D6.3 Case study 3: Barcelona

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1. Introduction

Barcelona is one of the three case study cities (together with London and Zurich) included in EUNOIA WP6 'Case studies'. The purpose of WP6 was to bring the data collected and analysed in WP3 'Data collection' and WP4 'Data analysis', respectively, and the models and tools developed in WP5 'Modelling and simulation platform' to the point where stakeholders can employ them to assess different mobility policies. More specifically, the goal was to demonstrate the capabilities of the agent-based transport simulation model MATSim — implementing the paradigms of activity-based modelling and dynamic traffic assignment — enhanced with the results obtained by EUNOIA to test specific mobility policies at the three cities participating in the project either as partners (Barcelona) or through the EUNOIA Advisory Board (London and Zurich). After discussion with different representatives of the Mobility Department of the Barcelona City Council, Transport for London and the Division of Transport at the City of Zurich, we decided to focus the simulation effort on the analysis of different configurations of the public bike sharing schemes of the three cities. The reason for this choice is twofold:

- From a scientific/technical perspective, the selected case study has allowed to test some of the main results of the previous work packages:
  - In terms of the data sources used to build, calibrate and validate the model, one of our objectives was to make use of some of different combination of conventional data (e.g., travel surveys) and the non-conventional, ICT-based data collected and analysed in WP3 and WP4. In this sense, the London case study provides an application for the active use of the Oyster card data sample made available by TfL, as well as to explore the usage of data collected on the London bike sharing scheme; the Barcelona case study includes two main novelties: the use of phone call records for generating the agents' activity plans, and the use of the data from the Barcelona public bike sharing smart card for the calibration of the travel demand model; and finally, the Zurich case study is built using more conventional, survey data.
  - In terms of modelling and simulation, we have used a novel MATSim bike-sharing module developed in the context of WP5, which to our knowledge constitutes one of the first attempts to include public bike sharing systems in travel demand models.
  - Finally, the case studies have made use of the new visualisation tools developed in WP5 with the aim to provide clear and meaningful interactive information about public bike sharing usage flows.

- From a policy perspective, this is a subject of interest for the three cities: the public bike sharing schemes of Barcelona (Bicing) and London (popularly known as Boris Bikes, after Boris Johnson, who was the Mayor of London when the scheme was launched) have been in operation since 2007 and 2010 respectively, and the need to optimise the operation of the system (e.g., the bike relocation strategies) is a common concern for both cities; in the case of Zurich, there is not a public bike sharing system yet, but there is a plan for its implementation. Therefore the subject allows the analysis of problems that are common for London and Barcelona, as well as of the differences between both systems, and can in turn be useful to inform the deployment of the Zurich system;

The present document describes the results of the Barcelona case study. The purpose of the study is to evaluate the impact of different public bike-sharing schemes in the city. The study area covers the metropolitan area of Barcelona, with special focus on the city centre, where public bike-sharing stations are located.
1.1 Organisation of the document

The document is organised as follows:

- section 2 describes i) the input data used to build the travel demand model, with particular focus on the use of mobile phone records for reconstructing travel demand, ii) the calibration and validation process, and iii) the infrastructure used for running the simulations;
- section 3 provides an overview of the problems associated to the operation of public bike sharing systems, summarises the working sessions held with the Barcelona City Council to delineate the case study, and describes the scenarios tested in the simulations;
- section 4 presents the conclusions of the study, including the main achievements as well the difficulties found, and discusses future research directions.
2. Building the case study

The main features of our MATSim implementation for Barcelona are the following:

- Our case study area is the Barcelona metropolitan area. The transport supply network in the area covered by the public bike sharing scheme has been modelled with a finer level of detail.
- Our base year is 2009. The rationale behind this choice is that the phone call records used to reconstruct travel demand and the bike sharing smart card dataset available to the EUNOIA project correspond to that year. Regarding the supply network, the road network is also that of 2009; for the public transport network we were not able to find the 2009 information, so we have used the 2014 network as retrieved from the Barcelona Open Data platform as well as from the Barcelona transport authority website.
- The activity types available to our agents are: ‘home’, ‘work’, and ‘other’.
- We have not included freight.
- Commuters from outside the case study area and passers-by are also excluded.
- The model includes four travel modes: private car, public transport, walk and bike. The public transport mode includes buses, underground, tram, train and bike-sharing.

