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Organizational-based model and agent-based simulation for long-term carpooling

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Modeling the interaction between individual agents becomes progressively important in recent research. Carpooling for commuters is a specific transportation problem where cooperation between agents is essential while executing their daily schedule. Organization-based modeling provides the ability to determine where the relationships between agents exist and how these relationships influence the results. This paper presents both the design of an organizational model that is mapped to an agent-based simulation model and a proof of concept implementation. It analyzes various effects of agent interaction and behavior adaptation for sets of candidate carpoolers. The goal is to limit the interactions of autonomous agents, to enable communication to trigger the negotiation process within social groups. The start of the carpooling process depends on the individuals' objectives and intention to carpool. The success of negotiation highly depends on the trip departure time preference, on the individuals' profile, route optimization and on the effect of constraining activities. In order to cooperate individuals adapt their agenda according to personal preferences and limitations. The carpooling social network was established using results predicted by the FEATHERS operational activity-based model for Flanders (Belgium). From the simulation's discussions, it is possible to portray the real picture of the potential carpoolers throughout their carpooling period. The Janus (multi-agent) platform is used for simulating the interactions of autonomous individuals.

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1. Introduction

Modeling the interaction between individual agents becomes progressively important in recent research. Traditional modeling tools have difficulties for handling the complexity of communication, negotiation and coordination that are required in carpooling simulations. A method that is more suited for the interaction of autonomous entities is agent-based modeling (ABM). ABM is an essentially decentralized and individual-centric approach which allows one to understand the interactions of physical particles, and describe many problems of astronomy, biology, ecology and social sciences. ABM has been applied to a broad range of topics in transportation sciences including simulation of vehicles or pedestrian flow, route choice modeling, car-following and lane changing models, and traffic simulation. Organization-based modeling provides the ability to model the relationships between roles played by agents in a system and the contribution of these relationships to the general behavior of the system. It enables a clear representation of structural and strategic concerns and their adaptation to changes in the environment.

Currently many research areas including transportation behavior need to analyze and model complex interactions between autonomous entities. Carpooling for commuters is a specific transportation problem where cooperation between individuals (agents) is essential. Carpooling is considered to be an effective alternative transportation mode that is eco-friendly and sustainable as it enables commuters to share travel expenses, save on fuel and parking costs, improve mobility options for non-drivers. It also reduces emission and traffic congestion. Change in some factors such as the increase in fuel price, in parking costs, or in the implementation of a new traffic policy, may prove to be an incentive to carpool. In order to commute by carpooling, individuals need to communicate, negotiate and coordinate, and in most cases adapt their daily schedule to enable cooperation. Effective negotiation requires that individuals effectively convey and interpret information to enable carpooling. However, strict timing constraints in the schedule of the day have the opposite effect (Knapen *et al.*, 2014a & Horvitz *et al*. 2005).

The aim of this research is to investigate the **effect of time constraints and generalize previous work where cooperating carpoolers were restricted to share the respective home and work areas**. In this case, sets of agents working in a particular traffic analysis zone (TAZ) and living in spatially dispersed zones are considered for co-traveling. Agents' communication, negotiation and coordination in a multiple trip negotiation model are investigated. This is done while taking into account the constraints induced by flexible activity scheduling. The existing studies do not consider the direct interaction between agents in the carpooling except Hussain *et al.*, 2015 which only allows interactions between agents living in the same TAZ.

In order to observe the effect of limitations to agenda (daily schedule) adaptation, the actions performed by each individual are divided into following steps: (i) decision to carpool, (ii) exploration and communication, (iii) negotiation, (iv) coordination and schedule adaptation, (v) trip execution (carpooling), (vi) negotiation during carpooling and (vii) carpool termination. These steps exemplify a model that represents an extension of the simple but analytically tractable negotiation model for carpooling. The new model is based on an agent-based and organizational-based meta-model (Cossentino *et al.*, 2010), in which the role and organization concepts are first class entities. To cooperate on commuting trips, the agents living in mutually different TAZ can interact with others sharing the same work TAZ. A *carpooling social network* is considered. It was established using results predicted by the FEATHERS (Bellemans *et al.*, 2010), an operational activity-based model for Flanders (Belgium). The expected travel times between travel analysis zones for the morning peak period, generated by the WIDRS tool (Knapen *et al*. 2014b), are used. The success of negotiation highly depends on the trip departure time decision, on the individuals' profile, on the route optimization and on the effect of constraining activities. Driver selection is based on individual attributes (vehicle ownership and driving-license availability). The ability to carpool for commuting depends on schedule flexibility. The schedule adaptation is limited by the flexibility of the individual schedules. A daily schedule for an individual is a timed sequence of trips and activities of different categories (work activities with fixed or flexible timings). The Janus (Gaud *et al.* 2008), multi-agent based platform is used: it provides an efficient implementation of agent-based and organizational-based concepts.

1.1. Research Objectives

This research presents both the design of an organizational model that is mapped to an agent-based simulation model and a proof of concept implementation. It analyzes various effects of agent interaction and behavior adaptation of a set of candidate carpoolers. The goal is to limit the interactions of autonomous agents, to enable communication to trigger the negotiation process within social groups to find matching partners in order to co-travel. This research results in a model for carpooling by dividing the procedure of negotiation and trip execution into separate generic steps. In this research, a progressive negotiation model on trip start time and driver selection is presented. The purpose of this research is to model (1) how people adapt their daily schedule to enable cooperation and to analyze (2) how the consequent carpooling participation evolves over time. The simulation is aimed to find out what is the share of carpooling among the available transportation modes given behavioral constraints with respect to activity timing.

1.2. Paper's organization

This paper is organized as follows. Section 2 summarizes the related work on agent-based negotiation models, rescheduling activities in a daily schedule, joint activity and trip execution and profile matching in carpooling. Section 3 presents the design of the organization-based model that maps to an agent-based simulation model for the carpooling. This section is divided into two main parts. First, the problem domain is discussed by defining the carpooling process constructed on the bases of individual activity and agendas. The organizational layer and the negotiation model based on trip start times and the vehicle and driver selection are presented in this section. Secondly, the design of an agent domain (solution domain) is presented. The agent's behavior is discussed in detail at the end of section 3. Section 4 explains the experimental setup and discusses some of the results. Finally, conclusions and future work are presented in Section 5.

2. Related Work

In recent years, agent-based simulation has come into the field of transportation science because of its capability to analyse aggregated consequences of individual specific behaviour variations. ABM can provide valuable information on the society and the outcomes of social actions or phenomena. The existing works related to the different types of negotiation techniques and models, rescheduling activities in the agenda for a day, joint activity and joint trip execution, and profile matching in carpooling, is presented in this section.

In the first category of the research exertions, the agent-based negotiation models for carpooling are studied. Hussain *et al.* 2014 proposed a single trip negotiation model for carpooling using a simple negotiation mechanism. The authors measured the direct interaction between agents from belonging to a *carpooling social network*. The first implementation used home and work TAZ as well as preferred trip start times and carpool periods determined by uniformly sampling given sets. Hussain *et al.* 2015a extend the single-trip negotiation mechanism into a multiple trip negotiation model (combining the forward and backward commuting trips for a day in a single negotiation) by taking the possibility of *flexible activity scheduling* into account and limit the interaction between agents within small groups based on home and work TAZ. The authors extended the negotiation model by applying constraining activities and by considering the personal daily schedule of each individual. Galland *et al.*, 2014 present a conceptual design of an ABM for the carpooling application, that is used for simulating the autonomous agents and to analyze the effects of change in factors of infrastructure, behavior and cost. This model used agents' profiles and social networks to initialize communication and then employs a routing algorithm and a utility function to trigger the negotiation process between agents.

A large body of literature (e.g. Nijland *et al.*, 2009 and Guo *et al.*, 2012) has been published about the concept of *rescheduling activities* in a daily schedule of the individuals. This however, considered schedule adaptation to unexpected events as opposed to rescheduling in the context of negotiation to cooperate. Knapen, *et al.*, 2014b offer a framework to investigate algorithms for rescheduling at a large scale. This enables explicit modeling of the information flow between traffic information services and travelers. It combines macroscopic traffic assignment with microscopic simulation of agents. The authors investigated marginal utility that monotonically decreases with activity duration, and a monotonically converging relaxation algorithm to efficiently determine the new activity timing. The Aurora model developed by Joh 2004 provides schedule generation and dynamic activity travel rescheduling decisions. Aurora is based on S-shaped utility functions. The maximal utility value attainable for a given activity is given by the product of functions modeling the attenuation by start time, location, position in the daily schedule and time break since last execution of the activity. Bounded rationality individuals are assumed. Arentze *et al*,. 2005 present a comprehensive description of the Aurora activity-based model for schedule generation and adaptation. A complete model has been specified describing the insertion, shifting, deletion and replacement of activities as well as changing locations, trip chaining options and transport modes. Models of this level of detail are required to integrate cooperation concepts in the carpooling.

