IMPLEMENTATION FRAMEWORK AND DEVELOPMENT TRAJECTORY OF THE FEATHERS ACTIVITY-BASED SIMULATION PLATFORM

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ABSTRACT

In order to facilitate the development of dynamic activity-based models for transport demand, the FEATHERS framework was developed. This framework suggests a four stage development trajectory for a smooth transition from the four-step models towards static activity based models in the short term and dynamic activity based models in the longer term. The development stages discussed in this paper range from an initial static activity-based model without traffic assignment to ultimately a dynamic activity-based model incorporating rescheduling, learning effects and traffic routing.

To illustrate the FEATHERS framework, work that has been done on the development of both static and dynamic activity-based models for Flanders (Belgium) and the Netherlands is discussed. First, the data collection is presented. Next, the four stage activity-based model development trajectory is discussed in detail.

The paper concludes with the presentation of the modular FEATHERS framework, which discusses the functionalities of the modules and how they accommodate the requirements imposed on the framework by each of the four stages.

Keywords: dynamics, activity-based modelling, implementation, FEATHERS, Parrots

INTRODUCTION AND PROBLEM STATEMENT

Over the last decade, several micro-simulation models of activity-travel demand (e.g. Cemdap ([1]), Famos ([2]) and Albatross ([3], [4])) have become operational. It led to an increased concern to move the currently operational, and newly developed activity-based models, into practice. Especially in Europe, advanced tour-based models also introduced already some of these interdependencies and hence operational applications of models that involve microsimulation of activity-travel patterns have remained limited. While several practical reasons for this slow dissemination can be thought of ([5]), one of the main challenges faced by the travel demand forecasting industry is the ability to rapidly deploy several new theoretical advances in a time and cost efficient manner. While small laboratory experiments are needed for exploring these theoretical advances from a scientific point of view, it is of utmost importance to rely upon a sound basic platform where several of these advancements can serve as add-ons, if one is concerned about the final operationalization of the developed tools. A nice example of such a platform is the open source MATSIM-T project (Multi-Agent Transport Simulation Toolkit) where some basic functionality of a multi-agent micro-simulation for transport planning has been implemented ([6]), featuring implementations of dynamic traffic network assignments.

Taking the above into account, the idea was conceived in Flanders (Belgium) to develop a modular activity-based model of transport demand, where the emphasis is on the one hand on methodologically innovative (dynamic) activity-travel demand generation and on the other hand on the practical use of the system by practitioners and end users. The modularity of the software is assured by design in using the object-oriented paradigm, allowing for a more flexible application programming structure.

A four-stage development trajectory has been postulated in the context of FEATHERS: stage 1 is the development of a static activity-based model; stage 2 is the development of a semi-static model accounting for evolutionary and non-stationary behaviour (for instance different time periods during the day, different days, etc.); stage 3 is the development of a fully dynamic activity-based model accounting for short-term adaptation behaviour and learning and stage 4 is the development of a full dynamic agent-based micro-simulation framework involving traffic and route assignment on a microscopic level. This development trajectory is innovative due to the fact that most microsimulation models of activity-travel demand are either situated in stages 1 or 2. Indeed, in terms of short term dynamics in activity-travel patterns and travel execution (stage 3 and 4), activity-based models at their current state of development have little to offer. Apart from the MATSIM-T framework, the aggregate impact of individual-level route choice decisions on activity generation and rescheduling behaviour is not included in activity-based models. Issues such as uncertainty, learning and non-stationary environments are also not considered. Of course, there is a wide variety of literature available about traffic assignment, route and departure choice models, but at their current state of development it is fair to say that the behavioural contents of these models from an activity-based perspective are still relatively weak and that comprehensive dynamic models are still lacking.

The multi-stage process outlined above is crucial in understanding and accounting for end-user (Flemish government, environmental agencies, public transport providers) concerns, where currently a traditional four-step modeling approach is used in Flanders. Moving directly towards a full agent-based microsimulation framework is therefore not appealing from an end-user point of view given the challenges of data collection and computational complexity. Hence, the four stage approach presented in this paper allows for a gradual evolution towards more sophisticated models as time and budget constraints permit, while aiming at maximally reusing previous efforts and investments. The research described in this paper has been given the acronym FEATHERS and the application area is in line with other existing activity-based models but is extended towards environmental, health and in the medium term also traffic safety applications.

In order to set up an activity-based microsimulation, one needs considerable amounts of data. The remainder of this paper therefore first discusses an extensive hybrid, multi-method data collection approach which is necessary for the operationalization of the model. The discussion is mainly about data requirements in terms of travel demand; supply data is available within the existing four-step models and can be derived from a number of alternative data sources. Section 3 discusses the methodological challenges and techniques related to the multi-stage development trajectory. The modular framework that has been implemented to translate the methodological challenges to an operational platform are discussed in section 4. In the final section conclusions are drawn and topics for future development and research are discussed.

SPECIFIC ACTIVITY-BASED DATA COLLECTION METHODOLOGIES

Introduction: Data for Modeling Dynamic Activity-Travel Behaviour

The data requirements of both the static and the dynamic model applications that have been outlined above, constitute a real challenge. Especially the dynamic activity-travel model application needs considerable additional effort in terms of data collection. Therefore, in addition to traditional activity-travel diaries, the model needs data on activity (re)scheduling decisions of individuals, data on household multi-day activity scheduling, data on life trajectory events and how they impact activity-travel decisions, data on how individuals learn and data on how short-term dynamics are linked to long-term decisions. Such data are available in typical cross-sectional travel surveys, time use surveys and some need to be collected by means of a panel survey. In fact, in Flanders, neither data on activity-travel schedules, nor on panel surveys are available. The data collection therefore involved an extensive hybrid, multi-method approach. The different efforts have been described below.

The Parrots tool

The use of GPS-enhanced data collections (as reported in several application areas; see for instance [7]) is particularly important in our dynamic application case because rescheduling decisions are probably not only undertaken at the level of activity, but are consequently probably also reflected in travel execution (e.g. other routes taken). Furthermore, automated data collection techniques are particularly well suited to obtain data which require a significant effort from the respondent like for instance the rescheduling of activities for the development of dynamic models.