2.1 Supply network: representing Barcelona transport infrastructure

2.1.1 Road network

The road network has been extracted from the TRANSCAD model used by the city of Barcelona for the year 2009. The network has a total of 17,821 links. Each road link provides information about:

- Length: Real length of the road segment.
- Direction: Traffic directions allowed.
- Type: Type of the road (from highways to pedestrian streets)
- Speed: Free speed in km/h
- Capacity: Road capacity per lane.
- Lanes: Number of lanes per link.
- fs: Corrective factor to estimate link capacity.
- Road counts: Number of vehicles that pass through the link along in a day (only available for some links).
Minor refinements have been needed to convert the TRANSCAD network into a readable MATSim network. The main modifications from the original network are:

- Non-connected nodes: there were a few isolated nodes that have been removed.
- Removing original links: TRANSCAD network contains auxiliary links connecting transport zone centroids with road links. These are non-real links that have been removed. Additionally, links not allowing motorised modes have been also removed.
- Direction: road links in MATSim are unidirectional, so it has been necessary to create additional links transforming TRANSCAD bidirectional links into two independent unidirectional links.
- Capacity: in order to determine the capacity of each road link, the following formula has been used: capacity * lanes * fs * 16.
- Speed: speed needs to be introduced in meters by second.
2.1.2 Public transport

The public transport services considered for the Barcelona scenario comprise:

- bus,
- underground,
- tram,
- train,
- bike-sharing.

Bus and underground

The city of Barcelona is well served by four interconnected public transport networks: bus, underground, urban railway and tram. The bus network has 96 lines and 2,464 stops. The underground is composed of 8 lines and 139 stops. Information about stops, routes, schedules and departures has been obtained from the public information available at the Barcelona Open Data platform.

Train and tram

Barcelona also has an urban and metropolitan rail network composed of 14 lines and 72 stops. The tram has two networks with a combined total of 6 lines and 56 stops. Tram and urban railway data had to be crawled. In all datasets and for each line, we needed an identifier such as the name, the stops, the schedules and the travel time between two consecutive stops. Data extraction has been done by using Scrapy, an application framework for crawling web sites and extracting structured data. Although specific code has been written to download and parse the data from the different sources, the process was the same for all the data sources:

1. detect the lines and assign them a unique identifier;
2. for each line, extract the stops in both directions (and give them a unique identifier). It has to be noted that in some cases the stops were not the same in both directions;
3. for every pair of consecutive stops along every line, extract the duration of the journey;
4. for every head stop (in both directions), get the time the convoy starts the journeys;
5. store the data in the proper format.

Tram data have been extracted from the official website http://www.tram.cat/linies-i-horaris/. As can be seen in Figure 2, the line stops are shown clearly in a web page. Schedule retrieval and interstop time involved a harder interaction with the web page by filling a form with the line, the departure and arrival stations and the date and time of travel. The list with times and line names was parsed.
Urban railway data has been extracted from the official websites http://fgc.cat and http://www.renfe.com. In this case, we needed to retrieve information of the four main traditional railway networks and also from the funicular railways. Figure 3a shows the page containing the line map and additional information on the stops. This information included services located in the stops and links between all Barcelona public transport stops. Schedule retrieval and interstop time involved filling a form and parsing the data, as shown in Figure 3b.
Figure 3. Urban railway data
Bicing

Bicing is the public bike-sharing system of the city of Barcelona. Since its inauguration in 2007, the number of users has increased exponentially. Nowadays Bicing is used by around 100,000 users with more than 1 million trips per month. Bicing comprises 420 stations distributed all over the city and 6,000 conventional bicycles. From December 2014 some conventional bikes will be replaced by electric bikes, in order to encourage uphill against downhill trips. Information about the location of the stations was obtained from the Barcelona Open Data platform. For each station, the following information was available:

- Station ID
- Number of slots
- Location: latitude and longitude
- Elevation with respect to sea level
- Street name and number
- IDs of the nearby stations

Figure 4. Bicing stations

MATSim mainly needs information about the station characteristics (location, number of bikes, etc.) and a definition of a redistribution strategy in order to move bikes from one station to another aiming to satisfy the demand. Information about the redistribution strategy was not available by the time this report was written; hence, an optimal redistribution algorithm was implemented instead of the actual relocation strategy.

Barcelona public transport system: summary table

Table 1. Main characteristics of the Barcelona public transport networks

<table>
<thead>
<tr>
<th>Transport Mode</th>
<th>Number of lines</th>
<th>Number of stations</th>
<th>Number of directed links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>96</td>
<td>2464</td>
<td>4667</td>
</tr>
<tr>
<td>Underground</td>
<td>8</td>
<td>139</td>
<td>268</td>
</tr>
<tr>
<td>Urban railway</td>
<td>14</td>
<td>72</td>
<td>472</td>
</tr>
<tr>
<td>Tram</td>
<td>6</td>
<td>56</td>
<td>194</td>
</tr>
<tr>
<td>Bike sharing</td>
<td>N/A</td>
<td>420</td>
<td>N/A</td>
</tr>
</tbody>
</table>
2.2 Modelling travel demand for Barcelona

Agent plans have been defined using anonymised mobile phone registers (call detail records, hereafter CDRs). From mobile phone data it is possible to identify places where the agents perform activities and their corresponding trips derived from those activities. Mobile phone registers have the advantage of capturing all transport modes, including “slow” modes such as walking and cycling. Activities have been classified as ‘home’, ‘work’ and ‘other’ (‘other’ is to be understood as leisure, shopping, etc.). For the simulation, a sample of around 15% of the population has been used.