In the context of *travel demand*, cooperation aspects apply to joint activity execution and joint trip execution. Ronald *et al.*, 2009 present an agent-based model that focuses on the negotiation method for joint activity execution. The proposed model includes a well-defined and structured interaction protocol: integrating the transport and social layer. A utility function is presented on the basis of individual and combined attributes. The agents negotiate on the type, location and the start time of their social activities. Chun and Wong, 2003 present a generalized agent-based framework that uses negotiation to schedule dynamically the events. Authors describe a group and a negotiation protocol for building agreements on agenda schedules. Each agent is assumed to specify its most preferred option first and to identify consecutive new proposals in non-increasing order of preference. Each one uses a private utility function. The protocol originator makes use of a proposal evaluation function. Luetzenberger *et al.* 2011 introduce an approach which considers a driver's mind and examines the effect of environmental conditions. Authors planned to integrate the agent interactions necessary when carpooling. Kamar and Horvitz, 2009 describe an ABM aiming to optimally combine demand and supply in an advisory system for frequent ride-sharing. The authors focus on the mechanisms required to model users cooperating on joint plans and focus on the economic value of the shared plans.

Knapen *et al.*, 2014a present an automated, *Global Car Carpooling Matching Service* (GCPMS), advisory service to match commuting trips for carpooling. The probability for successful negotiation is calculated by means of a learning mechanism. The matcher needs to deal with dynamically changing graph w.r.t. topology and edge weights. The same authors Knapen *et al.*, 2012 study the problem of finding an optimal route for carpooling. They propose an algorithm to find the optimal solution for the join tree. Each individual declares the maximal time and/or distance that is acceptable to move from origin to destination.

Varrentrapp *et al.*, 2002 provide informal and formal declaration for the *long-term carpooling problem*. The soundness of the problem formulation is discussed and some properties are verified. Finally the problem is proved to be NP-complete. This research assumed that carpools are stable in time and that every member in turn acts as the driver. Manzini *et al.*, 2012 describe an interactive system to support the mobility manager (officer) operating on the long-term carpooling problem. The proposed methods and models make use of clustering analysis. The basic assumption is that in a group the driver of the shared car turns among the participants. Clustering procedures using methods available in standard decision support system are proposed. After clustering, for each driver a *traveling salesman problem* is to be solved.

None of the reported research analyses the effect of negotiated agenda adaptation required for carpooling (joint trip execution). In this paper, we propose a model to investigate the problem.

3. Long-term carpooling model

As explained in the introduction, an agent-based approach is used for assessing the effects of individual's decision-making and for simulating the interactions of autonomous agents. Agent-Based Modeling approach, which is essentially distributed and individual-centric is appropriate for the systems (1) which require modeling complex, nonlinear, discontinuous or discrete the interactions between individuals (2) where the pace is crucial, and agents' positions are not fixed (3) where the population is heterogeneous and the behavior of agents is stochastic in nature (4) where the topology of the interactions is heterogeneous and complex (5) where agents exhibit complex behavior, especially involving learning, interactions, and adaptation.

Such systems may be complex to design. The "Capacity, Role, Interaction and Organization" (CRIO) meta-model (Cossentino *et al.*, 2010) provides organizational concepts for modeling complex systems in terms of role and their relationships. This meta-model provides also the mapping from the organizational concepts to the ones that are used for building an agent-based simulation model, and its implementation. According to (Jennings, 2000 and Ferber et al., 2003) this approach is appropriate because the carpooling individuals are dynamically changing of role in the *carpooling social network*. Adopting an organizational approach enables the agents to dynamically change their behaviors without changing their internal architecture.

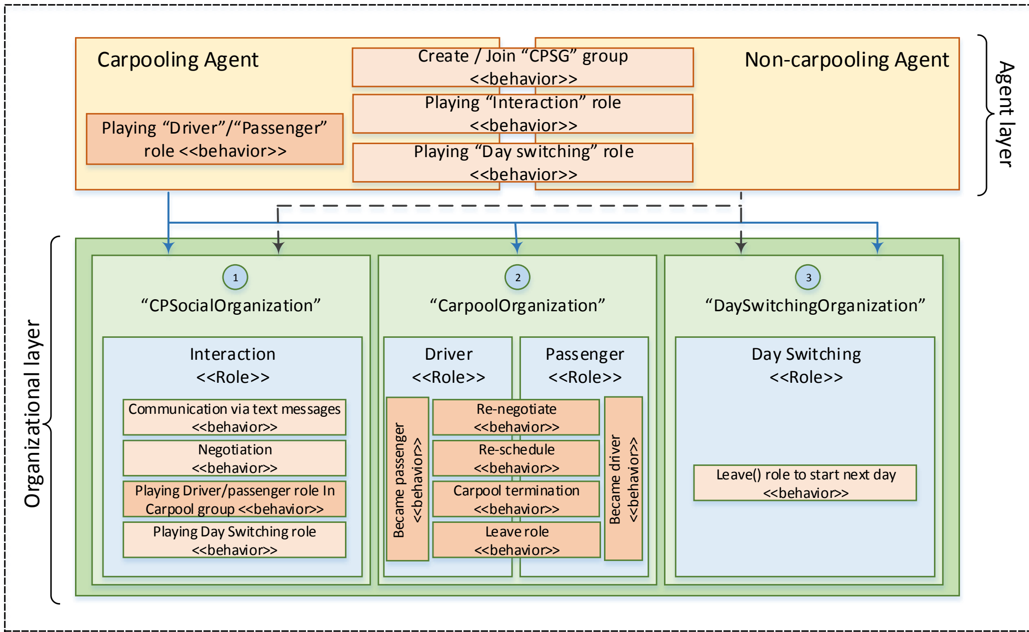

Figure 1. Organizational-based model that is mapped to an agent-based simulation model for the long-term carpooling.

The CRIO approach views "*an organization as collection of roles that take part in organized systematic institutionalized patterns of interactions with other roles in a common context. This context consists in shared knowledge and social rules or norms, social feelings, etc. and is defined according to an ontology. The aim of an organization is to fulfill some requirements*." A role is an "*expected behavior, a set of role tasks ordered by a plan, and a set of rights and obligations in the organization context*." Each role contributes to the fulfilment of, a part of, the requirements of the organization within which it is defined. Roles describe groups of actors that have similar functionality, rights and capabilities from the perspective of the organization. Every agent is able to play a role inside the group of an organization. The organizational-based modeling allows the scenarios to be defined in a structured way. It provides the ability to determine where the relationships between agents exist and how these relationships influence the results (Cossentino *et al.*, 2010).

The main objective of our research is to generalize the concept of **multi-zonal interaction in the carpooling social network**, in which individuals are working in a particular TAZ and living in spatially dispersed zones. The *carpooling social network* is made up of nodes representing individuals and social links between them. The individual (or agent) is someone who lives in the study area and executes his/her daily schedule in order to satisfy his/her requirements. A daily schedule is a combination of activities and trips with a specified start time and duration of each activity and trip. The commuting trips (home-to-work *HW* and work-to-home *WH*) in daily schedules are detailed and discussed related to long term carpooling. Agents' communication, negotiation and coordination in a multiple trips negotiation model are investigated; this is done while taking into account the constraints induced by flexible activity scheduling.

This section presents the design of the organization-based model for our carpooling problem (Fig. 1), and the related agent-based simulation model. This section is divided into two main parts. The *problem domain* and the *agent domain (solution domain)* have been defined in the ASPECS methodology (Cossentino et *al.*, 2010). The *problem domain* section focuses on the organizations of the long-term carpooling system and the activities in terms of role behaviors of the individual in this context. The organization layer of the proposed model and the multiple trips negotiation model (on trip start times and on the driver selection) is also presented in the *problem domain* section. The *agent domain* section presents the *agent layer* of our organizational model. The agent's behavior is also modelled and discussed in detail. Subsequently, the design of *day switching mechanism* is revealed.

3.1. The problem domain

The conceptual model for long-term carpooling is illustrated in Fig. 2. An individual can perform the following activities throughout his/her carpooling process namely: (i) decision to carpool, (ii) communication and exploration, (iii) negotiation, (iv) coordination and schedule adaptation, (v) long term trip execution (carpooling), (vi) negotiation during carpooling and (vii) carpool termination. In what follows, each of these steps is described in more detail. Note that candidates for carpooling can find partners while still driving solo and can be invited by other ones while they are already participating in a carpool.