To this end, an automated activity-travel diary survey tool named PARROTS, which is the acronym for PDA (Personal Digital Assistant) system for Activity Registration and Recording of Travel Scheduling, uses the Global Positioning System (GPS) to automatically record location data ([8]). The PDA was programmed such that besides automatically registering its location, respondents can provide information about their activity-travel behaviour as well. Both planned and executed activities and trips are registered with the possibility to alter all the attributes of the planned activities. This way, information is collected regarding the decision and scheduling processes, which results in an evolution from an intention to execute some activities and trips to an executed activity-travel diary. A similar philosophy was adopted in Rindsfüser *et al.* ([9]). Replanning information in our case however is collected by allowing the respondent to update all attributes and by querying the reasons of the registered changes.

Currently, about 900 persons have been questioned by means of the PARROTS tool, which means that this study is probably one of the largest using GPS in the field of activity-travel data collection and one of the few that we are aware of that uses GPS-enabled PDA's. Also the weekly survey period makes it fairly unique in the field. More detailed analyses with respect to the collected data by means of PARROTS, like the analysis of the impact of GPS-enabled PDA technology on the user response rates, the impact of PDA technology on the quality of the collected diary data and PARROTS usage patterns, can be found in Bellemans *et al.* ([8]). The functional design of the tool has been discussed in Kochan *et al.* ([10], [11]).

Paper-and-pencil data collection

Another part of the sample (about 1500 persons; part of them belonging to the same households as the people who are questioned by means of the PARROTS tool, therefore enabling future modeling of intra-household decision making) are being questioned by means of a traditional paper-and-pencil method to account for the sample bias which is introduced when only computer-assisted forms of data collection are used. Furthermore, this choice enables carrying out comparative studies with respect to the behaviour of both target groups in terms of response rates, experience, etc.

Social network data

At the time of the pick-up of the PDA, participants are also questioned about their social network (see section 2.1). This takes place during a short interview, using Wellmann's instrument ([12]). In the application of this method, one gets information about egocentric social networks, using only one name generator per group. Questions were asked about people the respondent feels closest to; these could be friends, neighbours or relatives. The named alteri were recorded and described in detail for parents, brothers/sisters, other family members, friends, neighbours, colleagues and (sports-)club members.

Stated adaptation experiments

As mentioned previously, the goal of collecting data that measures the adaptation behaviour of people, aims at developing a dynamic component that more efficiently captures the complex process of activity generation and therefore enhances the behavioural realism of activity-scheduling models. However, decisions that constitute the short-term adaptation process of people are not trivial to be solely captured by means of activity-travel diaries (e.g. activities that have been undertaken more than a week ago). For this reason, and for benchmarking purposes (with the weekly activity-diary information which has been collected), a specific internet-based stated preference experiment was undertaken to gather additional data. While this technique can be used for different activities, it proved to be particularly relevant for flexible non-routine activities that are frequently scheduled. More detailed information about the analysis results of the collected data, can be found in van Bladel *et al.* ([13]) and in van Bladel *et al.* ([14]).

Event-based (long-term) data collection

Finally, a dynamic model should ideally also account for a continuous change over time as a function of life trajectory events. An "ideal" scenario, of course, would be to keep the sample for a whole year and refresh it thereafter, hereby measuring people's activity and travel behaviour at each of the different events (ideally then before, during and after the occurrence of the key event). The solution which was implemented to capture this type of travel information in relation to regular and key events was to implement a long term panel survey that has been carried out by means of a VEDETT-device, which has been specifically developed for this purpose. VEDETT stands for a Vehicle Embedded Data acquisition Enabling Tracking & Tracing device. The logged in-vehicle data of the VEDETT tool can be transmitted to a central data collection point as a real time data stream or in batches. The system was installed and is currently running in 14 vehicles. A website application has been developed for the survey participants in order to communicate with the VEDETT device. On the website, the motivations or reasons behind all the trips made by car, and all the additional travel facets can be indicated. To minimize the burden for the participators in the long term field trial, addresses which are frequently visited, can be designated as point of interests (POI's). Second, the system is embedded with a self-learning capacity, to allow for some trips from two POI's that are frequently made, to automatically suggest the motivation and amount of passengers. More detailed information about the VEDETT application can be found in Broekx *et al.* ([15]).

STATIC AND DYNAMIC ACTIVITY-BASED MODELING

It was already stated in the introduction that the first step in the four-stage development trajectory of the model includes the development of a static activity-based model for Flanders. While the emphasis in this paper clearly is on developing a framework allowing for the development of dynamic activity-based models, it has been highlighted that advancing directly towards a full agent-based microsimulation framework is not always the most appealing from an end-user point of view. The remainder of this section describes the current status and future research steps in the development of the four-stage trajectory.

Static activity based modeling

The scheduling model that is currently implemented in the FEATHERS framework is based on the scheduling model that is present in Albatross ([4]). Currently, the framework is fully operational at the level of Flanders. The real-life representation of Flanders, is embedded in an agent-based simulation model which consists of over six million agents, each agent representing one member of the Flemish population. The scheduling is static and based on decision trees, where a sequence of 27 decision trees is used in the scheduling process. Decisions are made based on a number of attributes of the individual (e.g., age, gender), of the household (e.g., number of cars) and of the geographical zone (e.g., population density, number of shops). For each agent with its specific attributes, it is for example decided whether an activity is performed or not. Subsequently, amongst others, the location, transport mode and duration of the activity are determined, taking into account the attributes of the individual.

The Albatross model was re-implemented in the FEATHERS framework for the Flanders study area.(see section 4 for a more detailed description). Due to the modular framework, the model can be rapidly adapted to use other core scheduling models relying upon other artificial intelligence techniques like Bayesian networks ([16], [17]), simple classifiers ([18]), association rules ([19]), and many others. Thus, in addition to the specific tree induction algorithm used in Albatross, users can opt for a wide variety of knowledge extraction techniques and meanwhile benefit from the functionalities that are provided by the other FEATHERS modules (e.g. preprocessing). Ease of transferability of the models to other study areas, which has been investigated for a static activity based model in e.g. Arentze *et al.* ([20]), was a design goal of FEATHERS. This resulted in provisions for easy incorporation of the input data of new study areas into the system and in an easy extension of existing datasets with new, context-specific attributes.

