the complexity of public transit networks while considering all available transportation modalities (e.g., bus, metro, tram, walking, and cycling) in order to provide sophisticated route planning tailored to both residents and visitors of urban areas. The EU-funded eCOMPASS research project has addressed this challenge through establishing a methodological framework for route planning optimization. A core objective of the project has been to employ novel algorithm engineering approaches for delivering a comprehensive set of tools and services (accessible from web/mobile application interfaces) for mobile end users to enable eco-awareness in urban multi-modal transfers. eCOMPASS delivered web and mobile services providing multi-modal public transportation route planning, considering contextual information as well as various restrictions and/or user constraints. Herein, we report the motivation, main scientific innovations and present the end-products of eCOMPASS with respect to multimodal human mobility.

Keywords—Multimodal route planning; tourist tour planning; algorithm engineering; combinatorial optimization.

I. INTRODUCTION

The environmental impact of the steadily increasing demand for mobility of people and goods, especially in urban environments, raises public concern and presents challenges that need to be addressed in the interest of long-term sustainability. The quality of life and economy in Europe very much depends on the efficiency and environmental friendliness of humans and goods mobility in the urban space, while there is less and less opportunity to create new transport infrastructure.

Since private car transports are associated with much higher energy consumption and environmental burden than the respective public transportation transfers per passenger, the role of ICTs in promoting the use of public transportation is critical. However, metropolitan public transportation networks tend to grow and densely cover cities, hence, multiple alternatives exist for moving from one point to another; this complicates the use of public means of transport for permanent residents, even more so for occasional visitors and tourists. Hence, context-aware services that hide the complexity of public transportation
networks are needed to provide sophisticated public transportation route planning tailored to both residents and visitors of urban areas, while considering all available transportation modalities (e.g., bus, metro, tram, walking and cycling).

To this end, several web/mobile applications exist nowadays for deriving and visualizing routes over public transportation networks, considering all available transport modalities (walking, bus, metro, etc). However, those tools typically derive shortest-path or shortest-time routes and do not consider alternative objectives, such as recommendation of routes with minimum carbon footprint, minimum number of transfers amongst different means of transportation or minimal use of a specific transportation mode (e.g., walking). Furthermore, several extensions on the above-described public transport route planning features could be investigated. For instance, personalized daily itineraries for visitors and tourists including all sites and attractions which the user would be interested in visiting.

The FP7 research project eCOMPASS\(^1\) focused on the aforementioned urban mobility issues through delivering innovative algorithmic machinery which tackles the problem of multimodal (public transit) route planning. eCOMPASS aimed at developing advanced web and mobile information services that facilitate the use of complex contemporary urban public transportation networks, thereby making inherently ‘green’ human transports more appealing and usable to urban resident populations and tourists.

In particular, eCOMPASS delivered two end-products and services, each integrating a substantial core algorithmic component relevant to multimodal route planning:

- **A multimodal public transportation route planner** providing A-to-B route instructions through available public transportation modalities (e.g. walking, bus, metro, train, etc). Unlike similar tools which typically derive shortest-time routes, the eCOMPASS service takes into account several objective optimization parameters such as use of the most eco-friendly means of transport or least number of transfers amongst different means of transportation.

- **A personalized multimodal tourist tour planner** dedicated to tourists visiting a city and provided through web and mobile applications. This service derives daily tourist tours comprising ordered sets of visits at points of interest (POIs) that match tourist preferences, thereby maximizing tourist satisfaction. It has the following novel aspects (not in offer by current tourist planners): it incorporates multimodal public transit within its routing logic for moving around; it allows users to schedule lunch/coffee breaks; it allows users to define arbitrary start/end locations (mobile users may choose to start their tour from their current location and end it anywhere else).

The remainder of this article is structured as follows: Sections II and III discuss our major scientific innovations and end products, respectively, related with multimodal route planning. Section IV presents the pilot tests undertaken to validate our products and services. Finally, Section V concludes this article.

### II. Algorithms for Multimodal Human Mobility

Our efforts in the context of multimodal human mobility are culminated in two main results: (1) the quick computation of meaningful multi-criteria multimodal journeys in large metropolitan transportation systems, (2) the automated planning of daily tours for tourists, proposing POIs to visit, while taking into account the multimodal transportation options for traveling from one POI to another.