3.1.1. Decision to carpool

In this step, participants decide to carpool and determine their trips and schedule for long-term carpooling. It may be difficult to find an ideal carpool partner from a large space (*carpooling social network*). The *carpooling social network* can be subdivided into disconnected components, so that each one of which corresponds to a carpooling social group. They can be formed by considering similar characteristics (e.g. similar work TAZ) of the individuals. Sets of individuals who are working in a particular TAZ and living in spatially dispersed zones are considered. Within these carpooling social groups, individuals can communicate and negotiate on trips (*HW* and *WH*), start times, vehicle and driver selection. We assume that, if individuals share features, such as job, age and education, identical or overlapping routes to the destination TAZ, then they are sufficiently similar to successfully negotiate.

The organization concept is used to model *carpooling social groups* (CPSG) to limit the communication requirements. According to our

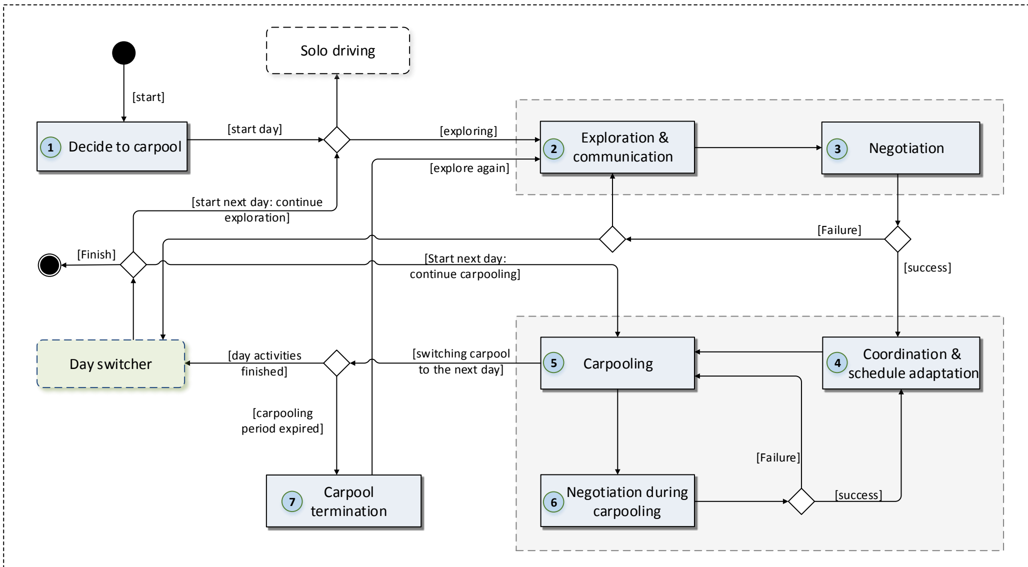

Figure 2. Activity-diagram of the behavior of a carpooling individual.

organizational approach, the individuals who are negotiating together are members of the same organization ‘‘*CPSocialOrganization*’’ (see Fig. 3). Immediately after the individual created or joined an instance (CPSG) of “*CPSocialOrganization*”, (s)he starts playing the role (*InteractionRole*) in that CPSG. The individuals can communicate, negotiate and coordinate with each other in order to determine effective trip start times (for both morning and evening) and to agree who will be the driver.

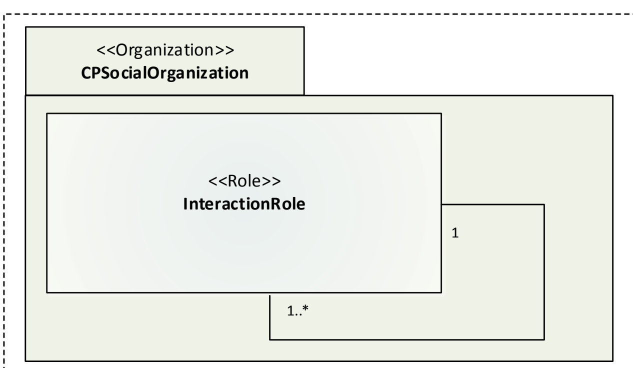

Figure 3. The individuals are negotiating together, are member of the organization *(CPSocialOrganization)* by playing *InteractionRole*.

3.1.2. Exploration and communication

In this step, each individual looks for other individuals to cooperate while executing their periodic trips by exploring the CPSG (carpooling social group) of the *carpooling social network*. The individual may continue driving solo in the exploration phase throughout the period (in case (s)he is unable to find a carpool partner). In this carpooling model, the individual can interact with each other by sending and receiving messages. The relationship information of the carpoolers provides *the path*, *profile* and *the time interval* similarity values. In general, each individual has a basic set of public characteristics such as common interests and requirements. In order to interact, the common interests and requirements for the respective individuals need to match sufficiently well. In this model, they are conveyed by means of a parameter *probabilityToInvite* (the probability value to invite someone for carpooling, specified by a parameter):

$$probabilityToInvite = f(\{interests, requirements\})$$

Common interest includes intention to carpool, subjects for conversations etc. and *Requirements* include the traveling route, time, origin and destination TAZ and the traveling cost.

Each participant (*sender*) may search for a partner (*receiver*) by sending a carpool invitation. The both participants must belong to the same *carpooling social group*. The emission of the invitations depends on the given *probabilityToInvite* parameter. An individual can explore social network for multiple times in a day. The receiver individual accepts the sender as a carpooling partner after reviewing his/her profile. During carpooling, the carpoolers (either driver or the passengers) can receive additional invitations to carpool which they accept or reject depending on the car capacity and on the negotiation outcome for the extended group candidates.

3.1.3. Negotiation

The outcome of the negotiation is simulated by finding the optimal solution that meets the conditions stated by the candidate participants. The final decision to carpool is revealed in the negotiation phase where the participants negotiate on trips (*HW* and *WH*) departure times and also on the vehicle and driver selection. We assume that the vehicle owner is the driver. Constraints induced by a flexible activity scheduling are taken into account. For the trips starting in a specific TAZ, the intersection of time intervals for the respective participants is considered. Every individual owning a vehicle and driving-license can act as the driver. Participants can join the carpool for a given trip in several sequence orders. Such order is valid if and only if the first participant can act as a driver. Every valid pick-up order of participants is evaluated (which is computationally feasible since the car capacity is small) using personal preferences. Details are described in the following subsections.

3.1.3.1. Lower and upper bounds for trip timing

In the simplest case, the individual is assumed to accept a symmetric deviation $\pm\Delta T$ w.r.t. the preferred trip start times. In general, activities

Table 1. The symbols used and their meanings.

Symbols	Meanings
$\boldsymbol{N}$	set of all individuals or agents
$\boldsymbol{a_i}$	represent an individual or agent, $a_i \in N$
$\boldsymbol{T^b_{a_i}, T^e_{a_i}}$	earliest and latest possible departure time for both trips of an agent a_i
$\boldsymbol{T^b_{HW,a_i}\ T^e_{HW,a_i}}$	earliest and latest possible departure time for *HW* trip
$\boldsymbol{T^b_{WH,a_i}\ T^e_{WH,a_i}}$	earliest and latest possible departure time for *WH* trip
$\boldsymbol{t_{a_i}}$	The preferred trip start time
$\boldsymbol{t_{HW,a_i}, t_{WH,a_i}}$	The preferred trip start time for *HW* and *WH*.
$\boldsymbol{\pm\Delta T}$	a symmetric deviation of time window *T* w.r.t. the preferred trip start times of an a_i.
$\boldsymbol{\overline{\Delta T}}$	is the tolerance period before HW or after WH trips
$\boldsymbol{C}$	represents the constraining activity (e. g. pick-drop or shopping)
$\boldsymbol{C_{finTime,a_i}}$	Finishing time (including trip and activity) of *C*
$\boldsymbol{C_{startTime,a_i}}$	Start time of *C* of an a_i.
$\boldsymbol{L}$	Set of all locations (TAZ)
$\boldsymbol{l_i}$	Specific TAZ location, $l_i \in L$
$\boldsymbol{T_{carpool,\,l_N}}$	the arrival time window at the work zone.
$\boldsymbol{T_{carpool,l}}$	the carpool time window for the *l*.
$\boldsymbol{d_{l_i}}$	the duration to drive from the l_i to the destination.
$\boldsymbol{T_{a_i,l_i}}$	time window of agent at specified l_i
$\boldsymbol{T^e_{carpool,\,l_k}}$	the start of the feasible time window (lower bound) for the carpool at l_k
$\boldsymbol{T^b_{carpool,\,l_k}}$	the end of the feasible time window (upper bound) for the carpool l_k
$\boldsymbol{t_0}$	denotes the trip start time in the l_0.

preceding or succeeding the home work commuting can induce timing constraints which leads to asymmetric cases.