2.2.1 Overview of CDR data for Barcelona Metropolitan Area

Figure 5 shows the different Base Transceiver Stations (hereafter BTSs) of the phone operator providing the CDRs data in the Metropolitan Area of Barcelona.

![Figure 5. Location of the BTSs in the metropolitan area of Barcelona](image.png)

Around 2 million users have been identified in the Metropolitan Area of Barcelona. After discarding the “non-valid users” (see section 2.2.2), the sample selected to carry out the trip analysis is reduced down to around 70,000 users. From these users, trips are estimated and trip statistics are calculated.
2.2.2 Methodology for obtaining activities and origin-destination matrices from phone call registers

The methodology for obtaining activities and origin-destination matrices from phone call registers comprises the following main steps:

1. Identify the ID of the cells within the study area. The telecommunications company provides information about the linkages between ID cells and city/province. It is common that the spatial definition of the study area does not exactly match with the administrative definition of cities and provinces, and it is therefore necessary to identify which cells belong to the study area.

2. Filter CDRs corresponding to the study area. From all the sample of CDRs, only those belonging to the study area are selected.

3. Sample selection. Only those users for which we have enough information are retained.

4. Link positions with transport zones. In order to identify trips between zones, BTS locations are assigned to transport zones.

5. Classify activities. Repeated daily patterns are analysed to classify the different activities performed by the users as ‘home’, ‘work’ or ‘other’.

6. Build OD matrices and other trip statistics. Finally, the results are extrapolated to the whole population of the study area to build the OD matrices and compute different trip statistics (trips per user, number of trips per time interval, etc.).

2.2.3 Validation of mobile phone registers as an alternative to traditional travel surveys for travel demand modelling

To validate the obtained OD matrices, a comparison with the results of the 2009 Working Day Mobility Survey of the Metropolitan Area of Barcelona (Enquesta de Mobilitat en dia Feiner, EMEF 2009) has been carried out. The EMEF sample consists of 5,797 persons of the Metropolitan Area of Barcelona. From this sample the results are extrapolated to the total population of the study area (4,231,425 inhabitants). The mobile phone data sample consists of around 70,000 users, i.e. it is about 10 times bigger than the survey sample.

Table 2 contains some basic trip statistics comparing both procedures. EMEF differentiates between three types of people: people who perform at least one trip, people who don’t perform any trip, and transport professionals. Our methodology does not distinguish between transport and non-transport professionals. The main differences between EMEF 2009 and our method are found in the percentage of people that perform at least one trip (91.1 % versus 80.3 %). The average number of trips per user estimated by our method is 6% smaller than that obtained by the EMEF.

Table 2. Basic trip statistics

<table>
<thead>
<tr>
<th></th>
<th>EMEF 2009</th>
<th>Mobile phone method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of the sample (number of individuals)</td>
<td>5,797</td>
<td>68,247</td>
</tr>
<tr>
<td>Percentage of people who perform at least one trip</td>
<td>90.1%</td>
<td>86.3%</td>
</tr>
<tr>
<td>Average number of trips per user</td>
<td>3.72</td>
<td>3.58</td>
</tr>
</tbody>
</table>
Trip distribution between areas

The Metropolitan Area of Barcelona is divided into 7 zones: Alt Penedès, Vallès Occidental, Maresme, Baix Llobregat, Vallès Oriental, Barcelonès and Garraf. For each of these zones, the EMEF 2009 provides:

- the percentage of internal trips compared to the total number of trips with their origin in that zone;
- the number of trips between zones (only if the number of trips is bigger than 20,000).

Figures 6 and 7 show that our methodology produces a good estimation of the percentage of internal trips, as well as of the trip distribution between areas.

![Figure 6. Percentage of intrazonal trips](image)

![Figure 7. Distribution of trips with origin in Barcelonès](image)
Trip time distribution along the day

The time profiles of both trip distributions are also quite similar, though some relatively small differences are observed at peak hours. Our method shows a slightly higher percentage of trips during morning peak hour (7.82% versus 7.07%), while the EMEF 2009 shows an earlier and higher night peak hour (8.47% of trips between 5pm and 6pm, versus 7.37% of trips between 7pm and 8pm calculated from CDRs). According to EMEF 2009, 90.3% of the trips take place between 7 and 21 hours, similar to the 87.35% calculated from CDRs.