#### A. Multi-criteria multimodal journeys

Online services for journey planning have become a commodity used daily by millions of commuters. However, computing good journeys in transportation networks still presents several modeling and algorithmic challenges, i.e., finding a measure of what a “good” journey amounts to and finding such journeys quickly (so that the user does not have to wait too long for a response) and with few computational resources (so that many users can be served by the same web service). Much focus has been given to the computation of routes both in road networks and in scheduled-based public transit, but these are often considered separately. In practice, however, users want an integrated solution that can find the “best” way to get to their destination considering all available modes of transportation, e.g., within a metropolitan area including buses, trains, driving, cycling, taxis, and walking. We refer to this as the *multimodal route planning* problem [1], [2].

In fact, any public transportation network necessarily has a multimodal component, since journeys naturally require some amount of walking. Existing solutions often handle this by predefining transfer footpaths between nearby stations. Unlike the road networks, however, defining “best” is not straightforward. For example, while some people want to arrive as early as possible, others are willing to spend a little more time to avoid extra transfers. Most recent approaches therefore use multi criteria optimization to compute several alternative journeys to offer user choice, which is practical even for large metropolitan areas. Still, restricting walking to predefined footpaths only between certain pairs of stops might usually work quite well, but outside of peak hours (e.g., during the night) or in case of larger construction efforts, experienced users of the considered urban transport system often report of good journeys not found by the journey planning service of the transport operator.

Extending public transportation solutions to a full multimodal scenario (with unrestricted walking, biking, and taxis) may seem trivial at first: One could just incorporate routing techniques for road networks as a replacement for predefined walking paths. Unfortunately, meaningful multimodal optimization needs to take more criteria into account, such as walking duration and costs [2]. Some people are happy to walk 10 minutes to avoid an extra transfer, while

\(^1\) [http://www.ecompass-project.eu/](http://www.ecompass-project.eu/)
others are not. In fact, some will walk half an hour to avoid using public transportation at all. Taking a taxi all the way to the airport maybe a good solution for someone, but users on a budget may prefer a cheaper solution. Not only do these additional criteria significantly increase the solution set of multi-criteria search, but some of the resulting journeys tend to look unreasonable, as Figure 1 illustrates.

Figure 1: Exemplary multi-criteria multimodal query on London with criteria arrival time, number of transfers, walking duration, and cost. The left figure shows the full Pareto set (65 journeys), while the right figure shows the three journeys with highest score. Each dot represents a transfer and included transportation modes are walking (thin black), taxi (thick purple), buses (thin red), and tube (other thick colors).

Given the limitations of current approaches, in the eCOMPASS project we revisited the problem of finding multi-criteria multimodal journeys on a metropolitan scale. Instead of optimizing each mode of transportation independently, we argued that most users optimize multiple criteria, e.g., travel time, convenience, and costs. To find only those journeys that offer significant trade-offs in these criteria, we used fuzzy logic to filter and present a modest-sized set of representative journeys [2]. This post processing step is not only quick, but can also be user-dependent, incorporating personal preferences. Fine tuning our algorithmic approach allowed us to answer exact queries optimizing time and convenience very quickly within a large metropolitan area.

To enable the eco-awareness feature of the eCOMPASS prototype we have added CO₂ emission calculations to our implementation, based on road characteristics, travel speed and distance traveled, as well as the mode of transportation used. As such, the user awareness of eco-friendlier means of transportation is increased, offering the user the choice between faster and more environmentally sustainable journeys [3]. See Figure 2 and Table I for an example and an in-depth analysis, respectively.

Figure 2: Multi-criteria optimization of multimodal journeys in Berlin, Germany. For the given source and destination locations several alternative journeys are suggested based on arrival time, walking duration, number of transfers. Eco-friendliness estimates are visualized as colored leaves, where green indicates the most ecological, dark red the most non-ecological travel alternative. This example shows that eco-friendly means of travelling are available at just small costs of additional travel time.

<table>
<thead>
<tr>
<th></th>
<th>Taxi only</th>
<th>1st fastest</th>
<th>2nd fastest</th>
<th>1st eco</th>
<th>2nd eco</th>
<th>Walking only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative travel time</td>
<td>46.4%</td>
<td>100%</td>
<td>109.4%</td>
<td>164.3%</td>
<td>119.2%</td>
<td>325.5%</td>
</tr>
<tr>
<td>Relative consumption</td>
<td>219.7%</td>
<td>100%</td>
<td>97.1%</td>
<td>79.2%</td>
<td>86.8%</td>
<td>0%</td>
</tr>
</tbody>
</table>

B. Personalized daily multimodal tours for tourists

In eCOMPASS, we have also considered the multimodal tour planning problem for tourists interested in visiting multiple points of interest (POIs). Here, the goal is to derive daily tourist tours, which respect tourists’ constraints and POIs’ attributes. The main objective is to select POIs that match tourist preferences, thereby maximizing tourist satisfaction (referred to as “profit”), while taking into account a multitude of parameters and constraints (e.g., distances among POIs, visiting time required for each POI, POIs opening days/hours, entrance fees, weather conditions) and respecting the time available for sightseeing on a daily basis. This optimization problem (illustrated in Figure 3a) is referred to in the literature as the Tourist Trip Design Problem (TTDP) [4].