Assume that a constraining activity C immediately precedes the HW trip or succeeds the WH trip. The lower and upper bounds of the trips (HW and WH) can be determined by considering cases (Fig. 4):

1. The possible lower and upper bounds for the preferences of a_i for both the trips (HW and WH) without any constraining activities are given by the Eq. (1).

$$T^b_{a_i} = t_{a_i} - \Delta T \qquad T^e_{a_i} = t_{a_i} + \Delta T \tag{1}$$

2. The Eq. (2) helps to determine the lower and upper limits of the departure time window for the HW trip of a_i who has certain fixed constraining activities before the morning trip. Here $\overline{\Delta T}$ is the tolerance period before the HW trip.

$$\overline{\Delta T} = t_{HW,a_i} - C_{finTime,a_i} \qquad T^b_{HW,a_i} = t_{HW,a_i} - \overline{\Delta T} \qquad T^e_{HW,a_i} = t_{HW,a_i} + \Delta T \tag{2}$$

3. When there is a constraining activity scheduled immediately after the work activity at the work zone, then the lower bound for the WH trip departure time for a_i will be the $C_{finTime,a_i}$ as in Eq. (3).

$$T^b_{WH,a_i} = C_{finTime,a_i} \qquad T^e_{WH,a_i} = t_{WH,a_i} + \Delta T \tag{3}$$

4. When the constraining activity scheduled after work activity at any other TAZ different from the work zone and if timely arrival is compulsory for that activity, then the upper bound of time window for a_i will depend on the $C_{startTime,a_i}$ as in Eq. (4). Here $\overline{\Delta T}$ is during the WH trip.

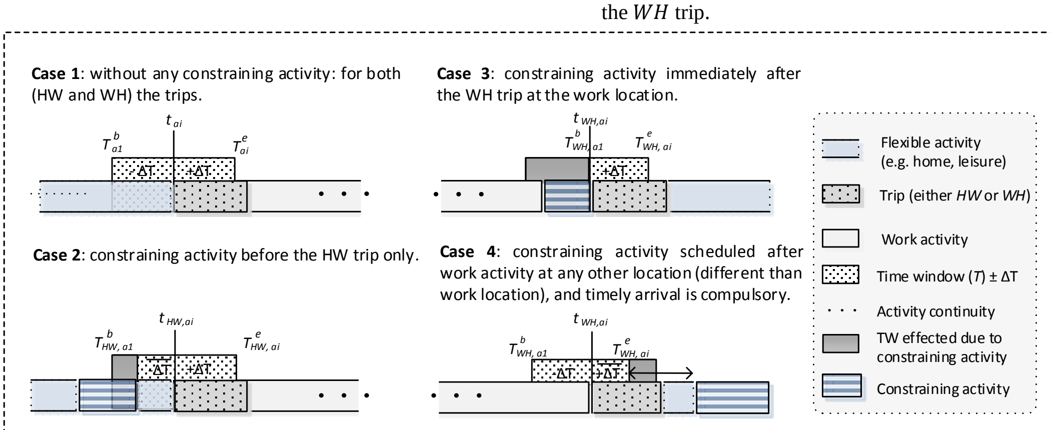

Figure 4. The effect of constraining activities on carpooling trips (*HW* and *WH*).

$$\overline{\Delta T} = C_{startTime,a_i} - t_{WH,a_i}$$
$$T^{b}_{WH,a_i} = t_{WH,a_i} - \Delta T \qquad (2)$$
$$T^{e}_{WH,a_i} = t_{WH,a_i} + \overline{\Delta T}$$

Both negotiated trip start time shall be in the intersection of the respective *HW* and *WH* time intervals of the individuals in the specific TAZ.

3.1.3.2. Driver assignment, pickup order and time intervals

The driver in the carpool needs to pick up every carpooler at home. Since the carpool capacity is limited (usually, 4 or 5 persons), it is feasible to check every permutation of the candidate participants. The first participant in the permutation shall be the driver. Hence permutations, where the first participant cannot act as the driver are infeasible. They can be dropped immediately. For the valid cases, the order of participants in the permutation defines the pick-up order in HW trip and the drop-off order in WH trip. The HW trip case is described below (see Fig. 5); and the WH case is similar.

The arrival time window of carpooling participants at destination zone (work zone) is $T_{carpool,\,l_N}$. It is the intersection of the arrival time windows for the respective participants. The $T_{carpool,l}$ for TAZ location l is calculated in reverse TAZ visit order. The $T_{carpool,l}$ for l follows from the one for $l+1$ by subtracting the expected travel time and calculating the intersection with the time window specified by the participants to be picked up at l (Eq. (5)). The circled minus applied to a time window and a scalar, denotes a time window shift.

$$T_{carpool,l_i} = (T_{carpool,l_i+1} \ominus d_{l_i+1}) \cap T_{a_i,l_i} \qquad (5)$$

When for some l_i, if the time window $T_{carpool,l_i}$ of the negotiators is empty (time windows do not intersect) then the case is infeasible and the negotiation on the trip start time is failed.

$$\forall_l : \begin{array}{ll} T_{carpool,l_i} = 0 & \text{infeasible case} \\ T_{carpool,l_i} \neq 0 & \text{feasible case} \end{array} \qquad (6)$$

If the case is feasible it is considered as a candidate solution. The set of candidates exhibiting the lowest travel time is kept. The shortest trip and all trips for which the duration does not exceed the shortest value plus a given tolerance Δdur are kept in the set. Finally the quality score specified by Eq. (7) are calculated for each candidate. The score represents the minimum value (computed over all locations) for the valid trip start time interval length: this is a measure for the degree of freedom for the departure time at each location and hence for the ability to meet the schedule (because travel times might be uncertain). The candidate delivering the highest score is kept. Finally, the trip start time (discussed in sub-section 3.1.3.3) is determined.

$$score = \min_{k=1\ldots N} (T^{e}_{carpool,\,l_k} - T^{b}_{carpool,\,l_k}) \qquad (7)$$

3.1.3.3. Trip start time determination

In this paper, every moment (the intervals between lower and upper bounds) in the time windows specified by the candidates is assumed to be equivalent: i.e. the *start time preference function* is assumed to be constant and identical for each participant over the time. The trip start time is calculated as follows.

Let d_k denote the duration to drive from TAZ l_{k-1} to TAZ l_k. Then the start time at l_k is given by $t_0 + \sum_{i=1}^{k} d_k$. For each TAZ the start time needs to be in the feasible time window. Hence at the l_k:

$$T_{carpool,\,l_k} = T_{carpool,\,l_0} \oplus \sum_{i=1}^{k} d_i \qquad (8)$$

The arrival time window of the carpool is:

$$T_{carpool,\,l_N} = T_{carpool,\,l_0} \oplus \sum_{i=1}^{N} d_i \qquad (9)$$

The lower bound of the time window shall be less than the sum of the durations to the trips start time at the specific l_k.

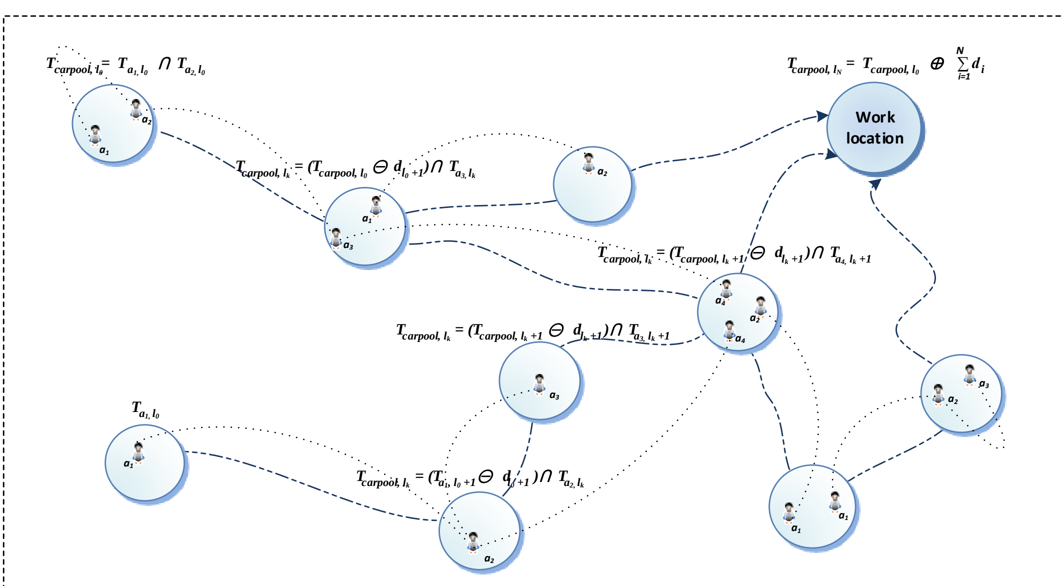

Figure 5. The driver assignment, pickup order and time intervals at each TAZ (where the driver can visit).

