Agent-based Simulation Model and Matching Support Framework for Carpooling

Iftikhar Hussain

Acknowledgments

This thesis is the outcome of four years of research within the Transportation Research Institute (IMOB) at Hasselt University, Belgium. A very special gratitude goes to the Higher Education Commission, Pakistan, for helping me by providing the funding for this work. I am also grateful to IMOB for providing a decent work place. Undertaking this PhD has been a truly life-changing experience for me and it would not have been possible to do without the support and guidance that I received from many people. I am indebted to a great number of people who generously offered friendship, inspiration, advice, and encouragement throughout my PhD work, but words cannot express how grateful I am.

First of all, I am deeply grateful to my supervisor Prof. Dr. Davy Janssens for his guidance, insight, for encouraging my research and for allowing me to grow as a research scientist. His advice on both research as well as on my career have been invaluable. The success of my PhD project was in a large part due to his constant encouragement. I would also like to thank my co-supervisor Prof. Dr. Ir. Tom Bellemans for his insightful comments and suggestions, but also for the questions which incented me to widen my research in the initial stage of my PhD from various perspectives. I am also grateful to the rest of the members of my PhD committee, Prof. Dr. Geert Wets and Prof. Dr. Ir. Ansar-Ul-Haque Yasar, for their patience and support in overcoming numerous obstacles I have been facing throughout my research and for the opportunity they gave me to join the research team at IMOB.

I would like to express my special appreciation and thanks to my mentor, Dr. Ir. Luk Knapen, who is the person most committed for helping me throughout my research and writing of this thesis together with my supervisor. He has been a friend and coach. He taught me how to write academic research papers, made me a better programmer, had confidence in me when I doubted myself, and brought out the good ideas in me. Academically, he has been a tremendous mentor and the discussions with him have always been enlightening. Without his encouragement and constant guidance, I could not have finished this dissertation. In daily life, his unique characteristics and sense of humor are inspiring, cheering me up at those dark moments. I still remembered my first meeting with him and his words “don’t call me sir! ☺”. I am really thankful for his patience and motivation. I truly feel that his immense knowledge, sharp views and concise advice are valuable not only for this study, but also for my career development.

My thanks also go out to the international jury members Prof. Dr. Stephane Galland (UTBM, Belfort, France) and Prof. Dr. Nicole Ronald (Swinburne University of Technology, Australia), for the effort they made by reading my thesis and for their valuable feedback which helped me to improve the thesis. I am also thankful to Prof. Dr. Stephane Galland for the time he spent on guiding me during my stay at UTBM, Belford (France).

I would also like to thank my fellow researchers for their feedback, cooperation and of course friendship. In addition I would like to express my gratitude to the staff of the IT department and secretariat for the last minute favors. I would like to express my appreciation to all colleagues at IMOB and especially those with whom I worked. I would also like to thank all the friends I encountered in Hasselt for their support and companionship and for all the fun we have had in the last four years.

And finally, last but by no means least, my deepest gratitude goes to my parents for their unwavering support, for starting me on a lifetime of learning and for all of the sacrifices that they have made on my behalf. Your prayer for me was what sustained me thus far. Most importantly, I would like to thank my wife and children for their continuous love, support and understanding. I am also grateful to my other family members and friends who have supported me along the way.

I made the decision to start the journey myself but managed to finish it because of all of you.

Thanks for all your encouragement!

Iftikhar Hussain

October, 2017

Executive Summary

Carpooling is a specific instance of cooperation between two or more individuals regarding the use of a single vehicle to meet their mutual commuting needs. In actual practice, carpooling and similar concepts can be supported by intelligent advisory systems for individuals: one of these is trip matching. Evaluating the operational fitness of such systems in the testing phase requires an active community of users. Therefore the need for agent-based simulation arises to test the advisory system because (i) on one hand individuals have their own goals and plans and (ii) on the other hand they need to communicate, negotiate, coordinate and adapt their daily schedule to enable cooperation to achieve their goals. The negotiation between individuals requires that they effectively convey and interpret information to enable carpooling. Negotiation is essential to cooperation both on activity and on trip execution.

Mutual coordination and matching for carpooling are challenging tasks both for the driver and for all the passengers. This thesis specifies mechanisms to simulate carpooling for commuting in the long term. Firstly an agent-based simulation model for carpooling is presented; the focus is on mechanisms to simulate human behavior that affect the decisions for cooperation. Secondly an employer-based matching framework to support closed-group carpooling is presented.

Part I: Agent-based Simulation Model

Motivated by the limitations of coordination and negotiation mechanisms, one of the major contributions of this research is to model and simulate the agents' behavior in the carpooling simulation to investigate the effect of *cooperation* between individuals with regard to the trip execution. The study of human behavior is important to investigate its effect on the outcome of cooperation decisions. Another major contribution of this research is to develop a mechanism to simulate the outcome of *multiple trips based negotiation*; this is used to find and evaluate feasible carpool sequences for the participants and to select the optimal one. This research considers autonomous individuals and the similarity relationships between them. At the start of the PhD research project it was observed that no activity-based travel demand research studied coordination and negotiation and the effect of negotiated agenda adaptation required for carpooling.