Within the FEATHERS framework, the developed activity-based models are micro-simulation models, simulating each member of the population individually. Hence, for each of the car trips generated, one can obtain information regarding the type of activity that is associated with this trip as well as other context information such as e.g. socio-economic data on the traveller and its activity schedule for the day. It is reasonable to assume that on an individual level, the context of a trip plays a role in how an individual assesses the cost/utility of a certain route, giving for instance preference to other routes taken in the context of flexible activities, like for instance leisure. Preliminary research results ([21]) indeed report on a significant impact of travel purpose on driving behaviour, which illustrates the relevance of the trip context when investigating behaviour during trips.

The link between activity-based models and traffic assignment is a key factor in increasing the deployment of activity-based models in practice since the resulting visualization and network functionalities meet the needs and concerns of practitioners. Indeed, the traditional network assignment functionality has always existed before in four-step models. Hence, in this first stage, the link between activity-based models and traffic assignment results in a coupling of new activity-based modelling techniques with models and applications that have been operational in practice for a long time.

Semi-static activity based modelling

Because of the microsimulation of activity-travel patterns, most activity-based models do not suffer from aggregation biases. Microsimulation provides a practical method with which to implement probabilistic models at the level of the individual. The basic argument is that people travel, not zones, and by averaging to the level of zones, much information is lost and the aggregation bias is significant. Because of microsimulation it is possible to produce for instance origin-destination matrices at an hourly (or even more detailed) level, for different days in the week (see section 2 for data requirements), or under specific circumstances like extreme weather conditions. However, the behavioural modelling process in itself is not changed.

Indeed, it is known that most currently operational activity-based models are only applicable in a stationary environment. This characteristic is inconsistent with other studies where it has been proven that travel behaviour is highly evolutionary ([22]) and non-stationary.

To this end, we have undertaken some first studies to extract non-stationary information from longitudinal data. In a first application ([23], [24]), traffic counts have been used to observe the impact of day of the week, but also the impact of regular events such as holidays etc on the observed traffic states. Also weather information has been accounted for.

The different techniques pointed out the significance of the day-of-week effects: weekly cycles seem to determine the variation of daily traffic flows. With respect to weather information, the most appealing result for policy makers, is the heterogeneity of the weather effects between different traffic count locations. Furthermore, the results indicated that precipitation, cloudiness, and wind speed have a clear diminishing effect on traffic intensity, while maximum temperature, sunshine duration and hail, significantly increase traffic intensity.

Obviously, these analyses are only preliminary. Tools like the VEDETT application (see section 2.6) further allow for a more detailed behavioural impact study, enabling one to keep the sample for a whole year, hereby measuring and comparing people's (non-stationary) activity and travel behaviour before, during and after the occurrence of an event. The functionalities required to accommodate the data for the analyses discussed above are currently operational in FEATHERS.

Dynamic activity-based model

The next step in the trajectory, deals with the development of a dynamic agent-based micro-simulator that allows one to simulate activity-travel scheduling decisions, within day re-scheduling and learning processes in high resolution of space and time. A priori, the dynamic activity-based simulation system is based on the Aurora framework, a full dynamic activity-based model focusing on the rescheduling of activity-travel patterns.

The basis of the Aurora implemented model appear in Timmermans *et al.* ([25]) and Joh *et al.* ([26], [27]) focusing on the formulation of a comprehensive theory and model of activity rescheduling and re-programming decisions as a function of time pressure. Apart from duration adjustment processes, Aurora incorporates also other potential dynamics such as change of destination, transport mode, and other facets of activity-travel patterns. Later, this model was extended to deal with uncertainty ([28]), various types of learning ([29]), and responses to information provision ([30], [31]). Finally, the model has been implemented as a multi-agent simulation system ([32]). Currently, some proof of concepts for this third stage in the deployment process are operational in FEATHERS.

Full microscopic activity-based model with microscopic route choice

Given the level of detail of the activity-based models discussed in the previous sections, the implementation of the bi-directional interaction between the activity-based model and the transportation system on a non-microscopic level exhibits some drawbacks.

The origin-destination matrices that are constructed based on the predicted activity-travel diaries can be aggregated at different levels of detail. While it is desirable to retain as much information as possible, and hence work at a low level of aggregation, the level of desaggregation of the origin-destination matrices is quite limited in practice, e.g. a matrix segmentation by trip purpose only. While some other general socio-demographic variables can additionally be accounted for in the segmentation, the assignment procedures that are used in the conventional four-step models and in stage 1, remain limited in the maximum level of desaggregation of the matrix that can be dealt with.

The presence of uncertainty and of incomplete information can yield a discrepancy between the attributes of intended and executed activities or trips. This issue is dealt with by dynamic activity-based models by introducing the concept of schedule execution as presented in the previous section. This schedule execution introduces a feedback between the state of the transportation network and the scheduling process. By using non-microscopic traffic assignment algorithms, the agent-based concept is broken and the concept of individual route choice is replaced by a model of a higher level of aggregation. This aggregation restricts the level of detail at which effects of policies on the behaviour of (very specific groups of) individuals can be assessed.

The issues discussed above are resolved by incorporating microscopic route choice behaviour in the dynamic activity-based model. Individual travelers in this case are endowed with the capability to consider alternatives with respect to their intended route, enabling them to cope with changes in the traffic state in an autonomous manner. Indeed, traffic assignment is inherently dynamic in the sense that the traffic state of the road network changes frequently. Consequently, the optimal route of a traveler can be affected by changes in the traffic state. Such changes typically lead to travelers reassessing their current situation, and considering alternative routes. However, changes in the traffic state not only introduce rerouting behaviour, but, due to the schedule execution mechanism, information on the traffic state of the transportation network effectively propagates towards the agent-based scheduling process. In this way, schedules that are consistent with the traffic state on the transportation network can be achieved. Enabling microscopic route choice within the FEATHERS framework is the topic of ongoing activities.