$$\forall_k:\ T^{b}_{carpool,\, l_k} \leq \ \ t_k = \ t_0 + \sum_{i=1}^{k} d_i \tag{10}$$

$$\forall_k:\ T^{b}_{carpool,\, l_k} - \sum_{i=1}^{k} d_i \leq \ t_0 \tag{11}$$

For the upper bound of the time window one finds

$$\forall_k:\ \ t_0 \ + \sum_{i=1}^{k} d_i \ \leq \ \ T^{e}_{carpool,\, l_k} \tag{12}$$

$$\forall_k:\ t_0 \leq \ T^{e}_{carpool,\, l_k} - \sum_{i=1}^{k} d_i \tag{13}$$

The lower and upper bounds at TAZ l_k are shown in Eq. (14) and Eq. (15).

$$T^{b}_{carpool,\, l_k} = \ \max_{j=1\ldots N} (T^{b}_{a_i,\, l_k} - \sum_{i=1}^{k} d_i) \tag{14}$$

$$T^{e}_{carpool,\, l_k} = \ \min_{j=1\ldots N} (T^{e}_{a_i,\, l_k} - \sum_{i=1}^{k} d_i) \tag{15}$$

The trip start time t_0 at TAZ l_0 can be in between the lower and upper bounds of the time window is given by Eq. (16).

$$T^{b}_{carpool,\, l_0} \leq \ \ t_0 \ \leq T^{e}_{carpool,\, l_0} \tag{16}$$

Similarly, trip start time t_k for each of the l_k can be:

$$\forall_k\ :\ T^{b}_{carpool,\, l_k} \leq \ \ t_k \ \leq T^{e}_{carpool,\, l_k} \tag{17}$$

We assume that the feasible trip start time at specific TAZ is at the middle of the time intervals because it results in largest safety:

$$t_k = (T^{b}_{carpool,\, l_k} + T^{e}_{carpool,\, l_k})/2 \tag{18}$$

When the negotiation becomes successful, the participants may coordinate and dynamically adapt their daily schedule in step 4 (*coordination and schedule adaptation*). Otherwise, the negotiation has failed, and they should continue to explore for carpool partners in step 2 (*exploration and communication*).

3.1.4. Coordination and schedule adaptation

When the negotiation is successful according to the negotiation model discussed in this *section 3.1.3*, a carpooling group "*CarpoolGroups*" of the carpooling organization ''*CarpoolOrganization''* is created (see Fig. 6). The carpoolers becomes members of this group by playing their respective roles: the driver plays the driving role (*DrivingRole*), and the passengers play the passenger role (*PassengerRole*).

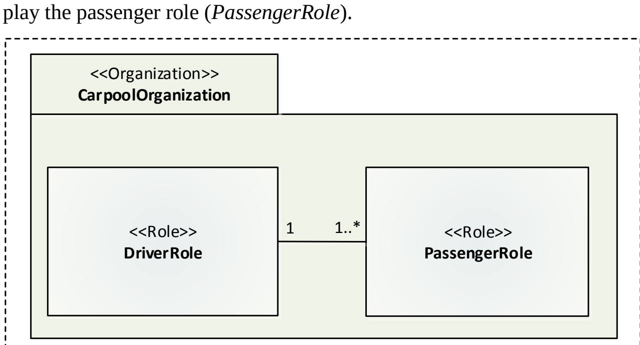

Figure 6. The carpoolers are members of "*CarpoolOrganization*" by playing either *driver* or *passenger* role in the *carpool* group.

In general, during this step, the carpoolers agree on pick-up times and place, pick-up and drop-off order, trip start times (for HW and WH) of the carpool taking into account the constraints imposed by their agenda. At negotiation time, each individual specifies the period (number of days) during which to carpool for the trip. After the '*negotiation during carpooling* step, the carpoolers need to update the "*CarpoolGroup*" information again by adapting their daily schedule. Normally this occurs when someone wants to join or leave the "*CarpoolGroup*" permanently. When it appends the negotiation procedure described above is executed again as long as there are at least two participants, and one of them can act as a driver. This leads to a new trip (TAZ visit sequence) and timing.

3.1.5. Trip execution (carpooling)

The carpooling activity corresponds to the execution of the trips (*HW* and *WH*) over multiple days. The individuals' daily schedule of a working day remains the same for all working days. The model assumes that travel times are insensitive to the level of carpooling (i.e. carpooling does not significantly decrease congestion). Travel times between TAZ have been computed a priori. The associated expected travel times between TAZ for the morning peak period are used. This is to be refined by making the negotiation aware of travel time.

3.1.6. Additional negotiation during carpooling

During the carpool life time, the carpoolers need to negotiate again when someone wants to join or decides to leave the carpool. Each carpooler (either *driver* or *passenger*) can receive carpool invitations to carpool from solo drivers. Each such invitation leads to re-negotiation (same as the initial negotiation discussed before) which results in either accepting or rejecting the candidate

When changes in the carpool occur, the carpoolers adapt their schedule, update the carpool settings in *step 4* and continue carpooling.

3.1.7. Carpool termination

Each participant (drivers or passenger) leaves the *carpool* at the end of the individual specific participation period. A "*CarpoolGroup*" is terminated if only one individual is left or if no persons with a car and a driving license are available. After each change in the carpool composition, the remaining members re-negotiate. As soon as an individual leaves the carpool, (s)he immediately starts exploring CPSG of the *carpooling social network* in *step 2* of the carpooling model to find a new carpool.

3.2. The agent domain (or solution domain)

According to (Cossentino *et al.,* 2010), the agent domain is dedicated to the design of an agent-oriented model (see class-diagram in Fig. 7) that is a solution to the model described in the problem domain. The steps for designing our agent-based simulation model for the carpooling are: (1) agent identification, (2) agents' grouping (the instantiation of organizations and roles) (3) agents' behaviour modelling, (4) integrating agents in a certain environment and (5) establishing connections between them.

3.2.1. Agent's general behavior

Agents represent people in the population whose personal characteristics and social relationships are programmed at the discrete level. Agents are autonomous, meaning that they can each act independently. A group, used for partitioning organizations, is an organizational entity in which all members are able to interact according to predefined interaction definitions and protocols. Groups are used to refer collectively to a set of roles and to specify shared norms for the roles in the group.

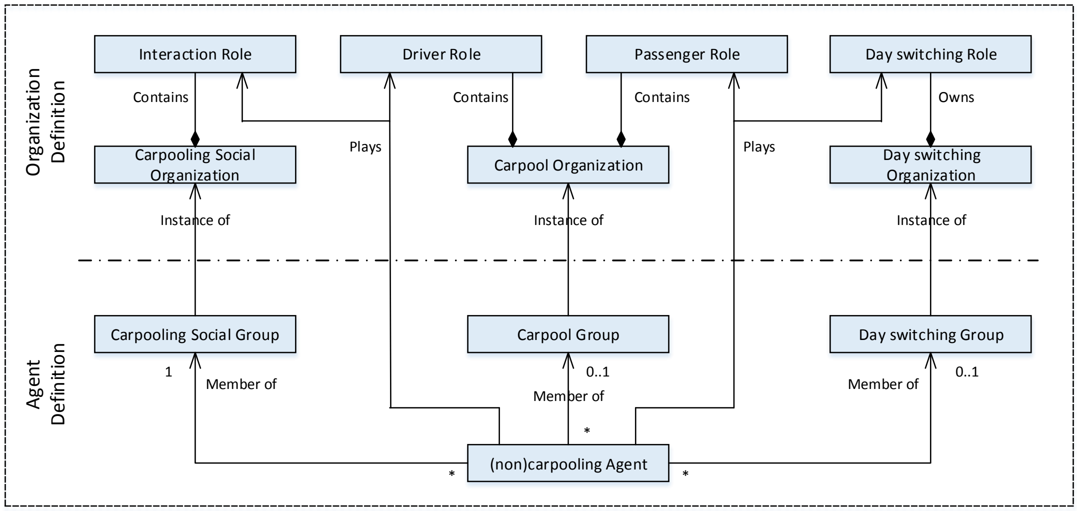

Figure 8. Class-diagram of our organizational model that is mapped to the agent-oriented model for long-term carpooling.

In our simulation model, the agent environment* is established as the spatiotemporal aggregate where the agents live and conduct their own daily schedule. Fig. 8 shows the activities performed by each agent during the carpooling process in the agent-oriented simulation. The simulation launches each agent, with their profile, according to data generated by the FEATHERS framework (Bellemans *et al.*, 2010). The OD travel time matrix for the Flanders region is also loaded. The agent's behaviour is modelled by a hierarchical finite state-machine composed of two states: GROUPING and RUNNING (see Fig. 9 (a)).

3.2.1.1. GROUPING state

In this state, the agent becomes member of a group determined by its destination *TAZ* in order to limit the communication requirements. Each agent once in its lifetime creates or joins such group (*CPSG*) which is an instance of the given organization (*CPSocialOrganization*). As the agent joins a *CPSG*, it starts playing the role (*InteractionRole*) in that group. The simulator contains at most one CPSG for each *TAZ* (only *TAZ* containing work *TAZ* are relevant).