The design of a comprehensive model to simulate the carpooling process is presented. It is mapped to an agent-based simulation which requires the setup of a framework and the establishment of a network of carpooling candidates. It

analyzes various effects of individuals' interaction and behavior adaptation of a set of candidate carpoolers. Agents' coordination in a multiple-trip negotiation model is investigated. Both home-to-work (HW) and work-to-home (WH) commuting trips are negotiated at once. The carpooling social network of candidates is established starting from results predicted by FEATHERS. The agent-based simulation for carpooling has been implemented using *Janus* (multi-agent platform) and by several increments: each increment is discussed in a different chapter.

Chapter 2 presents an agent based framework and simulation setup to evaluate the evolution of aggregate behavior of the carpooling society under several conditions. The direct interaction between agents is modeled within restricted carpooling social groups (CPSG) and the CPSG are formed by considering their home and work TAZs. A negotiation model for carpooling on the trips departure times and also on driver assignment is presented. In this chapter the evaluation process is not aimed to find the optimal passenger pick-up sequence. The base model presented in this chapter is used to measure the carpool potential on similar trips and without taking into account the pick-up and drop-off orders of the passengers. The negotiation *outcome* is determined by a deterministic function based on the candidates' profiles and time windows.

Chapter 3 presents an agent-based framework for long term carpooling using the CRIO organizational meta-model. It has been setup to simulate the emergence of carpooling and analyzes various effects of agent interaction and behavior adaptation for sets of candidate carpoolers. It enables the interaction between agents by establishing the CPSGs on the basis of work TAZs. A multiple-trip negotiation model is presented for the departure time decisions, driver and vehicle selection, and pick-up and drop-off orders of the carpoolers. The model is also used to measure the evolution of carpooling potential over time and takes into account the pick-up and drop-off order of the passengers. In order to find the optimal sequence, different options are evaluated by a scoring function based on the degree of flexibility (degree of freedom).

Chapter 4 presents an extension of the work described in chapter 2 where cooperating carpoolers were restricted to share the respective home and work areas and in chapter 3 where the constant preferences for the trips start times were used. The presented carpooling model analyzes various effects of *multi-zonal* individuals' interaction and behavior adaptation for sets of candidate carpoolers. The multiple trips negotiation model is extended and highly depends on the factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. The driver and vehicle selection, pick-up and drop-off order, and the preferred trip start time intervals of the optimal carpool group are evaluated by using *scoring functions*: (i) time of day, (ii) the time loss and (iii) degree of flexibility.

Chapter 5 further extends the agent-based carpooling simulation model by the use of address disaggregation so that all aspects of the complete carpooling problem can be examined. It presents a mechanism to simulate the interactions of autonomous agents which enables communication within CPSGs that coincide with the sets of agents working at a particular company or institution. The street addresses of the individuals are used to extract the actual trip duration information on the road network from the OpenStreetMap (OSM) dataset. A multiple trip negotiation model for work trips (HW and WH) is also presented to enable agent matching. The driver and vehicle selection, pick-up and drop-off order and the preferred trip start times of feasible carpool groups are evaluated by means of scoring functions: (i) degree of flexibility and (ii) the time loss. One of the objectives of the reported research is to investigate the computational performance of the model that contains all features described in this chapter.

Part II: Matching Support Framework and Service

Large companies may incorporate a variety of means to encourage employees to carpool, including by providing an employees' matching service to identify colleagues. Motivated by the expected benefits of using the personnel databases of large employers to provide carpooling advice, this research contributes by providing a mechanism to find all the feasible carpool groups for each employee using mutually compatibility indicators along with a *scoring mechanism* to evaluate solutions in order to propose a limited set of the feasible carpools to each employee for further negotiation.

In **chapter 6,** an innovative carpool matching advisory framework is presented that is to be rolled out by large companies to expand the range of ways that employees can carpool. It was designed to be operated by employers in order to find optimal carpool matching solutions which are to be proposed to the candidate carpoolers. It has the capability to account for dynamic evolution of the extracted personnel database in order to minimize burden on the users. It notifies interested candidate carpoolers about new opportunities to find partners belonging to the closed managed group. The framework is capable to match candidates based on home and target locations as well as on the time windows and maximum excess durations specified by the interested individuals. The innovative advisory framework proposes suitable groups of people (carpools) to the registered users. For a given group, the timely feasible pick-up and drop-off orders are evaluated. Those are scored at the carpool level. The best groups are kept and presented to the group members who in turn evaluate them using their own individual scoring criteria and start negotiation to take the final decision. As a proof-of-concept of the proposed framework, experiments were conducted at the scale of the Doppahuis database.

Beknopte Samenvatting

Carpoolen is een specifieke samenwerking tussen twee of meer personen met het oog op het gebruik van één voertuig voor hun dagelijkse woon-werk verplaatsingen. In de praktijk kunnen carpoolen en vergelijkbare concepten ondersteund worden door intelligente adviserende systemen: trip matching waarbij naar gelijkaardige verplaatsingen wordt gezocht is daarvan een voorbeeld. Om de operationele geschiktheid van dergelijke systemen in de testfase te evalueren is er een actieve community van gebruikers vereist. Hiervoor is een agent-gebaseerde simulatie nodig om het adviserende systeem te testen omdat personen (i) enerzijds hun eigen doelen en plannen hebben en (ii) anderzijds omdat zij onderling over hun dagindeling moeten communiceren en onderhandelen, deze moeten afstemmen en aanpassen om hun doelen te bereiken. Deze afspraken tussen personen vereisen dat zij op een efficiënte manier informatie uitwisselen en interpreteren om carpoolen mogelijk te maken. Afspraken maken, zowel met betrekking tot hun activiteiten als met betrekking tot de uitvoering van de verplaatsing, is essentieel om samen te werken.