![Trip distribution chart]

Figure 8. Distribution of trips along the day

2.3 Calibrating and validating MATSim for Barcelona

2.3.1 Utility function and calibration process

In MATSim, the scoring or utility function is the one that determines the agent choice (activities timing, transport mode, route chosen, etc.) from a set of alternatives generated through co-evolutionary algorithms.

![Utility function example]

Figure 9. Example of utility function
The mathematical formula of the utility functions is as follows:

\[ V = \sum_i (V_i^{perf} + V_i^{late}) + \sum_j V_j^{leg}. \]

where \( V_i^{perf} \) is the reward of performing an activity, \( V_i^{late} \) is the penalty of arriving late and \( V_j^{leg} \) penalty of traveling. These values are calculated as follows:

\[ V_i^{perf} = \beta_{perf} \cdot t_{typ,i} \cdot \ln(t_{perf}/t_{0,i}) \quad \text{for} \quad t_{perf} \geq t_{0,i} \]

- \( t_{perf} \) is how long the agent performed the activity,
- \( t_{typ,i} \) is its typical duration (e.g. 8 hours for “work”, 12 hours for “home”), and
- \( \beta_{perf} \) is a slope.
- \( t_{0,i} \) is more confusing than it looks, and has less influence than one may think, and therefore we ignore it for the time being.

\[ V_i^{late} = \beta_{late} \cdot t_{late} , \]

where \( t_{late} \) is the amount of time the agent arrived late, and \( \beta_{late} \) is a (normally negative) slope.

\[ V_j^{leg} = \beta_{trav,mode} \cdot t_{trav} + \beta_m \cdot m_{trav} + (\beta_{dist,mode} + \beta_m \cdot \gamma_{dist,mode}) \cdot d_{trav} + V_{transfer} \]

where

- \( t_{trav} \) is the time spent traveling
- \( \beta_{trav,mode} \) is a (normally negative or zero, see below) slope
- \( m_{trav} \) is the change of the monetary position caused by the travel (normally negative, e.g. a toll or a fare)
- \( \beta_m \) is a (normally positive) slope; this is the marginal utility of money
- \( d_{trav} \) is the distance of the leg
- \( \beta_{dist,mode} \) is a (normally negative) slope
- \( \gamma_{dist,mode} \) is a (normally negative) distance cost rate
- \( V_{transfer} \) is a transfer penalty e.g. incurred in public transit systems

In order to calibrate the model, it is needed to test different values of the undefined parameters described above. Calibration is an iterative process of providing different parameters values until the response of the agents is similar to the reality. More detailed information about the agents’ utility function and calibration tips can be found at www.matsim.org.
2.3.2 Calibration of the Barcelona scenario

To calibrate the Barcelona scenario, three main data sources have been used:

- modal split information from the EMEF survey (2009),
- road counts included in the TRANSCAD network (2009),
- smart card data of public bike service usage (origin-destination and time) (2009).

From the MATSim output file “events.xml”, information about modal choice, road counts and bike-sharing usage has been extracted in order to carry out the comparison between real performance and simulated results. The calibration (iterative) process can be summarised as follows:

1. Provide initial values to the utility function parameters
2. Run MATSim and obtain results
3. From the "events.xml" output file calculate results needed for comparison with real performance
4. Compare actual performance with simulated results providing indicators to measure similarity
5. Based on indicators, evaluate the adequacy of the utility functions parameters
6. If results are not as good as needed, new values are given to utility parameters and the process is repeated.

Below we explain more in detail how each particular data source is used for calibration purposes.

Modal split calibration

The EMEF survey (2009) provides aggregated information about the modal split distinguishing between soft modes, public transport and private transport.

Table 3. Modal split of the metropolitan area of Barcelona (source EMEF 2009)

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Percentage</th>
</tr>
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<tbody>
<tr>
<td>Walking</td>
<td>44.2 %</td>
</tr>
<tr>
<td>Bicycle</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Soft modes</td>
<td>45.2 %</td>
</tr>
<tr>
<td>Bus</td>
<td>8.8 %</td>
</tr>
<tr>
<td>Metro</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Train</td>
<td>4.9 %</td>
</tr>
<tr>
<td>Other public</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Public transport</td>
<td>22.2 %</td>
</tr>
<tr>
<td>Car</td>
<td>24.4 %</td>
</tr>
<tr>
<td>Car-pooling</td>
<td>4.4 %</td>
</tr>
<tr>
<td>Motorbike</td>
<td>3.4 %</td>
</tr>
<tr>
<td>Other private</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Private transport</td>
<td>32.6 %</td>
</tr>
</tbody>
</table>
The kind of information provided by the EMEF survey can be easily obtained from the MATSim outputs, by aggregating agents’ information. As a first approach, we compare results at a higher level (i.e., comparing the modal split among soft modes, public transport and private car). Once these values are similar to those obtained from the simulation, a second stage is to check how well the model developed is able to capture the specific modes of transport within the higher level groups.