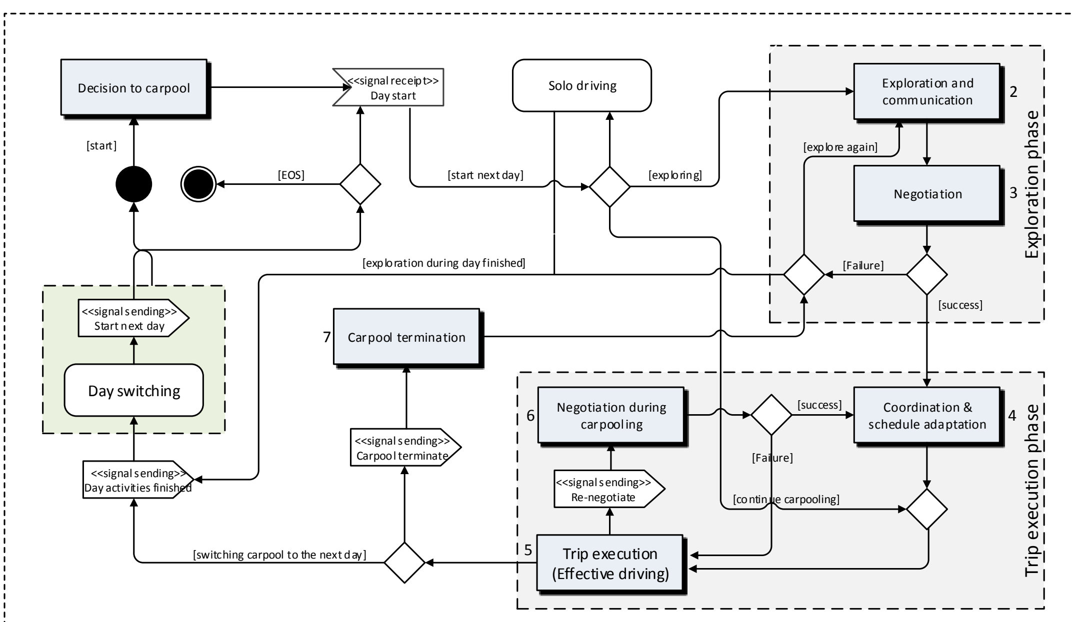

Figure 7. Activity-diagram of an agent of the carpooling process in the agent-based simulation model. It refines the behavior defined in the problem domain (see Fig. 2).

* Agent Environment: First-class abstraction of a part of the system that contains all non-agent elements of a multiagent system. It provides the surrounding conditions for agents to exist. And, it is an exploitable design abstraction to build MAS applications (Weyns et *al.*, 2005).

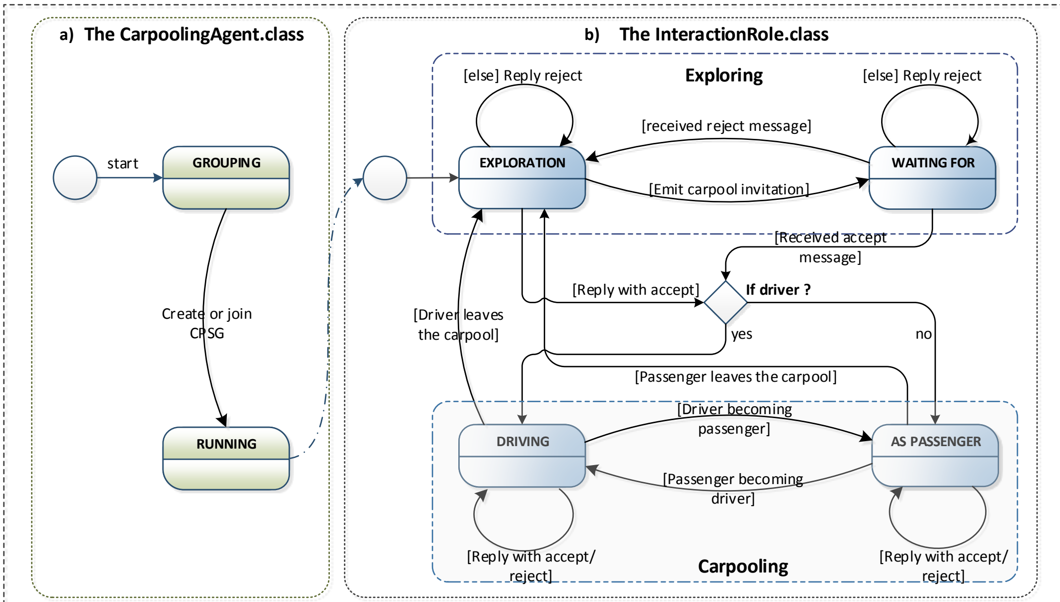

Figure 9. Agent's state machines: (a) the state-transition machine in agent's class, (2) state-transition machine in interaction role class of the *CPSocialOrganization*.

The *GROUPING* state is transitional: the agent moves to the *RUNNING* state as soon as it became a member of the group. Note that all agents having same *work location TAZ*, must join to the same *CPSG*. The pseudocode in Algorithm 1 shows, how each agent creates or joins *CPSG* and starts the role *(InteractionRole)* using the organization *(CPSocialOrganization)*.

Input: destTAZ;
Output: agent starts playing interaction role in CPSG
Begin

```
  gName ¬ "group" + destTAZ;
  if CPSG Exists ≠ null AND found CPSG
     groupAddr ¬ getExistingGroup(CPSocialOrg.class, gName);
   else
     groupAddr ¬ createGroup(CPSocialOrg.class, gName);
   end
  requestRole(InteractionRole.class, groupAddr);
End
```

Algorithm 1: Each agent creates or joins CPSG using *CPSocialOrg.class* and starts the role *InteractionRole.class*.

3.2.1.2. RUNNING state

In this state, the agent wants to carpool. It is playing the *InteractionRole* in the CPSG. It will remain in this state throughout the simulation period. When the agent is in the *RUNNING* state, it is executing a sub-state-machine that is described in the next section.

3.2.2. Agents interaction in "CPSG"

A finite state-machine is used to describe the interaction status of each agent. Each agent can send and receive messages to/from the other agents in the same *CPSG*. Negotiation to carpool is based on those messages. For every simulated day, emission of carpooling invitations depends on the given *probabilityToInvite* parameter. The value for *probabilityToInvite* is given (e.g. *probabilityToInvite = 0.9*). Following messages are used for interaction: *CarpoolInvitationMessage*, *AcceptMessage* and *RejectMessage*.

The state machine is shown in the right hand part of Fig. 9 (b) and the states are discussed below.

3.2.2.1. EXPLORATION state

In the *EXPLORATION* state, each agent (*sender*) may search for a partner (*receiver*) by sending a *CarpoolInvitationMessage* and sharing its daily agenda with a randomly chosen agent of the *CPSG*. As soon as an invitation has been emitted, the *sender* enters the *WAITING FOR* state, waiting for the receiver's response.

While in the *EXPLORATION* state the agent can receive a *CarpoolInvitationMessage* and reply with either an *AcceptMessage* or *RejectMessage* depending on the negotiation outcome. After the successful negotiation, the invited agent (*receiver*), creates an instance (*CarpoolGroup*) of the *CarpoolOrganization*. Depending on the outcome of a successful negotiation each participant registers either as a *driver* or as a *passenger* and starts playing the appropriate role (either *DriverRole* or *PassengerRole*).

This agent may remain in the *EXPLORATION* state throughout the simulation period in case (s)he is unable to find a carpool partner. An agent can explore CPSG more than once, by sending multiple *CarpoolInvitationMessage* sequentially and switch multiple times between *EXPLORATION* and *WAITING FOR* states within a day. A parameter *noOfExplorationsPerDay* is used to limit the number of carpool invitations emitted during a particular day.

3.2.2.2. WAITING FOR state

In the *WAITING FOR* state, as soon as an *AcceptMessage* is received the *sender* tries to join the *CarpoolGroup*, the *invited receiver* belongs to. The *AcceptMessage* specifies the role (*DriverRole* or *PassengerRole*) to play since that follows from the negotiation. The agent leaves the *WAITING FOR* state, joins the *CarpoolGroup* and starts playing the negotiated role (either *DriverRole* or *PassengerRole*).

If the response is a *RejectMessage*, the *inviting agent* changes its state to *EXPLORATION* again in order to try to find a partner.

While in the *WAITING FOR* state, the agent rejects any incoming invitation (simply by replying with a *RejectMessage*).

3.2.2.3. DRIVING state

In the *DRIVING* state the agent plays the *DriverRole* in the *CarpoolGroup*. The actual trip and associated pick-drop of passengers is not simulated. It can receive *CarpoolInvitationMessage* which triggers a new negotiation. If the negotiation succeeds and the *requester (sender agent)* is selected as driver, the existing driver must leave the *DriverRole* and starts as *PassengerRole* in the same *CarpoolGroup*. In this case, it will immediately change its state to *AS PASSENGER* state.