Het onderling coördineren en afstemmen voor carpoolen zijn uitdagende taken, zowel voor de bestuurder als voor alle passagiers. In deze verhandeling worden mechanismen gespecificeerd voor carpoolsimulatie met betrekking op woon-werkverkeer op de lange termijn. Allereerst wordt er een agent-gebaseerd simulatiemodel voor carpoolen voorgesteld; de focus ligt hierbij op mechanismen voor de simulatie van menselijk gedrag die beslissingen voor samenwerking beïnvloeden. Vervolgens wordt er een zoekplatform voorgesteld voor de ondersteuning van carpoolen in de gesloten groep van grote bedrijven.

Deel I: Agent-gebaseerd simulatiemodel

Omwille van de beperkingen van de mechanismen voor coördinatie en onderhandelingen, is één van de belangrijkste bijdragen van dit onderzoek het modelleren en simuleren van agent-gedrag in de carpoolsimulatie om het effect te onderzoeken van de samenwerking tussen personen met betrekking tot de uitvoering van de verplaatsing. De studie van het menselijk gedrag is belangrijk om het effect van dit gedrag op het resultaat van gezamenlijke beslissingen te onderzoeken. Een andere belangrijke bijdrage van dit onderzoek is de ontwikkeling van een mechanisme voor de simulatie van het tot stand komen van afspraken voor meerdere verplaatsingen tegelijkertijd. Dit mechanisme wordt gebruikt bij het zoeken en evalueren van mogelijke carpoolsequenties voor de deelnemers en om de optimale sequentie te selecteren. In dit onderzoek worden autonome individuen en hun onderlinge gelijkenissen bestudeerd. Aan het begin van het doctoraatsonderzoeksproject bleek dat er geen onderzoek liep naar activiteiten-gebaseerde modellen voor het voorspellen van de vraag naar verplaatsingen die rekening houden met de coördinatie, het maken van afspraken en de impact van aanpassingen van dagindelingen die nodig zijn om te kunnen carpoolen.

Er wordt een ontwerp van een omvattend model voor de simulatie van het carpoolproces voorgesteld. Het is verwezenlijkt met behulp van een agent-gebaseerde simulatie waarvoor er een platform en een netwerk van carpoolkandidaten gecreëerd dient te worden. Hierbij worden meerdere effecten van de interactie tussen individuen en gedragsaanpassingen van een aantal kandidaat-carpoolers geanalyseerd. De coördinatie van agenten in een model voor het maken van multi-trip afspraken wordt bestudeerd. Afspraken voor de woon-werk (HW) trip en de bijhorende werk-woon (WH) trip wordt tegelijkertijd vastgelegd. Het sociale netwerk van carpoolkandidaten wordt gecreëerd op basis van resultaten die voorspeld werden door FEATHERS. De agent-gebaseerde simulatie voor carpoolen werd geïmplementeerd door middel van Janus (multi-agent platform) en dit werd gedaan in verschillende stappen: elke stap wordt besproken in een ander hoofdstuk.

Hoofdstuk 2 introduceert een agent-gebaseerd platform en een simulatie om de evolutie van het gedrag van de volledige carpoolgroep onder verschillende omstandigheden te evalueren. De directe interactie tussen agenten is gemodelleerd binnen beperkte sociale carpoolgroepen (CPSG) en de CPSG worden gevormd op basis van hun woon-werk TAZ-zones. Er wordt een model voor het maken van afspraken m.b.t. carpoolen voorgesteld (waarbij het heen en terug woon-werkverkeer voor één dag in één enkele afspraak worden gecombineerd). Dit gebeurt op basis van de vertrektijden van de verplaatsingen, alsook op basis van de aanwijzing van de bestuurder. In dit hoofdstuk is het evaluatieproces niet gericht op het vinden van de optimale volgorde voor het oppikken van passagiers. Het basismodel dat in dit hoofdstuk voorgesteld wordt, wordt gebruikt voor het meten van het carpoolpotentieel voor gelijkaardige verplaatsingen, zonder rekening te houden met de volgorde voor het oppikken of afzetten van passagiers. Het resultaat van de onderhandeling om te komen tot een afspraak wordt bepaald door een deterministische functie die gebaseerd is op de profielen en de beschikbare tijdvensters van de kandidaten.

Hoofdstuk 3 introduceert een agent-gebaseerd platform voor lange termijn carpoolen met behulp van het organisatorische CRIO metamodel. Het werd ontwikkeld om de opkomst van carpoolen te simuleren en analyseert de verschillende effecten van interactie tussen individuen en van gedragsaanpassingen voor groepen van kandidaat-carpoolers. Het model laat enkel interactie toe tussen agenten binnen de CPSG groepen gevormd op basis van werk TAZ-zones. Er wordt een multi-trip afspraken-model voorgesteld voor de keuze van vertrektijd, bestuurder en voertuig alsook voor de volgorde van het oppikken en afzetten van carpoolgebruikers. Het model wordt ook gebruikt voor het meten van de evolutie van het carpoolpotentieel doorheen de tijd en houdt rekening met de volgorde van het oppikken en afzetten van passagiers. Om de optimale volgorde te vinden worden verschillende opties geëvalueerd door middel van een score die gebaseerd is op de mate van flexibiliteit (vrijheidsgraden).