Road assignment calibration

The network information extracted from the TRANSCAD model of the city of Barcelona contains information about road counts (note that count information is only available for some road sections). The total number of vehicles (without distinguishing type of vehicle) that pass through a specific road section in a standard day is provided. From MATSim it is possible to calculate the number of vehicles that cross a specific road link along the day. By comparing those values with the ones provided by the road network, it is possible to assess the goodness of fit of the model in relation to traffic assignment.

Bike-sharing calibration

Anonymised Bicing smart card information was provided by the City Council of Barcelona for a period of 3 months, from September to November 2009. Smart cards provide information each time the user picks up or leaves a bike in a station. Each smart card register contains:

- Anonymised ID of the user
- ID of the bike
- ID of the departure station
- ID of the departure station slot
- Departure time
- ID of the arrival station
- ID of the arrival station slot
- Arrival time

From the user’s bike-sharing smart card it is possible to determine the number of trips generated and attracted by a specific station as well as the origin and destination matrices at station level. Generation, attraction and trips between stations have been the variables used for calibration purposes. By filtering MATSim results, focusing only on bike-sharing trips, it is possible to calculate the generation/attraction and distribution of trips. The comparison of these indicators will provide how well the model captures bike-sharing users’ behaviour.

2.4 MATSim simulation infrastructure for Barcelona

MATSim is currently running in a dedicated server provided by IFISC. The server has two Intel Xeon E5-2680 v2 CPUs running at 2.80GHz with 10 cores each (Ivy Bridge-EP architecture), 16 DIMMs of 16 GB DDR3 memory running at 1867 MHz and two 256GB solid state disks for the operating system and temporal storage. Altogether the server has 20 physical cores and 256 GB of memory. Besides, hyper-threading has been
enabled allowing for up to 40 threads to be run in parallel. This is particularly relevant since MATSim, as many Java applications, performs better when it is allowed to run many parallel threads. The overall performance of the server as measured by the industry-standard SPEC tests is of 635 Specfp_rate2006 in floating point calculations and of 850 Specint_rate2006 in integer calculations.

In order to efficiently run MATSim and to take advantage of its potential, the computer runs Linux operating system, more specifically Ubuntu server 12.04 LTS. Java Runtime Environment, JRE, and Java Development Kit, JDK version 1.7 are installed, as required to run MATSim.
3. Exploring policy scenarios

3.1 Objective of the scenarios

3.1.1 The problem of public bike sharing systems

The idea and practice of bike-sharing schemes started in the Netherlands in the 60s, with the White Bicycle Plan in Amsterdam, and since then there have been several and diverse experiences in Europe and North America. Since the mid-2000s, the use of information and communication technologies allowed the mitigation of some of the traditional problems of bike-share schemes, such as vandalism and theft, and “smart” bike-share schemes have garnered considerable media attention and positive public opinion. Many public bike sharing systems were launched in an originally favourable context (e.g., Barcelona’s Bicing was launched in March 2007), so that their economic sustainability was of relatively little relevance in the decision making process. The fact these systems were usually sponsored by private companies sent the false message that they didn’t cost any money to taxpayers. Finally, bike-sharing schemes were surrounded by intense political communication campaigns, the case of London (where the system is popularly known as “Boris Bikes” after Mayor Boris Johnson, although the program was decided and designed under former Mayor Ken Livingstone) being a clear example.

This environment has sometimes blurred the necessary analysis about their effectiveness in economic, social and environmental terms. The success of bike sharing schemes has in most cases been considered in the light of two main factors:

- the level of use, so that the prices of the service for end users have usually been decided with the goal of maximising its use;
- the quality of service, focused on the immediate claims from users related to the system operation, such as lack of bicycles in some stations during certain times of day, lack of docks, broken bicycles, broken docks or stations, etc.