As soon as the carpool period for the driver expires, it will leave its *DriverRole* and change its state to *EXPLORATION*. If the *CarpoolGroup* size still exceeds one, the remaining agents will re-negotiate and select the driver. In case passengers leave the *CarpoolGroup* and the driver is the only one left. it leaves the *DriverRole*, destroy the *CarpoolGroup* and will change its state to *EXPLORATION*. In the *EXPLORATION* state, it may search again for a partner or continues driving solo.

3.2.2.4. AS PASSENGER state

The agent behavior w.r.t. carpool membership and negotiation while being in the AS *PASSENGER* state, is identical to the one in the *DRIVING* state. Except, when the *driver's* carpooling period expired and left the *CarpoolGroup*. The remaining passengers (if more than one) re-negotiate to select a driver. The selected driver will continue carpooling by starting *DriverRole* and by leaving the *PassengerRole* of the same *CarpoolGroup*.

3.2.3. Agents in CarpoolGroup

During carpooling, the agents (carpoolers) are members of a *CarpoolGroup* (instance of a *CarpoolOrganization*). The carpooling activity corresponds to the execution of the trips (*HW* and *WH*) over multiple days. Each agent checks expiration of its carpooling period daily.

3.2.4. "Day switching" mechanism

Since carpool membership periods and limits on the number of explorations during a simulated day are involved, progress of simulated time needs to be kept track of. Synchronizing simulated time in general is a complex problem. In this application synchronization using a time resolution of one day is sufficient. The agent activities relevant in this simulation context and lasting for a non-zero amount of simulated time are *exploring* and *carpooling*. Since the focus of the research is on the interaction for negotiation, the actual carpooling activity has no implementation and carpooling agents are simply moved to the *end-of-day* state. Exploring agents emit invitations and process responses. Their day ends after they are accepted as a carpool member of have emitted (but not necessarily received a response) the maximum number of invitations. As soon as the agent finishes its daily activities, it needs to join a *DaySwitchingGroup* (instance of *DaySwitchingOrganization*). If no such already exists, the first agent who needs to join creates the group and joins it. Every agent joining such group immediately starts playing the *DaySwitchingRole* in that group. It will wait for other agents to finish their daily activities and to join the *DaySwitchingGroup*. This mechanism is required to introduce the notion of coordinated time among agents. In this case the organizational-based concept is used solely for synchronization in simulated time.

As soon as the last agent joins the *DaySwitchingGroup*, it will signal all other agents to leave the group and in turn immediately leaves the *DaySwitchingGroup*. Note that one group is created for each simulated day. The step is repeating over and over up to end of the simulation period.

4. Simulation Experiment and Discussion

For giving a proof-of-concept of our agent-based simulation model, experiments were conducted at the scale of the Flanders region (Belgium). In this section, the input data are presented. The experiment scenario, and the result are discussed.

4.1.1. Population generation

In our model, the carpooling social network was established by generating a population using results predicted by FEATHERS operational activity-based traffic demand model for Flanders (Belgium) described in Bellemans *et al.*, 2010. It is used to generate the agenda (daily schedule) for each member of the synthetic population for a period of 24 h. The modeling structure claims that individuals spend the day taking part in activities and traveling between activities. The initial daily plans are assumed to be optimal, i.e. generating maximal utility and hence to reflect the owner's preferences. A daily schedule is a combination of activities and trips with a specified start time and duration of each activity and trip. The commuting trips (home-to-work *HW* and work-to-home *WH*) in daily schedules are detailed and discussed in relation to long term carpooling. The set of other activities including pick-drop, shopping etc. is also considered because they can induce timing constraints to trips commuting trips. Home and work TAZ trip start times for both trips (*HW* and *WH*) and their durations, activity duration, the socio-economic attributes, including vehicle and driving-license ownership are used as individual's profile. The framework is based on traffic flows between traffic analysis zones (TAZ). It is assumed that people board and alight at home and at work TAZ only.

4.1.2. OD based travel times

For this simulation a pre-calculated TAZ-based travel time matrix applying to peak periods for the Flanders region is used (because home-work commuting is studied). Those expected travel times estimate the durations of the trips. The success of negotiation may results in reconsideration of departure and arrival times for planned trips.

4.1.3. Simulation Scenario

There are about six million inhabitants in the Flanders region. The area is subdivided into *2386* zones. People working in the zone they live are not considered to be carpooling candidates since a zone covers $5[km^2]$ only.

4.1.4. Results and Discussion

One of the goals of our experiment is to compute the execution time of the agent-based interactions and to discover whether optimization is required when we want to restate reality and accurately predict carpooling negotiation outcome for the complete Flemish population. Fig. 10 shows the average computation time of the simulation for the number of days, on an Intel ® Xeon® CPU E5-2643 v2 @3.50GHz 3.50 GHz (2 processors), with 128GB RAM and 64 bits operating system. The benchmark is done by taking different amounts of agents as: *10, 20, 40, 80, 160, 320, 640, 1280, 2560, 5120, 10240, 20480, 40960, 81920* and *163840*. The simulation was run for *1* day, *5* days and *10* days only and used a time window of *30* minutes (constant). Each non-carpooling agent has a probability *100%* to

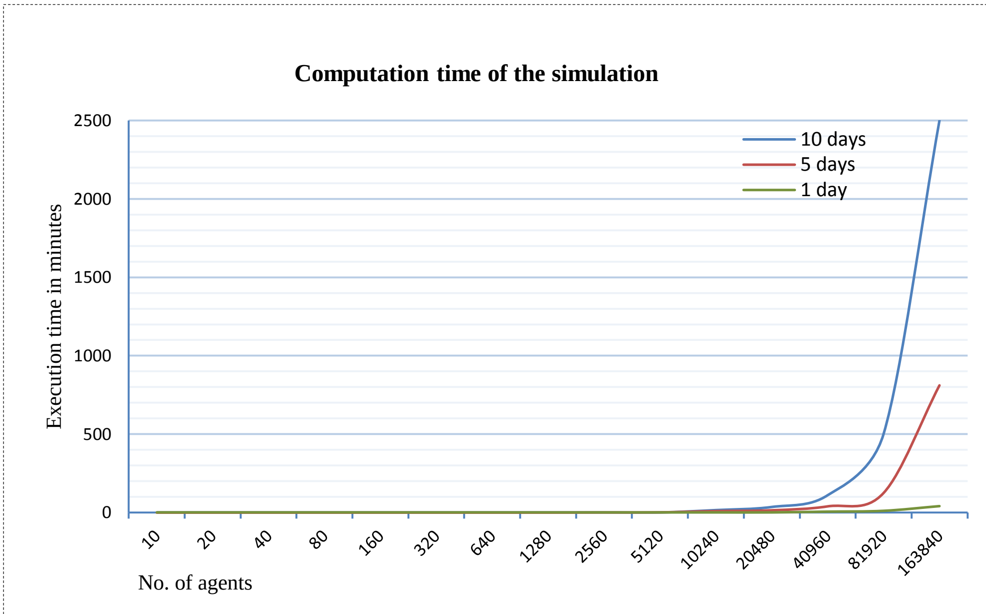

Figure 10. Computation time in minutes by running different amount of agents.

invite someone to carpool every day. An agent emits at most *10* carpool invitations and can receive *10* invitations from the other agents during each simulated day (each agent executes at most *20* times a day). The graph shows that the processing time increases exponentially with the number of agents to simulate.

For the experiments, to analyse the behavior of the carpoolers, data of the first *20,000* individuals from a set of TAZ (representing roughly half of a province in Flanders) is used. An exploring individual is allowed to contact at most 10 other people during every simulated day. If the *ProbabilityToInvite* is 100% then (s)he must send carpooling requests. Otherwise, (s)he can decide not to emit any request. A carpooler determines the number of working days to carpool by selecting a number in the [30 to 60] by sampling from a uniform distribution. Four people at most can share a car (driver included). The trip timings of the agents are constrained by other activities (e.g. pick-drop, shopping). Individuals can adapt the trip start time within specific time windows. Time windows of *10[min]*, *15[min]*, *20[min]*, *25[min]* and *30[min]* were used.