Hoofdstuk 4 gaat verder in op het werk dat beschreven wordt in hoofdstuk 2 waar samenwerking tussen carpoolers beperkt werd tot individuen met gemeenschappelijke woon- en werkzones en in hoofdstuk 3 waar vaste voorkeuren voor de vertrektijden van de verplaatsingen gebruikt werden. Het voorgestelde carpoolmodel analyseert voor groepen van kandidaat-carpoolers de verschillende effecten van de multi-zonale interactie tussen gebruikers en de gedragsaanpassing. Het multi-trip afspraken-model is uitgebreid en hangt in hoge mate af van de factoren die invloed hebben op de keuze van vertrektijd, het profiel van de gebruiker, route optimalisatie en van het effect van activiteiten die geen wijziging in het tijdschema toelaten. De selectie van de bestuurder en het voertuig, de volgorde van het oppikken en afzetten en de geprefereerde vertrektijdintervallen van de optimale carpoolgroep worden geëvalueerd met behulp van score functies: (i) het tijdstip, (ii) het tijdverlies en (iii) de mate van flexibiliteit.

Hoofdstuk 5 breidt het agent-gebaseerde carpoolsimulatiemodel uit door het gebruik van gedesaggregeerde adressen voor woon en werk locaties, waardoor alle aspecten van het volledige carpoolprobleem bestudeerd kunnen worden. Het bevat een mechanisme dat de interacties van autonome agenten simuleert waarmee communicatie mogelijk is binnen CPSGs die samenvallen met de groepen van agenten die werken bij een bepaald bedrijf of bepaalde instelling. De adressen van de carpoolers worden gebruikt om de werkelijke duur van de verplaatsing op het wegennet te extraheren op basis van de OpenStreetMap (OSM) dataset. Er wordt eveneens een multi-trip afspraken-model voor werkverplaatsingen (HW en WH) voorgesteld om individuen te kunnen koppelen. De selectie van de bestuurder en het voertuig, de volgorde van het oppikken en afzetten en de gewenste vertrektijden van mogelijke carpoolgroepen worden geëvalueerd door middel van volgende score functies (i) de mate van flexibiliteit en (ii) het tijdverlies. Een van de doelstellingen van het beschreven onderzoek is het bestuderen van de prestaties van het computermodel dat alle functies bevat die in dit hoofdstuk beschreven zijn.

Deel II: Het linken van het ondersteunend platform en dienstverlening

Grote ondernemingen kunnen een scala aan middelen aanwenden om medewerkers aan te sporen tot carpoolen, inclusief het aanbieden van een platform waarbij werknemers gelinkt kunnen worden aan collega's. Gemotiveerd door de verwachte voordelen bij het gebruik van het personeelsbestand van grote ondernemingen om carpooladvies te verstrekken, draagt dit onderzoek bij door het voorzien van een mechanisme om voor iedere werknemer alle mogelijke carpoolgroepen te vinden aan de hand van onderling compatibele indicatoren, samen met een scoringsmechanisme om oplossingen te evalueren om op basis hiervan een beperkte set van de mogelijke carpools voor te stellen aan iedere werknemer zodat er verdere afspraken gemaakt kunnen worden.

In **hoofdstuk 6** wordt er een innovatief adviserend carpoolplatform voorgesteld dat uitgerold dient te worden in grote bedrijven om de carpoolmogelijkheden voor hun werknemers uit te breiden. Dit werd ontworpen voor werkgevers om hen in staat te stellen de optimale carpoolpartners te vinden die voorgesteld kunnen worden aan kandidaat-carpoolers. Het is in staat om rekening te houden met een dynamische evolutie van het geëxtraheerde personeelsbestand om de overlast voor gebruikers tot een minimum te beperken. Het stuurt berichten naar geïnteresseerde kandidaat carpoolers over nieuwe mogelijkheden om partners te vinden die tot de gesloten groep behoren. Het platform kan kandidaten linken op basis van woonplaats en doelbestemming, alsook op basis van tijdvenster en de maximale extra reistijd, opgegeven door de geïnteresseerde personen. Het innovatief adviserend platform stelt geschikte groepen van mensen voor (carpools) aan geregistreerde gebruikers. Volgordes van oppikken en afzetten voor een bepaalde groep worden geëvalueerd op haalbaarheid van de bijhorende timing. Elke voorgestelde volgorde krijgt een score op carpool-niveau. De beste groepen worden behouden en voorgelegd aan de groepsleden, die deze op hun beurt evalueren aan de hand van hun eigen individuele criteria en daarna onderhandelen om tot een definitieve afspraak te komen. Om het haalbaarheid van concept van het voorgestelde platform aan te tonen, werden experimenten uitgevoerd op de schaal van het personeelsbestand van het Doppahuis.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABM	Agent-Based Model, Agent-Based Modeling
API	Application Program Interface
ASPECS	Agent-oriented Software Process for Engineering Complex Systems
CC	Company Car
CPP	Carpool Parking
CPSG	CarPooling Social Groups
CPSN	CarPooling Social Network
CRIO	Capacity, Role, Interaction and Organization
DCS	Dynamic Carpooling System
DoF	Degree of Flexibility, Degree of Freedom
FEATHERS	Forecasting Evolutionary Activity Travel of Households and their Environmental RepercussionS
FFTT	Free-Flow Travel Time
GCPMS	Global CarPooling Matching Service
GIS	Geographic Information Systems
GPS	Global Positioning System
GUI	Graphical User Interface
HW and WH	Home-to-Work and Work-to-Home
IMOB	Instituut voor MOBiliteit (IMOB)
LTCPP	Long Term Car Pooling Problem
MAS	Multi Agent System
MNL	Multinomial Logit
OD	Origin-Destination
OSM	OpenStreetMap
OVG	Onderzoek Verplaatsingsgedrag Vlaanderen
PST	Preferred trip Start Time