This perspective is progressively changing: some critical voices have begun to put into question the public expenditures involved in these schemes, pointing out issues such as the “gentrification” of a mode of transport, the bicycle, which has always been considered a highly inclusive means of transport (Banister, 2008). Those voices are asking for an open, rigorous and effective analysis of the role of these systems concerning the challenges facing cities on urban mobility, in the belief that bike-share schemes can be a precursor to a more sustainable urban mobility, but only if they integrate themselves in a systemic way in the local strategies on urban mobility. Essential aspects to be evaluated are, among others:

- the committed objectives to be met by the schemes;
- the cost of the system;
- the cost-effectiveness regarding the objectives;
- the relation between the costs of these services and those of the other subsidised means of public transport;
- the structure of costs and revenues;
• the social impact of the systems (profile of users, main beneficiary groups, marginalised groups, etc.);
• the optimal price structure;
• the geographical impacts, related to the maps of gaps on sustainable urban mobility, e.g. peripheral areas, transversal journeys, etc.;
• the rate of interaction with public transport networks.

All these issues directly affect the sustainability of these systems and could therefore put their own survival at risk. In Spain, for example, several schemes have recently been removed, and even in the case of Barcelona the new municipal government from 2011 expressed doubts about the continuity of the Bicing scheme. On the other hand, the city of Madrid didn’t start until 2014 its scheme, which is structurally different from the common cases (e.g., charging price from the first minute, and using variable prices depending on demand and orography).

In this context, our goal in EUNOIA was to make a first attempt to include public bike sharing into an activity-based travel demand model like MATSim, use the resulting model to address some of the above policy questions, and evaluate its the potential as well as the roadmap to reach a fully operational model.

3.1.2 Consultation with the City of Barcelona

The stakeholder consultation process with the city of Barcelona consisted of two meetings, one at the end of the project 1st year and another one at the middle of the 2nd year.

The objective of the stakeholder consultation process was twofold:

• Determine a relevant topic in which the new data sources collected and the new capabilities provided by the advanced MATSim model could shed light into relevant policy questions.
• Show the status of the model development process and discuss about relevant policy scenarios to be analysed.

During the first meeting, two main topics were considered of interest for the city of Barcelona: the analysis of the new bus network and the analysis of the bike-sharing scheme of the city. Taking into account the conclusions from the discussion with the representatives of the Barcelona City Council as well as from Transport for London and the Division of Transport at the City of Zurich, it was considered appropriate to focus the simulation effort on the analysis of public bike sharing schemes. Bike sharing schemes were already running in Barcelona and London and detailed information was available for both systems. Additionally, by that time, the city of Zurich was planning the establishment of a bike sharing system for the city.

In the second meeting, the development status of the Barcelona MATSim model and the visualisation tools developed for easing the interpretation and communication of the simulation results were presented. Additionally, the most relevant policy questions to be addressed in the simulation were discussed, leading to the specific list of policy questions described in section 3.1.3 below.
3.1.3 Policy questions

From the consultation with the stakeholders of the city of Barcelona, the following policy questions were selected as both relevant and suitable to be tackled within the EUNOIA case study:

- New stations: identify the best locations to place new stations aiming to enhance the current system as well as get new users.
- Adequacy of stations capacity: analyse the adequacy of the number of slots available in each station and study the impact of increasing the capacity in certain stations.
- Relocation of current stations: identify underutilised stations and propose new locations.
- New payment scheme or rewards for uphill trips: analyse how new payment schemes or rewards for uphill trips can influence demand.
- Redistribution of bike between stations: study new redistribution strategies aiming at reducing operational costs and improving the quality of service.

3.2 Calibration results

Modal share indicators have been used as the main source of information to calibrate the model. After several iterations testing different utility functions, the best result obtained leads to reasonably good model calibration with discrepancies of 1% to 4% regarding the three main modal share indicators (soft modes, public transport and private transport). The utility function defined also leads to reasonably good results in relation to traffic counts and bike trip distribution, although bike trips seem to be overestimated.

Table 4. Comparison between simulation results and transport survey

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>Percentage from survey</th>
<th>MATSim results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>44.2 %</td>
<td>37.8 %</td>
</tr>
<tr>
<td>Bicycle</td>
<td>1.0 %</td>
<td>6.19 %</td>
</tr>
<tr>
<td>Soft modes</td>
<td>45.2 %</td>
<td>44%</td>
</tr>
<tr>
<td>Bus</td>
<td>8.8 %</td>
<td>-</td>
</tr>
<tr>
<td>Metro</td>
<td>7.5 %</td>
<td>-</td>
</tr>
<tr>
<td>Train</td>
<td>4.9 %</td>
<td>-</td>
</tr>
<tr>
<td>Other public</td>
<td>1.0 %</td>
<td>-</td>
</tr>
<tr>
<td>Public transport</td>
<td>22.2 %</td>
<td>19.89 %</td>
</tr>
<tr>
<td>Car</td>
<td>24.4 %</td>
<td>36.10 %</td>
</tr>
<tr>
<td>Car-pooling</td>
<td>4.4 %</td>
<td>-</td>
</tr>
<tr>
<td>Motorbike</td>
<td>3.4 %</td>
<td>-</td>
</tr>
<tr>
<td>Other private</td>
<td>0.5 %</td>
<td>-</td>
</tr>
<tr>
<td>Private transport</td>
<td>32.6 %</td>
<td>36.10%</td>
</tr>
</tbody>
</table>
3.3 Bike-sharing simulation model for Barcelona