The graph in Fig. 11 shows the number of active carpoolers throughout the simulation period. The horizontal axis shows the working days and the vertical axis represents the number of active carpool groups for each day. It is observed that on average, a larger time tolerance window allows for more carpooling. For each time window, the number of active carpoolers rapidly increases at the start of the simulation up to about *30* days since the shortest possible carpooling period lasts for 30 days. After *30* days, the increase rate

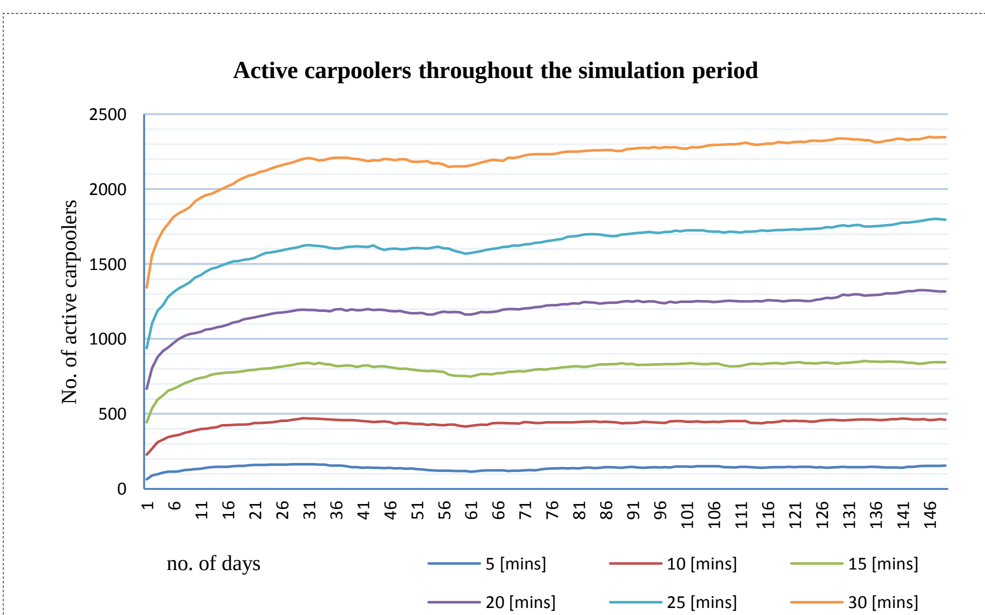

Figure 11. Number of active carpoolers for different time windows throughout the simulation period.

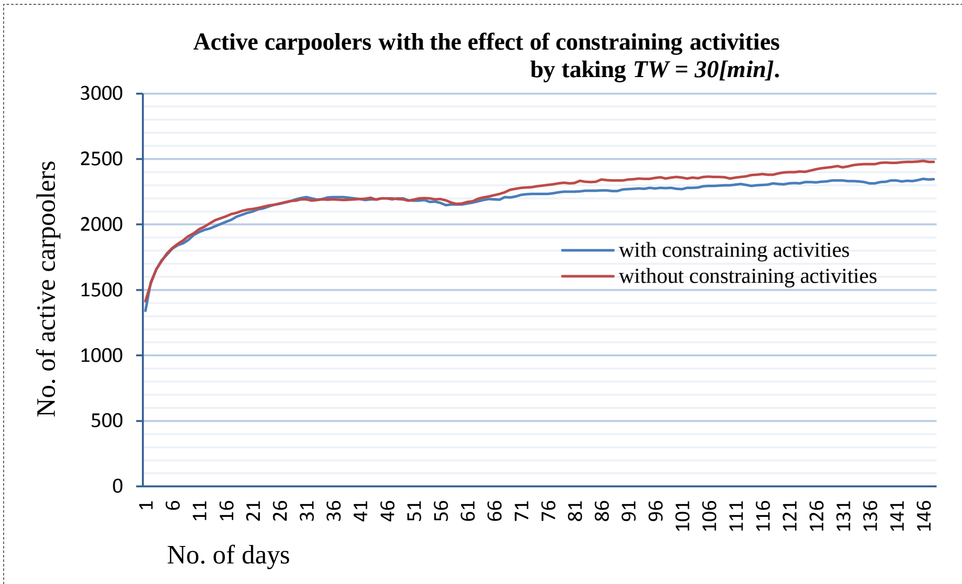

Figure 12. Number of active carpoolers with and without constraining activities.

is lower because joining and leaving carpools respectively cancel out. The share of carpooling individuals seems to have converged after *100* simulated working days except for the larger time windows case. The results show that when the time window is larger, the chances for negotiation success are greater than when using the smaller time window.

Fig. 12 shows the effect of constraining activities. All individuals used a *30[min]* time window for the trip start times. In the FEATHERS schedules 5% of the individuals have a *pick/drop* activity immediately preceding the commuting trips (*HW* and/or *WH*). Furthermore, 7% of the individuals are constrained in a similar way by a *shopping* activity. The graph shows that the constraining activities reduce the probability for negotiation success. The number of carpooling participants continue to increase up to the end of the simulation period in the both cases (constraining and without constraining activities).

Following conclusions are drawn: (1) the presented simulation needs a lot of computing resources (e.g. CPU time, memory, and data storage) because of the big data processing for each agent, (2) when the time window is larger, the chances for negotiation success are greater, and (3) the constraining activities limit the chances for the negotiation success.

The simulation model has scalability issues that are still to be solved. Indeed, it is necessary to consider a sufficiently large region and accurate input data to evaluate the carpooling process. In the future, apart from scalability issues, mainly focus on the effect of schedule adaptation and enhancing the mechanisms for communication and negotiation between agents.

5. Conclusion and Future Work

An agent-based framework for long term carpooling using the CRIO organizational meta-model has been setup to simulate the emergence of carpooling under several conditions. The model aims to analyze various effects of agent interaction and behavior adaptation. This paper covers the concept of communication, negotiation and coordination for the long term carpooling of a multiple trip model and takes the possibility of flexible activity scheduling into account. The agents negotiate on trip (*HW* and *WH*) departure times and on the driver assignment within the carpool group. During the negotiation process the agents may adapt their daily schedules to enable cooperation. Individuals living in different TAZ and heading to the same work area are allowed to negotiate for carpooling. The experiments try to limit the amount of communication between agents by establishing groups based on the same work TAZ. The data used for implementation have been created by the FEATHERS activity-based model for the Flanders region. Pre-computed expected travel times between TAZ for the peak period are used. From the discussions, it is possible to determine an upper bound for the market share of carpooling in a given region. The simulation provides an efficient solution to a complex problem but needs a lot of computing resources (e.g. CPU execution time, memory consumption and data storage) because of the high number of agents to simulate, and the big data processing for each agent. In addition to the conclusions related to the carpooling application, we consider that organizational and agent-based approaches are relevant for designing a model of a long-term carpooling system. Indeed, the organizational approach enables to break-down the design complexity of such as system. The agent-based model focuses on the mapping between the agents and the roles they are playing in the system. Finally, the Janus platform, which is implementing the organizational and agent-based concepts, provides an efficient tool for conducting simulation experiments.

The simulation model requires a large amount of accurate input data, and has scalability issues that are still to be solved. Indeed, it is necessary to consider a sufficiently large region to evaluate the carpooling process. Apart from scalability issues, future research will mainly focus on the effect of schedule adaptation and enhancing the mechanisms for communication and negotiation between agents. Out-of-home activities immediately preceding the commuting trips were assumed to be fixed in time which is a strong constraint. One of the major problems to solve is synchronization of simulated time among agents over a distributed system. Other areas of future work include the development of a visual representation of the scenario, including the use of web services to simulate, for example, routing of personnel and equipment to locations.

Appendix A

```
# cands: Ordered carpool candidates set
# promising: Set of promising pick-up orders
# Delta_dur: Given constant
# optimal: The promising candidate pickup order generating highest
score
Input: OrderedSet cands, Delta_dur
Output: optimal
Begin
    promising ← ∅
    pickupOrder ← ∅
    minDur ← +∞
    maxDur ← +∞
    permutSelector (cands,pickupOrder) # generates 'promising'
    optimal ← null
    For puo in promising do # puo = pick-up order
        If optimal is null or score(puo) < score(optimal) Then
            optimal ← puo
        End If
    End For
End
# Generates all permutations of the candidates set and evaluates them.
Function permutSelector(source : OrderedSet, target : OrderedSet)
Begin
    If source ≠ ∅ Then
        For i in  [0 .. sizeof(source) ) do
            e ← source[i]
            target.append(e)
            source.remove(e)
            permutSelector(source,target)
            source.insertAtPosition(e,i)
            target.remove(e)
        End For
    Else
        eval(target,promising)
    End If
End
# Evaluates pick-up order for membership of the 'promising' set
# using a dynamic criterion.
Function eval (pickupOrder : OrderedSet, promising : Set of OrderedSet)
Begin
    If (pickupOrder.head.canDrive) Then # first individual is potential
                                           driver
        If tripDur(pickupOrder) < maxDur Then # trip duration
            promising.add(pickupOrder)
            If tripDur(pickupOrder) < minDur Then
                # establish new limits
                minDur ← tripDur(pickupOrder)
                maxDur ← minDur + Delta_dur
                promising.drop(maxDur) # drop cases for which
                                         duration is too long
            End If
        End If
    End If
End
```

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