FEATHERS' MODULAR SYSTEM DESIGN

Facing the challenge to be able to implement several new theoretical advances like the ones that are reflected in the four-stage development process in the FEATHERS platform, a modular framework to conduct research on agent- and activity-based models has been developed. The modularity of the FEATHERS framework is guaranteed by means of the module-based design and by the usage of the object-oriented paradigm. This design results in an agile environment that allows for easy removal, exchange and insertion of functionalities and even complete modules.

An overview of the current modular structure of the FEATHERS framework is presented in figure 1. In the remainder of this section, the functionality of the modules and the implications of the 4 stage timeline on the evolving functionality of the modules will be discussed.

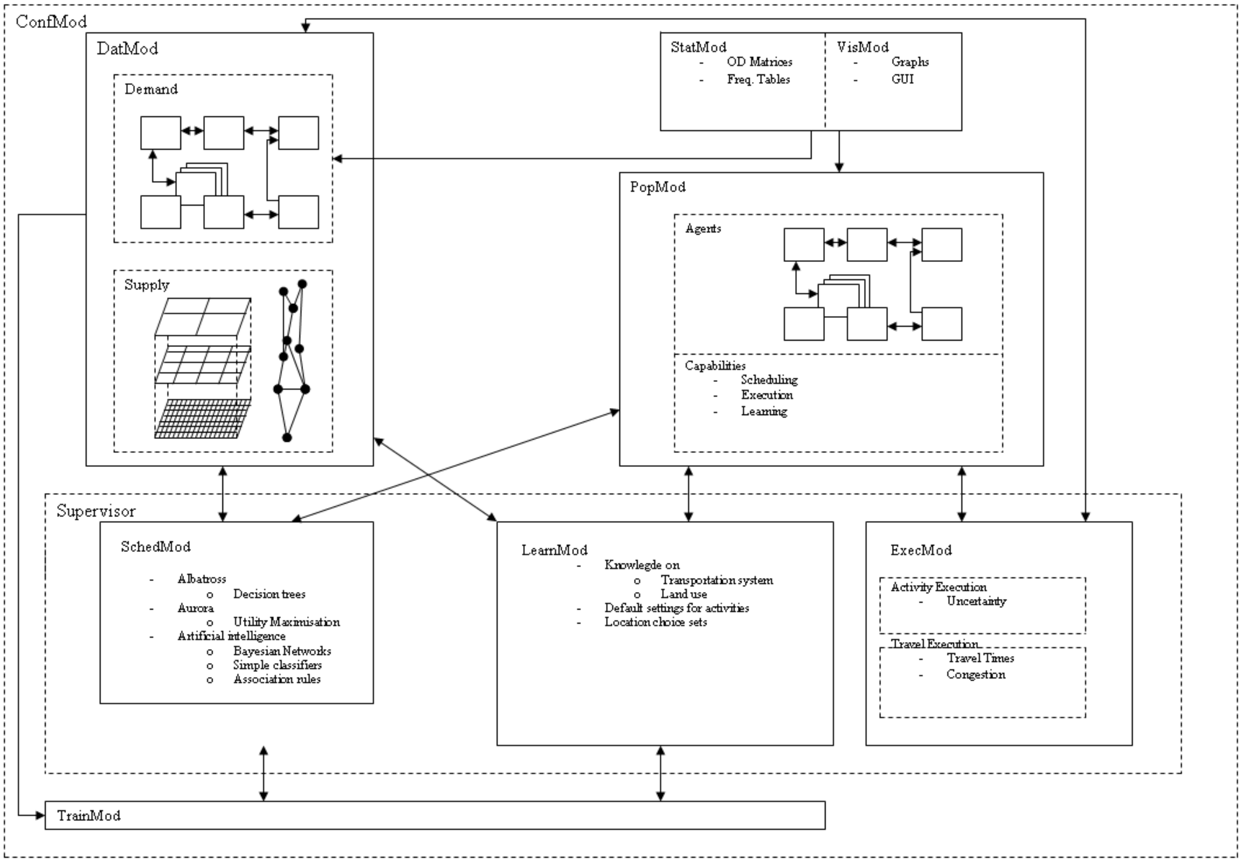

FIGURE 1 A schematic overview of the FEATHERS modules, their functionalities and their interactions.

Configuration module (ConfMod)

In order to be able to exploit FEATHERS' modular structure to the maximum extent, a flexible configuration functionality is required. Every module that is active in FEATHERS communicates with the configuration module in order to obtain its specific required settings (see Figure 2). This approach allows for a central configuration management, from where the relevant settings are dispatched to each of the modules. Modules can be switched (in-)active using the configuration module to facilitate the multi-stage development strategy described above. If for a module no settings are available in the configuration file, it is considered to be inactive by default. This way, users are not burdened by functionality that is provided by the framework but that is not needed for the current experiments (cfr. simultaneous development of functionalities for several stages).

In order to guarantee extensible and structured configuration settings, which are required to accommodate future and currently unknown configuration settings, the configuration module stores all the configuration settings for the FEATHERS modules in XML format ([33]). This makes the addition of new parameter settings for a (new) module a simple matter of updating the XML configuration file.

Data module (DatMod)

One of the core modules in the system is the data module. The data module provides access to the data that needs to be accessible throughout all other modules. Two major types of data are provided by the data module: supply and demand data (see Figure 1).

The (geographic) supply data not only includes the transportation network but also includes information on geographical zones in the study area such as e.g. the attractiveness of a zone for conducting certain activities. Also information on the availability and performance of the transportation system between the zones in the study area (e.g. travel times, travel costs, bus fares) is included in the geographic supply data. In summary, the supply data consists of the data describing the 'context' in which the agents live and schedule their activity and travel episodes.