The MATSim model developed for the city of Barcelona covers most of the main questions raised by the city experts during the different EUNOIA stakeholder consultations. The model allows the study of different configurations of bike stations (the addition of new stations, modification of station capacity, relocation of existent stations, etc.) by simply modifying the bike-sharing input file. Additionally, the model allows the selection of different bike relocation strategies, in order to determine which relocation strategy is most effective. This feature is of high relevance since bike relocation is one of the most important problems faced by public bike systems today. Finally, the implementation of new payments schemes in the system is under development in collaboration with the city of Barcelona; as well as some preliminary ideas about the implementation of e-bikes in the model.

The software tool comes together with visualisations that facilitate the interpretation of the results (see figure 10). On the one hand, VIA (a visualisation tool developed by Senozon) shows disaggregated information of the scenario as well as of the results obtained. On the other hand, a new visualisation tool was developed by EUNOIA to represent information in a more aggregated manner (more information about this visualisation tool is provided in deliverable D5.3 - Analysis Module: User-Friendly Visualisation Tool).

Figure 10. VIA visualisation of agents movements (left), Bike sharing results (right)
4. Conclusions

The information to develop the simulation model for the city of Barcelona has been extracted from different data sources. Information has been gathered from traditional data sources, such as transport surveys or inductive loops as well as from more innovative data sources such as mobile phone data or bike-sharing smart cards. Regarding innovative data sources, the adequacy of mobile phone data to reliably estimate origin-destination matrices as well as other relevant transport information, such as trip time distribution, has been proved.

To calibrate the model, three main indicators have been used: modal share, traffic counts and bike-sharing trip distribution. A reasonably good calibration has been obtained after several tests. However, there already exist some discrepancies that need to be studied in detail before the use of this tool in the operational field.

The simulation model developed allows the study of different bike sharing configurations:

- The addition of new stations
- The relocation of existent stations
- The modification of the capacity of the stations
- Different bike relocations strategies

It has been demonstrated that the combination of innovative simulation transport models, such as activity-based transport models, together with new data sources, such as mobile phone data, can provide powerful explanatory simulation models.

It should be noted that the implementation of the model required more effort than initially expected. This reduced the time available for calibration and validation, and the number of scenarios and policy options that could be explored. The work done within EUNOIA will be extended in other ongoing projects with Barcelona in order to conduct a more rigorous and exhaustive calibration and validation and evaluate a wider variety of policy scenarios.
Annex I. Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
</tr>
<tr>
<td>CDR</td>
<td>Call Detail Record</td>
</tr>
<tr>
<td>EMEF</td>
<td>Enquesta de Mobilitat en Dia Feiner (Labour Day Mobility Survey)</td>
</tr>
<tr>
<td>TfL</td>
<td>Transport for London</td>
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</table>
Annex II. Overview of MATSim

II.1 Philosophy

MATSim is a software framework aiming at representing interactions between transport supply and mobility behaviour with a high level of detail. It is based on the convergence of three established streams of research, namely:

- activity-based mobility behaviour analysis, that explicitly looks at travel as a consequence of the desire of individuals to perform activities, to represent demand;
- microscopic traffic simulation methods, allowing the representation of complex but important effects in traffic flows, such as queue spillback, as well as other effects of individuals’ interactions, such as crowding of public transport vehicles;
- game theory and co-evolutionary computation methods, that provide a theoretical ground for modeling the interactions of supply and demand, as well as practical and efficient ways to find approximate solutions for the resulting theoretical model.

The software was implemented in the Java programming language, which is multi-platform and relatively easy to learn for modellers with little programming background. It is free and open-source, meaning that any interested researcher or modeller can analyse it, use it or extend it for his or her use (see www.matsim.org). The software is designed to allow usage in large-scale simulations, in particular by adopting a minimal yet powerful traffic flow model.

II.2 Modeling Principles: Game Theory and Co-evolutionary Computation

Given the philosophy above, the aim of MATSim can be summarised as modeling the influence of individuals interactions in the transport network on their activity and trip planning decisions. Modeling the interaction of individuals with possibly conflicting objectives has been the subject of game theory for decades, making this theoretical framework particularly well suited for the problem at hand.