SEC	Social Economic Characteristics
STM	State-Transition Machine
TAZ	Traffic Analysis Zone
TDM	Transportation Demand Management
TW	Time Window
WIDRS	WithIn Day Re-Scheduling

Chapter 1

Introduction

1.1 Overview

This study investigates the effect of communication, negotiation and coordination for carpooling by taking the possibility of flexible activity scheduling into account. It analyzes various effects of individuals' interaction and behavior adaptation of a set of candidate carpoolers. Two parts are presented in this dissertation: firstly the design of a comprehensive framework for the carpooling process is mapped to an agent-based simulation and secondly to support large companies a matching advisory system for employees who are candidates for carpooling is presented. This chapter sets the background for the research and provides an introduction to the study. It also provides an overview of the subsequent chapters of this dissertation.

The rest of this chapter is as follows. Section 1.2 provides the background of the research. Section 1.3 describes the motivation for the research. Section 1.4 of this chapter introduces the problem to be covered in a formal way. Section 1.5 presents the resulting research objectives and contributions pursued in this thesis. Section 1.6 provides the research approach and finally the thesis outline is presented in section 1.7.

1.2 Background

"It is a general trend in transportation planning to try to minimize the negative externalities of the transport system as a whole, such as noise or pollutant emissions" (Dubernet, et *al.*, 2013). Around the world, the share of different transportation modes differs between regions. But when oil prices are decreasing, most of the people prefer riding via their own vehicles. This increases the total number of vehicles on the road which in turn leads to several problems like congestion, environmental degradation, parking and energy problems. One of the ways to minimize the negative externalities is by reducing the number of vehicles on the roads. This can be achieved by different means: efficient public transport, usage of individual non-motorised modes, such as bike or walk, or sharing of a vehicle for all or a fraction of a trip. Vehicle sharing can be done in different ways: one of them is by carpooling.

Carpooling happens when two or more commuters, typically from different households, share a ride in one of their own cars in order to reach common, or nearby destinations. Carpool travelling is more common for people who work in places with more jobs nearby, and for who live in places with higher residential densities (Belz & Lee, 2012). The best carpooling arrangements are very flexible. In fact, you don't need to carpool every day, just as often as your schedule allows. A successful carpooling scheme provides a reliable alternate mode for travelers that is eco-friendly and sustainable. According to Amey, et *al.* (2010), the potential benefits from increased carpooling are significant, and impact a wide range of stakeholders. It enables commuters to share travel expenses, save on fuel and parking costs, travel time savings and improves mobility options for non-drivers. Employers can reduce expensive parking construction or leasing, and benefit from higher worker productivity. Society benefits from reduction of congestion, fuel consumption and emissions as well as increased social equity.

"Carpooling first became prominent in the United States as a rationing tactic during World War II and it returned in the mid-1970s due to the 1973 oil-crisis and the 1979 energy-crisis" (carpool, 2017). Unfortunately, carpooling historical success has been rather uncertain, with a significant decrease in popularity since the 1970's. The participation in carpooling remained nearly an all-time low until now. Clearly there is a discrepancy between the purported benefits and the real or perceived challenges associated with carpooling.

According to Amey, et *al.* (2010), the rapid increase in oil prices since 2005 combined with the decline in incomes as a result of the financial crisis of 2008, has been sufficient to generate renewed interest in the practice in spite of a lack of support from the government. The popularity of the Internet and smart phones has greatly helped carpooling to expand, enabling people to offer and find rides. The additional flexibility provided by modern information technology is making carpooling more viable than ever before. Travelers are supported by useable and reliable online transport marketplaces or websites which are commonly used for special long distance journeys with high fuel costs. Long distance carpooling has become increasingly popular over the past years in Europe, thanks to Germany's *mitfahrgelegenheit* (carpooling.com, 2017), and France's BlaBlaCar (Wauters, 2014). According to their respective websites, in early 2015 these online platforms counted more than 6 million and 10 million users respectively, across Europe and beyond (carpool, 2017). The carpooling.com was acquired by BlaBlaCar in 2015, and the URL now redirects to BlaBlaCar (carpooling.com, 2017).