The demand data (see the upper part of the data module block in Figure 1) consists of the activity-travel diaries or schedules that describe the demand for the execution of activities at certain locations as well as the resulting demand for transportation. The collected diaries are typically accompanied by person and household data for the persons executing the diaries. The data model for the demand data in the FEATHERS data module is aware of the following entities: persons, households, (optionally) cars, activities, journeys and lags and assumes they relate as presented in Figure 2. As FEATHERS is not only tailored towards the Flemish situation and the data survey discussed in Section 2, the attributes that are available in the data files for each of the entity types are fully customisable through the configuration module.

Both the supply and the demand data managed by the data module are made available to other modules through the data module's standardised interface.

As it is imperative that the demand data can be easily accessed by (future) modules it is important to efficiently implement the relationships between the entities in the data model. These relationships are defined in the data model that is presented in Figure 2. As the number of persons and households in a survey is typically rather small (e.g. 2500 households for the survey discussed in this paper), the demand data can be loaded into memory for fast access.

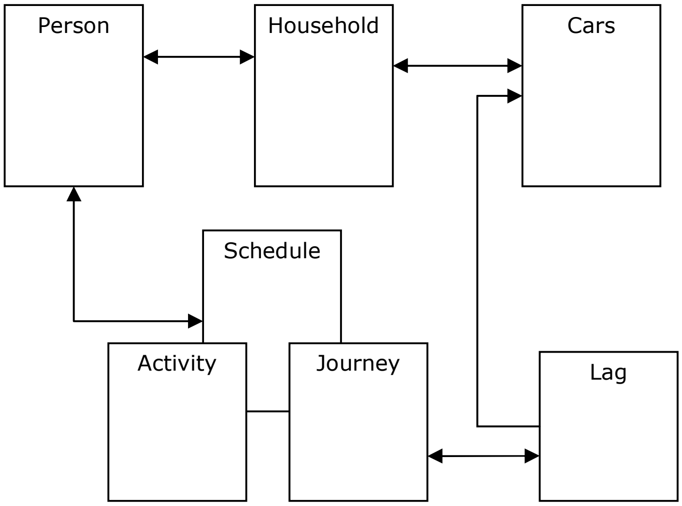

FIGURE 2 Schematic representation of the relations between the transportation demand data entities in the FEATHERS data module.

As not all geographic supply data is available at the same level of detail, the data module provides support for different levels of detail (currently 3, expandable if required). This support includes keeping track of the relation between the zones at the different levels of detail. In the current implementation it is assumed that each zone at the lower level (more detail) belongs to one higher level zone (less detail) only. These relations between the levels of geographic detail allow for (dis-)aggregation of simulation results to the desired geographical level of detail.

The attributes that are stored for the zones in a supply data layer are configured through the configuration module for flexibility. For the Flanders study area (total area of approximately 13 500 km²) the levels of detail used are: statistical sector (small administrative unit, comparable to districts or quarters, 10255 zones), sub-municipalities (1145 zones), and municipalities (327 zones). As the number of zones in each of the geographical data layers is rather limited for our study area, it is perfectly feasible to load all data in memory for fast access. Although it was not required for the current research, a configuration setting allows the data module to switch over from loading all data into memory to using direct access binary data files if not sufficiently memory is available. This switch is transparent to the modules consulting the data.

As information on the transportation system (e.g. bus fares between zones) cannot be attributed to one zone only, the data module also provides attributes for pairs of zones for each of the levels of geographical detail. The attributes that are stored for each pair of zones are configured through the configuration module. However, as the required storage capacity increases with the square of the number of zones, the data module provides the choice between loading all data in memory and using direct access files. For the Flemish case study, the data on pairs of municipalities and on sub-municipalities was loaded into memory while for the statistical sectors a direct access file was used.

The supply data on the attractiveness of zones for the execution of activities that is used for the model in Flanders is exceptionally rich due to the availability of the socio-economic survey, where the full Flemish population (6 million) was obligatory surveyed on several socio-demographic variables (age, gender, etc.). In addition to socio-demographic variables, the dataset also contains commuting behaviour of all persons in the study area (population level). Given this characteristic, one can derive from this data e.g. the level of employment by employment sector for each statistical sector, which can be used to calculate the availability and attractiveness of locations for different activities. Information about the transport system (road network data, congested travel times, etc.) is available from the existing four-step model that is currently used in Flanders. Also the traffic network that is used (see figure 1) results from the existing four-step model managed by the Flemish government. Although the data module manages geographical data, it needs to be noted that it currently does not provide geographic information system (GIS) functionalities. Hence, geographical manipulations such as e.g. overlays and map matching of GPS data need to be performed in a preprocessing step and the resulting data need to be imported into the FEATHERS data module afterwards.

Population module (PopMod)

The units of investigation in an activity-based model are the persons making scheduling decisions that result in activity-travel diaries. Hence, the agents in an agent-based activity-based model are the individual persons. During scheduling, the agent's person characteristics or attributes are used as inputs for the scheduler to drive the simulated decisions of the agent. The definition of which attributes are used in the agents is realised through the configuration module. Examples of person attributes that are commonly used are marital status, age, possession of driver license, etc.

Similar to the person entities in the data module, the persons (agents) in the population module relate to households, car (optional), activity, journey and lag entities (Figure 2). In the population module, these entities are virtual entities as opposed to the real entities in the data module. Through the relations between the entities, the attributes of all entities are accessible to be used in the agent's scheduling process in addition to its person attributes.

An important difference between the person entities in the data module and the agents in the population module is the fact that the agent entities possess important additional functionalities: scheduling, schedule execution and learning (Figure 1), which are implemented in the scheduling module, the schedule (activity and travel) execution module and the learning module respectively. These functionalities are implemented in separate modules in order to make replacement and extension of agent functionalities as convenient as possible.

In order to perform a simulation of activity and travel behaviour of individuals in a population, a synthetic population consisting of persons and households (and optionally cars belonging to the household) needs to be built. The population module is responsible for the management of the different agents (persons) that are used in the synthetic population. The synthetic population therefore consists of a collection of agents where each agent is characterised by a number of attributes. As mentioned previously, the data required are available at population level in Flanders by means of the socio-economic survey. These population data can then be updated to the current prediction year by the use of Iterative Proportion Fitting (IPF) technique. The IPF is a well established technique with the theoretical and practical considerations behind the method thoroughly explored and reported in literature ([34]). It uses the population or the larger sample margins to update the information at cell frequency level. Several applications of the technique in travel demand modeling have been reported ([35], [36], [37]).