Furthermore, tourists commonly chose restaurants on the basis of hard/soft constraints and preferences (e.g., price range, cuisine, customer reviews, etc) and their location since they prefer not to considerably deviate from their sightseeing routes.
Given the numerous restaurant options typically in offer, the selection of a suitable place for lunch break may be even more cumbersome than scheduling visits to attractions (see Figure 3b). However, existing tourist tour planners exclusively consider visits to attractions ignoring the need for lunch/rest breaks. In eCOMPASS, we address this issue by scheduling lunch breaks in restaurants located nearby the tourist tour [5].

During the project, we investigated several algorithmic approaches to compute personalized daily tourist trips. Our work on tourist tour planning has been towards tackling incrementally complex problem formulations, addressing realistic tourist requirements. First, we considered multiple tours via POIs with specific opening days/hours, assuming constant travel times among POIs (i.e., exclusively walking transfers). Building upon that, we then additionally have taken into account time-dependent (i.e., multimodal, walking and public transit) travel times in our modeling [5]. We then included lunch breaks scheduling at conveniently located restaurants. Finally, we incorporated choosing scenic routes (in addition to point POIs), while avoiding less tourist-friendly (or outright dangerous) parts of the city in our tour planning logic (see Figure 3c) [6].

Our approach derives high quality solutions (maximizing the profit gained by visiting the POIs and traversing the routes), while executing fast enough to support online web and mobile applications. By offering detailed plans that include navigation between POIs, we greatly improve the accessibility and mitigate the complexity of public transit networks, as perceived by tourists. Along this line, our solutions facilitate the use of public transit, which tourists would be reluctant to use otherwise. This enables tourists to comfortably make the modal shift towards more environmentally friendly modes of transportation.

III. END PRODUCTS

Building upon the aforementioned algorithmic developments on multimodal route planning and personalized (time-dependent) tourist tour planning, we have implemented two core services: (a) a multimodal route planner; (b) a personalized multimodal tourist tour planner. Both prototypes adopt a client-server architecture, wherein the clients are offered as web and mobile web applications and the server-side components are exposed as Restful web services, which materialize the most efficient algorithmic solutions on multimodal route & tour planning. In the following, we present the main issues related to the two prototypes.

A. Multimodal route planner

The multimodal route planner (MmRP) service addresses a common mobility scenario, wherein an individual requests an optimal route recommendation among the many alternatives to travel from one location to another using any available public transportation modality (e.g., walking, bus, metro, train, etc). Unlike similar tools which typically derive shortest-time routes, MmRP takes into account several objective optimization parameters such as use of the most eco-friendly means of transport or least number of transfers amongst different means of transportation.

The use of the MmRP interface is straightforward and resembles the numerous similar existing web applications (public transit route planners). The user determines the start/end trip locations through a map interface (in the mobile version, the start location is typically the current user’s location), and selects the preferred route optimization criterion (eco-
friendliest, fastest, least number of transfers). The default trip’s departure time is the current (i.e., user request) time. The request is sent to the routing server which responds providing a route recommendation, which may be visualized in textual form and overlayed on a map interface. The recommendation includes the overall travel time and distance as well as the different transport modes involved and transfer locations. The user is provided with the option to request alternative routes. Through a settings page, the use may: enter a POI or an address as a start/end location; set the departure time to an arbitrary date/time; specify restrictions on the overall allowed walking distance; choose among the different prototyped multimodal route planning algorithms, in order to realize the differences in their generated outputs. Figure 4 illustrates representative screens of the MmRP captured from a tablet PC.