A game theoretic view of transportation systems has indeed been popular for more than half a century, since the seminal work of Wardrop (Wardrop, 1952). The essential idea behind it is to see the transportation system as a set of shared resources (road space, public transport vehicle seats...), for which individuals compete, individuals in the population trying to maximize their own satisfaction, given the resources left available by others. Game theory studies solution concepts for such strategic interactions. A game theoretic solution concept is a definition of which states are equilibria, that is, stable under assumption of rationality — a state being considered stable if no agent/player has an incentive to change its behavior. The static, trip-based approach of Wardrop has been refined and extended with time. In particular, the equilibrium idea can be pretty naturally transferred to the activity based framework: individuals do not just try to optimize their trips, but their whole day. The implementation of this idea in a practical, usable software framework, was the aim of the MATSim software framework from the beginning (Axhausen, 2006; Nagel and Flötteröd, 2009). MATSim simulates agents having daily activity plans, consisting of activities located in space, and the trips between those activities.
Co-evolutionary algorithms are particularly well suited for searching for states approximately satisfying game theoretic solution concepts, when the search space is too big for exhaustive search (Popovici et al., 2012; Ficici, 2004). In this kinds of algorithm, an evolutionary process is performed on sub-solutions, that are evaluated by interaction. In the case of MATSim, those sub-solutions are individual daily plans, that are evaluated by interaction in a mobility simulation, that represents congestion. This process can be seen as an emulation of a learning process (Nagel and Marchal, 2006). The steps of this process, represented on Figure 1, are the following:

1. Initial demand. All agents have an initial daily plan, which will serve as a starting point for the iterative improvement process. Some characteristics of the plans are left untouched during the simulation, and should therefore come from data or external model. This is typically the case of long term decisions, such as home and work locations, or decisions involving a larger time frame than a single day (e.g. do the weekly shopping or not).

2. Mobility simulation. Plans of all agents are executed concurrently, to allow estimating the influence of the plans of the agents on each other.

3. Scoring. The information from the simulation is used to estimate the score of each individual plan. This information typically takes the form of travel times and time spent performing activities; experiments also included information such as facility crowding (Horni et al., 2009). The functional form is the one used by Charypar and Nagel (2005). It uses a linear disutility of travel time, and a logarithmic utility of time passed performing activities. Different parameters can be defined for each mode/activity type.

4. Replanning. This step actually groups two of the important components of co-evolutionary algorithms: (a) selection of the interactions for evaluation, and (b) application of the evolutionary operators (selection and mutation).

   To do so, part of the agents select a past plan based on the experienced score, following a Logit selection probability. This will have two consequences: (a) the state of the transport system, used for evaluation, will only evolve slowly from iteration to iteration, giving the time to the agents to adapt, and (b) those plans will be re-evaluated, given the new plans of the other agents. The other agents copy and mutate one of their past plans. If the number of plans in an agent’s memory exceeds a predefined threshold (usually 4 or 5), the worst plan is deleted, pushing the evolution towards plans with higher scores. Steps 2 to 4 are then iterated until the system reaches a stable state.

What kind of mutation is performed determines which alternative plans will be tried out by the agent. Typical replanning strategies include least cost rerouting using travel time estimates from the previous iteration, departure time mutation, and mode mutation at the subtour level, considering mode chaining constraints. A tour is a sequence of consecutive trips starting and ending at the same location, named anchor point. A subtour is a tour, possibly without other tours it contains. Vehicular modes can only be performed for whole subtours, which must be anchored at home or in subtours of the same mode. Experiments included secondary activity location choice (Horni et al., 2009) and activity sequence (Feil, 2010)

Those steps are iterated until a stationary state is reached, and the state of the system in this stationary state is taken as a result.
II.3 The physical world in MATSim

With the scoring function, an important element is the mobility simulation, that is used to evaluate the influence of agents on each other’s satisfaction.

The standard mobility simulation uses a step-base queue model to simulate road infrastructure, that agents might use with a car, or by boarding a public transport vehicle. Other modes are assumed not to suffer from congestion, and are simply “teleported” with a pre-computed travel time. This simulation framework was found to allow fast large-scale simulation, while still representing the essential dynamics of congestion.

II.4 Summary

MATSim is a freely available open-source simulation software, that has already been used in Switzerland (Meister et al., 2010), Berlin, or Singapore (Erath et al., 2012), to cite only a few examples.

It searches for an equilibrium for daily plans in a synthetic population, where individuals cannot improve the satisfaction they get from their day, given the state of the transport system, that depends on how individuals use it.
References