A common functionality of all agents throughout the four development stages is the scheduling functionality. Based on its personal, household related, environmental and schedule related attributes, the agent is able to predict an activity-travel schedule using functionalities provided by the scheduling module. The resulting activity and travel episodes for an agent are stored in the activity, journey and lag entities linked to that agent (Figure 2).

During the simulation, the person, household and optionally car entities of the agents (corresponding to the upper part of Figure 2) are used in order to predict the schedules for the agents, which constitute an important model output and which correspond to the lower part of Figure 2.

Schedule module

The schedule module is a generic module in which different scheduling algorithms can be implemented. The configuration module determines which of the scheduling algorithms that are available is activated. The schedule module is tightly interfaced with the (agents in) the population module as it implements the scheduling algorithm that uses input data from the population module and stores the results in the schedules in the population module.

In the scope of stages 1 and 2 of the FEATHERS development trajectory, a decision tree-based scheduling algorithm was implemented in the schedule module. This implementation currently consists of a sequence of 27 decision trees, where each decision tree is used to model decisions on specific activity-travel schedule properties (e.g. going to work or not, transport mode for a journey, start time and duration of an activity, etc.). Besides the decision trees, the scheduling mechanism contains an algorithm to make the schedules consistent. In order to be consistent, a schedule needs to comply with a number of constraints: situational constraints (one can't be in two places at the same time), institutional constraints (opening hours constrain certain activity behaviour), household constraints (bringing children to school), spatial constraints (particular activities cannot be performed at particular locations), time constraints (activities require some minimum duration) and spatial-temporal constraints (travel time depends on transport mode). The output of the scheduler in the scheduling module is the collection of activity-travel diaries for all the agents in the population module.

Another, more advanced scheduler that is being investigated using the FEATHERS framework uses the diary utility maximising approach. Although this scheduling approach is fundamentally different from the decision tree based scheduler, both schedulers were implemented in the scheduling module side by side. This illustrates the flexibility of the design of the schedule module in the framework. This flexibility enables further research on alternative innovative scheduling mechanisms ([38]) and allows for benchmarking of the schedulers.

All stages of the four-stage development trajectory discussed in this paper require all of the modules discussed above to be operational.

Schedule execution module (ExecMod)

A dynamic activity-based model as described in stages 3 and 4 requires a schedule execution mechanism. This schedule execution mechanism is implemented in the ExecMod of the FEATHERS framework (see Figure 1) and simulates the simultaneous and synchronous execution of all activities and journeys for all agents. As can be observed from Figure 1, separate modules are provided for simulation of the execution of activities and for travel execution.

In the activity execution module, uncertainty on the scheduled activities can be modelled. Indeed, during the execution of activities unforeseen events can take place resulting in changes of activity attributes, e.g. the duration of the activity, compared to the attributes of the activity as it was originally scheduled.

In the travel execution module the relation between traffic demand and the performance of the transportation system (e.g. car travel speeds on a link as a function of traffic intensity) is accounted for. As the agent's schedule executions are simulated for all agents simultaneously, the total traffic demand can be computed for each transportation mode and at each moment in time. In order to obtain the traffic intensities on links in the transportation network, the traffic demand needs to be loaded onto the network. In stage 4, this is achieved by simulating the microscopic route choice behaviour.

The potential mismatch between the attributes of scheduled and simulated executed activities or travel results in a potential inconsistency in the schedules if no corrective rescheduling action is taken.

The rescheduling functionality, combined with the traffic assignment from the stage 4 model, results in a bidirectional coupling between the scheduling and the transportation network: the traffic demands predicted by the activity-based model impact the traffic states in the transportation network and vice versa.

Rescheduling of activities and travel is managed in the FEATHERS framework by the supervisor (see figure 1), which coordinates between the scheduling and the schedule execution for each agent. This coordination mainly consists of deciding when to check the partially executed schedule for inconsistencies and when to start the rescheduling (SchedMod) and the schedule execution (ExecMod).

Learning module (LearnMod)

The learning behaviour of persons stems from the fact that they observe that their assumed knowledge about the environment in which they operate (e.g. the transportation network) does not match reality. An indication of this mismatch is given by a mismatch between scheduled and executed activities or travel. The learning process of the agents is managed by the supervisor in combination with the (re-)scheduling and the schedule execution for that agent. The supervisor takes into account that the rescheduling processes typically run on a faster time scale than the learning processes. By adaptation of the supervisor and the scheduling, schedule execution and learning modules, a wide range of experiments can be conducted.

Statistics (StatMod) and visualisation (VisMod) modules

The statistics module provides reports regarding the (synthetic) population and the activity-travel schedules to the FEATHERS user. This includes information that can be extracted at the level of households (e.g. distribution of households according to availability of means of transportation); persons (e.g. usage of transportation modes), journeys (e.g. average number of journeys per day); lags (e.g. average number of lags per journey) and activities. Given the similarity in the person, household, car, activity, journey and lag entities and their relations in both the data module and the population module, the statistical module and the visualisation module make abstraction from the fact whether they consult the data module or the population module to extract the data to report to the user. Hence, statistics that are implemented for the survey data in the data module can readily be used to draw the corresponding statistics on simulated data from the population module. Which statistics are to be drawn by the statistical module is configured through the configuration module.

As the activity-travel diaries contain detailed travel information, the statistical module provides the functionality of skimming through all schedules and compiling an OD matrix. Given the level of detail of the data, the travel information can be aggregated in segmented

OD matrices such as e.g. time sliced OD matrices, OD matrices per transportation mode, and OD matrices per activity type. This functionality enables a transition step in the evolution from four step models towards activity-based models by exporting OD matrices that are assigned to the transportation network using the traffic assignment tools from the traditional four step model as was discussed in stage 1.