Nowadays, the potential candidates trips are organized by online carpooling matching platforms through Internet and Geographic Information System (GIS) components. There are over 70 different carpooling matching platforms operational in Europe (Kesternich, 2015). "They differ in terms of organizational form, internal structure, provided features on their websites and catchment areas. The carpooling market especially has grown because one platform provider established a fee-based use for carpooling offers" (Kesternich, 2015). Small companies have been grown and startups companies were developed offering carpooling support without the need to pay any fees.

Most of the carpooling matching platforms including BlaBlaCar effectively support an *ad-hoc based ridesharing* whereas this thesis specifies mechanisms to simulate *carpooling for commuting in the long term*. Carpooling for commuting was studied because of its practical relevance.

1.3 Motivation

Aspects of reality can be described by micro-models. Such models perform detailed analysis of activities to be executed. In recent years, computer-aided traffic simulation has gained more attention to monitor, maintain and improve traffic and transport system. Micro-simulation is often used to evaluate the effects of proposed interventions before they are implemented in the real world (Hagan & Dowd, 2013). These are excellent tools for understanding the evolution and consequences of complex processes whose interactions cannot be analytically predicted. Currently many research areas including transportation behavior need to analyse and model complex behavior including interactions between individuals (agents). Most current models simulate individuals acting in a mutually independent way except for the use of the shared transportation infrastructure. Modeling the interaction between individual agents becomes progressively important and generates new challenges. This results in rapidly increasing problem complexity.

The carpooling problem has been approached from diverse points of view e.g. "*how to match between people to share a ride?"*, and how to decide "*who picks up whom with their vehicle*?" (Hartman et *al.*, 2014). Carpooling is a specific instance of cooperation between people. Therefore individuals need to communicate, negotiate and coordinate, and in most cases adapt their daily schedule to enable cooperation. Matching and mutual coordination for carpooling may be a challenging task both for the driver and for all the passengers even if we assume that every driver can pick up at least one but maximum four passengers. Authors in (Furuhata et *al.*, 2013) & (Agatz, et *al.*, 2012) considered *finding matching passengers for the carpooling* as a combinatorial problem.

In actual practice, carpooling and similar concepts can be supported by intelligent advisory systems for trip matching. Evaluating the operational fitness of such systems in the testing phase requires an active community of users. Therefore the need for agent-based simulation arises to test or evaluate the advisory system because (i) on one hand individuals have their own goals and plans and (ii) on the other hand they need to communicate, negotiate, coordinate and adapt their daily schedule to enable cooperation to achieve their goals. Negotiation is essential to cooperation both on activity and on trip execution (Knapen et *al.*, 2014(a); Hartman et *al.*, 2014). Effective negotiation requires that individuals effectively convey and interpret information to enable carpooling. Each negotiation involves a small number of participants but the schedules can be interconnected by cooperation. During this process, the travelling, social economic characteristics (SEC) and time pressure factors can play vital role to find the favorable partners for carpooling.

Given the importance of human behavior for the outcome of cooperation in carpooling, the question arises is *how far human behavior is actually reflected?* Hence a mechanism is required to simulate human behavior when decisions for cooperation are to be taken. It is also important to find out what is the share of carpooling among the available transportation modes given behavioral constraints with respect to activity timing.

At the start of the PhD research project it was observed that no research studied coordination and negotiation and the effect of negotiated agenda adaptation required for carpooling. Most models for transportation demand either operate at aggregate levels or consider micro-simulated actors to be mutually independent, except for the space they occupy on the road network while traveling (Knapen, et *al.*, 2013). Consequently an agent-based simulation for carpooling, described as first part of this dissertation is presented to evaluate the advisory system for matching individuals. As a second part, a matching advisory system is offered to support employees in large companies who are candidates for carpooling in order to support large companies.

Since carpooling supports both employers and employees, many companies may be interested to adopt it to increase the efficiency of their organization (Sm, 2005). Large employers located in congested areas where parking space is expensive or scarce can successfully influence private household travel decisions while simultaneously advancing organization’s goals (Amey et *al*., 2010). The primary employer advantage is the need for fewer parking spaces and other advantages include less employee stress and improved productivity. Carpooling in a company context implies a closed group. People know each other and that is a basis for the trust required to cooperate. Furthermore, in the carpooling context, compatibility in space and time is important. This naturally occurs within a group of people working together. Companies may experience a variety of incentives to encourage carpooling: this includes good time-use, well-being of employees (because that affects productivity), cost cutting (time loss in traffic, parking cost), keeping employees happy at a low cost (e.g. by promoting carpooling in company cars that helps people and does induce nearly no additional cost).

Many regional carpooling organizations in most areas allow interested employees to register directly for no cost. Normally, employees choose to carpool without any assistance or involvement from the employer. However, providing a matching support framework for employees by company or institution (to identify the matching colleagues directly to minimize the burden of the employees) can be an effective way to encourage employees for carpooling.