B. Personalized multimodal tourist tour planner

The main purpose of the personalized multimodal tourist tour planning (MmTTP) service is to derive daily tourist tours comprising ordered sets of visits to POIs that match tourist preferences, thereby maximizing tourist satisfaction. The tour planning logic takes into account a multitude of parameters and constraints (e.g., distances among POIs, time estimated for visiting each POI, POIs’ opening hours) and respecting the time available for sightseeing on daily basis. The eCOMPASS MmTTP advances the state of the art (among all known research prototypes and commercial tools) with respect to several aspects:

- While existing tourist itinerary planners only consider walking tours, the MmTTP considers the option of using public transit for moving around. Namely, it incorporates multimodality within its routing logic aiming at deriving near-optimal sequencing of POIs along recommended tours so as to best utilize the time available for sightseeing and minimize waiting time at transit stops.
- In addition to planning visits at POIs, the MmTTP allows users to schedule lunch/coffee breaks through recommending restaurants/cafes based on both their price range and their location so as not to require long detours away from attraction areas.
- Existing tools restrict users to select the start/end points of their daily itineraries among a fixed set of locations (typically a list of accommodations and/or landmarks). Instead, the MmTTP allows users to define arbitrary start/end locations (e.g. mobile users may choose to start their tour from their current location).

Figure 5 illustrates screenshots taken from the mobile (Android) client application. The main tour planning service is invoked having specified the start and end location for each daily tour (the user is allowed to choose among available hotels, selected city landmarks, arbitrary locations pointed on a map interface and current location yield through GPS fix). The user also indicates his/her scheduled arrival date, the number of days to be spent at the destination and the preferred walking pace (to adjust the estimated walking travel times). The recommended tours may be visualized in both list and map views. The list view shows the visiting order of recommended POIs along with their title, category, rating, estimated arrival/departure time and visiting duration. A walking/transit icon placed on each list item may be tapped to yield walk or time-dependent transit directions from the previous POI towards the current one. Restaurants recommended for lunch breaks are designated with different background color and marker in the list and map view, respectively. The user may retrieve further information for selected POIs, including address, telephone number; entrance fee, accessibility of facilities and a short description.

IV. PILOT EVALUATION

The tourist tour planner prototype has undergone through official evaluation trials held in September 2014, in Berlin (Germany), in the context of the EU FP7 eCOMPASS project pilot activities [7]. Overall, 47 participants (mostly students and permanent residents of Berlin) have been recruited directly within their natural environment, e.g. waiting for the next bus or train on their current trip. The primary purpose of the pilot study has been to evaluate the core functionality of the applications, while the main usability & UX evaluation has been conducted by means of an expert review focusing on compliance to usability norms. The user research was performed in a qualitative way using the following methods: observation; thinking aloud; interview; heuristic evaluation; expert reviews (DIN EN ISO 9241 11 110); scenario walkthrough.
The heuristic evaluation aimed at testing the applications’ compliance with respect to: self-descriptiveness; suitability for the task; controllability; conformity to user expectations; suitability for learning and individualization; error tolerance. The outcome has been that the prototyped applications can already be used in an efficient, effective and “satisfying” way.

As regards the actual user evaluation of the MmRP application, an 87.3% of our sample evaluated very positively at least one of the two route suggestions (fastest and alternative) as regards its relevance. The user evaluation of the MmTTP involved tour planning for hypothetical half-day and three-day visits to Berlin, where the users entered their real preferences on POI categories. The participants’ feedback for the recommended tours has been positive with respect to: quality and attractiveness (POIs included); feasibility (POIs sequencing along itineraries, soundness of multimodal routing directions among POIs); POIs relevance with the users’ personal preferences; overall perceived utility of the application. The look-and-feel, usability and responsiveness (i.e. performance) of the application have been well received by all users, in agreement with the findings of the heuristic evaluation conducted prior to live testing.

V. CONCLUSIONS

This article has provided an overview of the key algorithmic innovations and end-products of the FP7 eCOMPASS with respect to multimodal route and tour planning in urban environments. The prototyped applications address the main requirements of citizens and tourists using the complex metropolitan public transit networks.

The main innovative aspects of the multimodal route planning service are: consideration of all available public transportation modalities (e.g. walking, bus, metro, train, taxi, etc); provision of eco-aware route planning as the user is offered the choice between faster and more environmentally sustainable journeys; incorporation of several objective optimization parameters such as use of the most eco-friendly means of transport or least number of transfers amongst different means of transportation. The multimodal tourist tour planning service also advances the state of the art with respect to the following aspects: consideration of multimodal transfers (in addition to walking) for moving from a POI to another; scheduling of suitable lunch breaks; allowance to set arbitrary start/end points for the recommended daily tourist tours.

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