The visualisation module relates strongly to the statistical module in the sense that the visualisation module will create graphical reports contrary to the numerical reports provided by the statistical module. Currently the visualization module is not operational yet and all FEATHERS reports are obtained through the statistical module. However, in order to improve user friendliness, a graphical user interface and a visualization module will be added to the FEATHERS framework in the future.

Training module (TrainMod)

All models used throughout the FEATHERS framework need to be calibrated using real-life data. This functionality is provided by the training module. The training module is configured through the configuration module and obtains the required data from the data module. The output of the training module is calibrated model parameters for the models that are used in the other modules (see Figure 1).

CONCLUSIONS

The main goal of the FEATHERS framework which has been presented in this paper is to allow for easy updating and/or replacement of functionalities used in activity-based models as the state-of-the-art in the activity-based research field progresses rapidly. We therefore believe that the modular framework holds considerable promise to facilitate the research on and the development of dynamic activity-based models for transport demand.

It was illustrated that the modular design of the FEATHERS framework is compatible with a long term four stage development trajectory of activity-based models that was postulated for Flanders (Belgium): stage 1 is the development of a static activity-based model; stage 2 is the development of a semi-static model accounting for evolutionary and non-stationary behaviour; stage 3 is the development of a fully dynamic activity-based model including short-term adaptation (rescheduling) and learning; and stage 4 is a full agent-based dynamic activity-based microsimulation framework including traffic assignment. Besides the discussion of the different modules within the FEATHERS framework and their interactions, it was shown how the FEATHERS modules' functionalities accommodate the requirements of each of the four development stages.

Along with this, it has been shown that data collection is a prerequisite for the application of both static and dynamic activity-based models. To this end, an extensive hybrid, multi-method data collection approach has been described in detail. It was shown that especially the dynamic activity-travel model application needs considerable additional effort in terms of data collection. It has been shown that in addition to traditional activity-travel diaries, such a model needs data on activity rescheduling decisions of individuals, data on household multi-day activity scheduling, data on life trajectory events and how they impact activity-travel decisions, data on how individuals learn and data on how short-term dynamics are linked to long-term decisions.

REFERENCES

[1] Bhat, C.R., Guo, J.Y., Srinivasan, S. and A. Sivakumar. A comprehensive micro-simulator for daily activity-travel patterns. Proceedings of the Conference on Progress in Activity-Based Models, CD-ROM, Maastricht, May 2004, pp. 28-32.

[2] Pendyala, R.M., Kitamura, R. Kikuchi, A., Yamamoto, T. and S. Fujji. FAMOS: Florida activity Mobility simulator. *Proceedings of the 84th Annual Meeting of the Transportation Research Board*, CD-ROM, Transportation Research Board of the National Academies Washington D.C., 9-13 January 2005.

[3] Arentze, T.A. and H.J.P. Timmermans. *Albatross: A Learning-Based Transportation Oriented Simulation System.* European Institute of Retailing and Services Studies. Eindhoven, The Netherlands, 2000.

[4] Arentze, T.A. and H.J.P. Timmermans. *Albatross 2: A Learning-Based Transportation Oriented Simulation System.* European Institute of Retailing and Services Studies. Eindhoven, The Netherlands, 2005a.

[5] Davidson, W., Donnelly, R., Vovsha, P., Freedman, J., Ruegg, S., Hicks, J., Castiglione, J., and R. Picado. Synthesis of first practices and operational research approaches in activity-based travel demand modelling. *Transportation Research Part A*, No. 41, Transportation Research Board of the National Academies, 2007, pp. 464-488.

[6] Balmer, M., Nagel K. and B. Raney. Agent-based demand modelling framework for large scale micro-simulations, Transportation Research Record, No. 1985, 2006, pp. 125-134.

[7] Goulias, K. and D. Janelle. *GPS Tracking and Time-Geography: Applications for Activity Modeling and Microsimulation.* Final Report FHWA-sponsored Peer Exchange and CSISS Specialist Meeting, 2006.

[8] Bellemans, T., Kochan, B., Janssens, D., Wets, G. and H.J.P. Timmermans. *Field evaluation of Personal Digital Assistant enabled by global positioning system: Impact on dualtity of activirt and Diary data.* Paper presented at the Annual Meeting of the Transportation Research Board, also forthcoming in Journal of the Transportation Research Board, Washington, USA, 2008.

[9] Rindsfüser, G., Mühlmans, H., Doherty, S.T., and K.J. Beckmann. *Tracing the planning and execution of and their attributes - Design and application of a hand-held scheduling process survey.* Paper, 10th International Conference on Travel Behaviour Research, Lucerne, Switzerland, 10-15 August 2003.

[10] Kochan, B., Bellemans, T., Janssens, D. and G. Wets. *Dynamic activity-travel diary data collection using a GPS-enabled personal digital assistant.* Proceedings of the Innovations in Travel Demand Modeling Conference, Austin, Texas, U.S.A, May 21-23 2006a.

[11] Kochan, B., Bellemans, T., Janssens, D., G. Wets. *Dynamic activity-travel diary data collection using a GPS-enabled personal digital assistant.* Paper presented at the 9th International Conference on Applications of Advanced Technology in Transportation (AATT 2006), Chicago, Illinois, U.S.A, 13-16 August 2006b.

[12] Wellmann, B. The community question: The intimate networks of East Yorkers, *The American Journal of Sociology*, No. 84(5), 1979, pp. 1201–1231.

[13] van Bladel, K., Bellemans, T., Wets, G., Arentze, T.A. and H.J.P. Timmermans. *Fitting S-shaped activity utility functions based on stated-preference data*. Paper presented at the 11th International Conference on Travel Behaviour Research, Kyoto, 16-20 August 2006.

[14] van Bladel, K., Bellemans, T., Janssens, D., Wets, G., Nijland, L., Arentze, T.A. and H.J.P. Timmermans. Design of Stated Adaptation Experiments: Discussion of Some Issues and Experiences. Paper presented at the International Conference On Survey Methods In *Transport: Harmonization And Data Comparability*. Annecy, France, 25-31 May 2008.