1.4 Problem Description

The problem can be described in a formal way (see Figure 1.1) as:

> *"A set P of identified participants $p_i \in P$ is given and for each participant p_i the origin $o_i \in O$ and destination $d_i \in D$ locations. P'_i is the set of participants who are mutually compatible with p_i for negotiation in carpooling where $P'_i \subseteq P$. The negotiation (for matching candidates) applies to both the trips (home-to-work HW and work-to-home WH) and covers trips start times, the driver and vehicle selection and the pick-up and drop-off orders of the carpoolers. An individual having trip duration T_{solo,p_i} also has a maximum detour time (maximum excess time) $T_{maxDetour,p_i}$ which is the upper limit for the extension to T_{solo,p_i} acceptable by p_i to travel from o_i to d_i. Individuals whose trips can be combined with respect to the detour time can picked-up by the driver.*
>
> *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 commuting trips (HW and WH) in daily schedules are detailed and discussed in relation to long term carpooling.*
>
> *Candidates who belong to the same carpooling social group in the carpooling social network can interact and negotiate with each other; this is modeled by the agent-based simulation."*

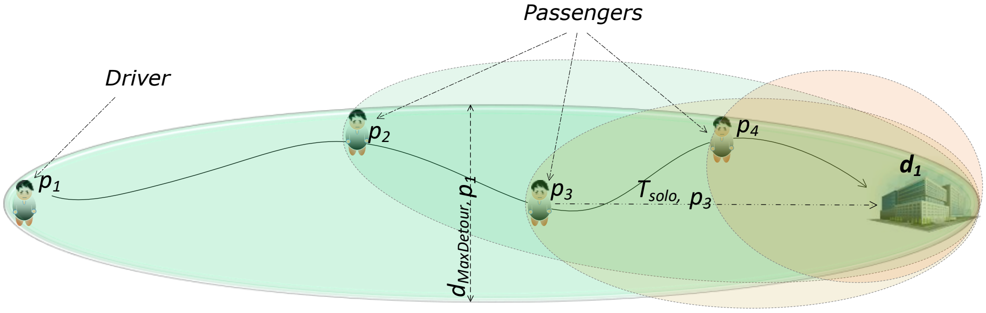


Figure 1.1. Problem description.

1.5 Objectives and Contributions

Motivated by the limitations of coordination and negotiation mechanisms, and the expected benefits of using the personnel databases of large employers to provide carpooling advice, this thesis makes following major contributions:

Contrib. 1: Modeling and simulation of agents' behavior in the carpooling model simulation to investigate the effect of *cooperation* among individuals with regard to the trip execution.

Contrib. 2: Development of a mechanism to simulate the outcome of *multiple trips based negotiation*; this is used to find and evaluate feasible carpool sequences for the participants and to select the optimal one.

Contrib. 3: In the matching support framework, a mechanism to find all the feasible carpool groups for each employee using mutually compatibility indicators is presented along with a *scoring mechanism* to evaluate solutions in order to propose a limited set of the feasible carpools to each employee for further negotiation.

The purpose of the research is to support topics both in the field of large scale agent based modeling and in the field of cooperation and rescheduling in activity based models. With respect to activity based modeling, research will focus on models for propagation of information, incentives an inhibitors for carpooling and on time pressure caused by cooperation (feasibility of joint operations).

This dissertation is divided into two parts and each part is covered by an objective. Firstly, a carpooling model is presented that is mapped to an agent-based simulation. Secondly, a framework for matching employees who are candidates for carpooling to support large employers is reported. The tasks covered in each part are described as follows.

1.5.1 Agent-based Simulation Model

An agent-based simulation model for carpooling is developed to measure the carpooling potential in terms of space and time. The intention is to study mechanisms and effects of carpooling at aggregated (TAZ) level as well as on the fully disaggregated level of individual addresses. Address disaggregation is important because even if people live in the same TAZ ($5km^2$) they may live more than 2km apart which may introduce a significant additional travel time. For giving a proof-of-concept, a carpooling network is established using results predicted by the FEATHERS (Bellemans et *al.*, 2010) simulator.

To achieve the final objective, the following tasks (Figure 1.2) are identified:

Task 1: The *formation of carpooling social groups* (CPSGs) of the carpooling social network (CPSN) based on similar (1) home and work Traffic Analysis Zone (TAZs), (2) work TAZ and (3) company. The goal is to limit the interactions of autonomous agents, to enable communication to trigger the negotiation process within CPSGs to find matching partners in order to co-travel.

Task 2: To model an *interaction mechanism* by exchanging messages between autonomous agents within CPSGs to simulate human behavior when decisions for cooperation are to be taken. It analyzes various effects of agent interaction and behavior adaptation of a set of candidate carpoolers.

Task 3: To *find feasible carpool(s)*, a multiple trips (home-to-work and work-to-home) negotiation model on trip start time, route choice, driver and vehicle selection as well as on the pick-up and drop-off order is presented.

Task 4: To present the selection of the most preferred *trips departure times* within a given interval by considering: (1) constant preferences, (2) preferences depending on the lifestyle factors (partly derived from the existing departure time studies) and (3) by taken into account the constraining activities that influence the departure time decision.

Task 5: To develop a *route or path choice* mechanism based on the maximum excess (detour) function, in order to introduce the path and time similarity concepts. For a specific route, the travel durations and distances between (1) home-work TAZs, (2) the multiple home-TAZs and (3) the disaggregate addresses, are used from (1) the FEATHERS schedules, (2) generated by WIDRS (Knapen, et *al.* 2014(b)) tool and (3) the OSM database respectively.

Task 6: To develop a mechanism for the *driver and vehicle selection*, and *pick-up and drop-off orders* of the carpoolers based on (1) home-work TAZs, (2) multiple home-TAZs and (3) disaggregate addresses. The driver in the carpool needs to pick up every carpooler and is the first one to board. The driver selection and timing constraints are interrelated.