[15] Broekx, S, Denys, T, and L. Int. Panis. Long-term travel surveys: how can the burden remain bearable, Paper presented at the 33rd Colloquium Vervoersplanologisch Speurwerk, , Amsterdam, The Netherlands, November 23-24, 2006.

[16] Janssens, D., Wets, G., Brijs, T., Vanhoof, K., Timmermans, H.J.P. and T.A. Arentze. Improving the performance of a multi-agent rule-based model for activity pattern decisions using Bayesian networks. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1894, Transportation Research Board of the National Academies, 2004, pp. 75-83.

[17] Janssens, D., Wets, G., Brijs, T., Vanhoof, K., Arentze, T.A. and H.J.P. Timmermans. Integrating Bayesian networks and decision trees in a sequential rule-based transportation model. *European Journal of Operational Research*, No.175, 2005, pp. 16-34.

[18] Moons, E. *Modelling Activity-Diary Data: Complexity or Parsimony?* Ph.D. Dissertation, Faculty of Sciences, Limburg University, Diepenbeek, 2005.

[19] Keuleers, B., Wets, G., Arentze, T.A. and H.J.P. Timmermans. Association rules in identification of spatial-temporal patterns in multiday activity diary data. *Transportation Research Record*, No. 1752, Transportation Research Board of the National Academies, 2001, pp. 32-37.

[20] Arentze, T.A., F. Hofman, H. van Mourik and H. Timmermans The Spatial Transferability of the Albatross Model System: Empirical Evidence from Two Case Studies, The 81-th Transportation Research Board Meeting, January 11 – 16, Washington D.C., 2002.

[21] Beckx, C., Int Panis, L., Wets, G., Torfs, R., Mensink, C., Broekx, S. and Janssens, D. Impact of trip purpose on driving behaviour: case study on commuter behaviour in Belgium. In: *proceedings of the 15th International Symposium Transport and Air Pollution*, Vol. 107, n°2, pp. 332-337. ISBN: 2-85782-639-7. Reims, France, 2006.

[22] Schönfelder, Stefan. *Urban rhythms : modelling the rhythms of individual travel behaviour*, Ph.D. Dissertation, Eidgenössische Technische Hochschule [ETH], Zürich, 2006

[23] Cools, M., Moons, E. and G. Wets. Investigating the effect of holidays on daily traffic counts: a time series approach. In *Transportation Research board: Journal of the Transportation Research Board*, No. 2019, Transportation Research board of the National Academies, 2007, pp. 22-31.

[24] Cools, M., Moons, E. and G. Wets. *Assessing the Impact of Weather on Traffic Intensity*, Paper presented at the Annual Meeting of the Transportation Research Board, Washington, USA, 2008.

[25] Timmermans, H.J.P., Arentze, T.A. and C.-H. Joh. *Modelling the effects of anticipated time pressure on the execution of activity programs, Journal of the Transportation Research Board*, No.1752, Transportation Research Board of the National Academies 2001 pp. 8-15.

[26] Joh, C.-H., Arentze, T.A. and H.J.P. Timmermans, Understanding activity scheduling and rescheduling behaviour: theory and numerical simulation. In *B. Boots, et al. (eds.), Modelling Geographical Systems. Kluwer Academic Publishers*, Dordrecht, 2003, pp. 73-95.

[27] Joh, C.-H., Arentze, T.A. and H.J.P. Timmermans. Activity-travel rescheduling decisions: empirical estimation of the Aurora model, *Transportation Research Record*, No. 1898, Transportation Research Board of the National Academies, 2004, pp. 10-18.

[28] Arentze, T.A. and H.J.P. Timmermans. A theoretical framework for modeling activity-travel scheduling decisions in non-stationary environments under conditions of uncertainty and learning. In: *Proceedings International Conference on Activity-Based Analysis*. CD-Rom. Maastricht, 2004, pp. 13.

[29] Arentze, T.A., C. Pelizaro and H.J.P. Timmermans Implementation of a model of dynamic activity-travel rescheduling decisions: an agent-based micro-simulation framework. In: *Proceedings of the Computers in Urban Planning and Urban Management Conference*, CD-Rom. London, 2005, pp. 16.

[30] Arentze, T.A. and H.J.P. Timmermans Information gain, novelty seeking and travel: *a model of dynamic activity-travel behavior under conditions of uncertainty*, No. 39, Transportation Research A: Policy and Practice, 2005b, pp. 125-145.

[31] Sun, Z., T.A. Arentze and H.J.P. Timmermans. Modelling the impact of travel information on activity-travel rescheduling decisions under conditions of travel time uncertainty, In: *Proceedings of the 84th Annual Meeting of the Transportation Research Board*, CD-ROM, Transportation Research Board of the National Academies, Washington D.C., 2005, pp .17.

[32] Arentze, T.A. and Timmermans, H.J.P. A cognitive agent-based simulation framework for dynamic activity-travel scheduling decisions. In: *Proceedings Knowledge, Planning and Integrated Spatial Analysis*, LISTA, 2005c.

[33] W3C (2006) eXtensible Markup Language (XML), World Wide Web Consortium (W3C), http://www.w3.org/XML.22.

[34] Beckman, R.J., Baggerly, K.A., and McKay, M.D. Creating synthetic baseline populations. Transportation Research Part A, No. 30(6), 1996, pp. 415-429.

[35] Arentze, T.A., Timmermans, H.J.P. and F. Hofman. Creating synthetic household populations: problems and approach. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2014, 2007, pp. 85-91.

[36] Guo, J.Y. and C.R. Bhat Population Synthesis for Microsimulating Travel Behavior, *Transportation Research Record*, No. 2014, Transportation Research Board of the National Acadamies, 2007, pp. 92-101.

[37] Wong, D.W.S. The reliability of using the iterative proportional fitting procedure. *Professional Geographer*, No. 44(3), 1992, pp. 340-348.

[38] Vanhulsel, M., Janssens, D., and G. Wets. Calibrating a new reinforcement learning mechanism for modeling dynamic activity-travel behavior and key events, *Electronic*

Proceedings of the Annual Meeting of the Transportation Research Board, January 21-25, Washington, USA, 2007.