Task 7: Participants can join a carpool group for a given trip in several sequence orders. For the selection of *optimal carpool group*, every valid pick-up/drop-off order of participants is evaluated using a *scoring mechanism* which combines following scoring functions: (1) time-of-day, (2) time loss and (3) degree of flexibility.

Task 8: The actual trips execution (carpooling) is handled where the trips are executed on *long-term* basis and the consequent carpooling participation evolves over time. Participants can carpool with multiple carpool groups (successive in time).

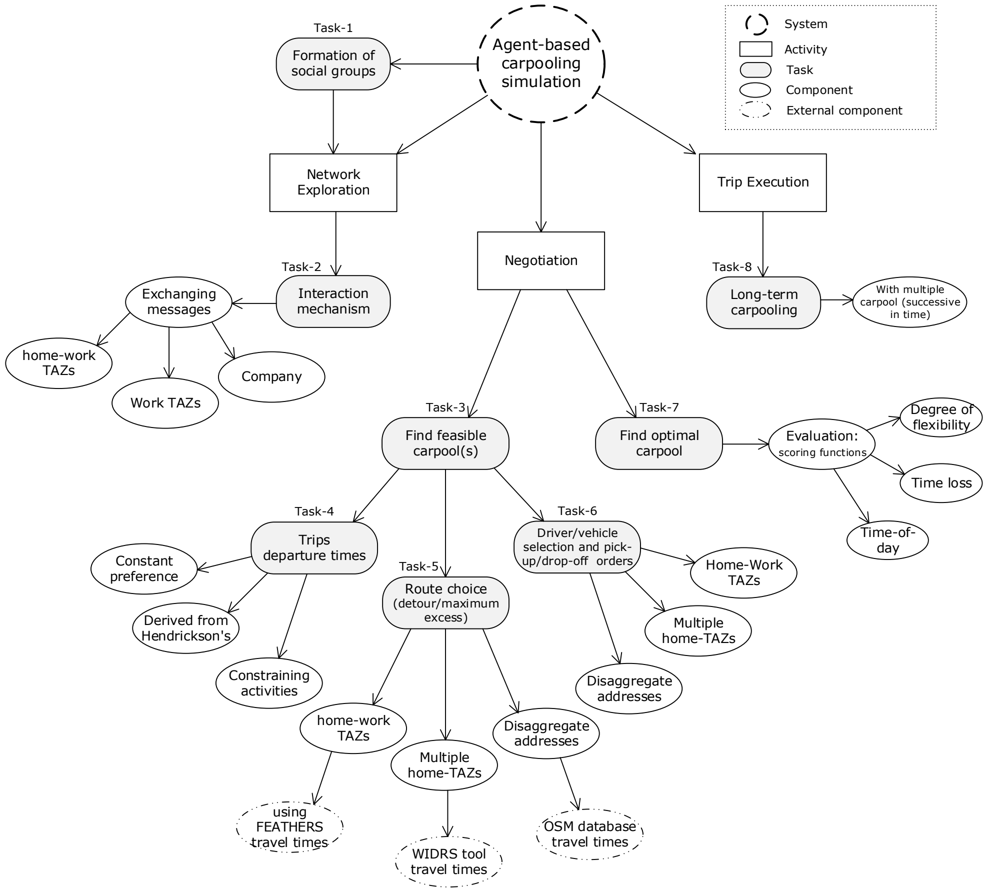


Figure 1.2. Tasks covered in the agent-based simulation model.

1.5.2 Matching Support Framework and Service

A matching support framework for employees who are candidates for carpooling to support large companies or institutions is developed. The goal is to notify people about new opportunities to find partners belonging to a closed managed group and interested in carpooling. The framework accounts for dynamic evolution of the extracted personnel database in order to minimize burden on the users. Intention is to show the feasibility of matching for recurrent travel demand.

To achieve the objective, the following tasks (Figure 1.3) are achieved:

Task 1: The *feasible pairs* of potential carpooling candidates are identified to sufficiently reduce the computational effort associated with database updates. In order to identify the feasible pairs, each employee is compared with every other employee and compatibility indicators are computed. The compatibility indicators are applied on both the commuting trips (*HW* and *WH*) in the *periodic scheme* (a multi-day schedule that is assumed to be repeated forever) of each candidate.

Task 2: Presents the mechanism to find all the *feasible carpool groups* (feasible solutions) up to the size of appropriate car capacity on the basis of mutually compatibility indicators (trips start times, the route choice, and the driver and vehicle selection / the pick-up and drop-off order) of the participants.

Task 3: Presents the selection of the most preferred *trips departure times* within a given interval by considering time windows and by taken into account the constraining activities that influence the departure time decision.

Task 4: The *route or path choice* mechanism is based on a maximum excess (detour) criterion: this is used to introduce the path and time similarity concepts. For specific route, the travel durations and distances between the disaggregate addresses are taken directly from the OSM database using GraphHopper API.

Task 5: For each feasible carpool group, a mechanism for the *driver and vehicle selection*, and *pick-up and drop-off orders* of the carpoolers based on disaggregate addresses is presented.

Task 6: To present some of the feasible solutions (*optimal carpool sequences*) for each day of the periodic scheme to the carpooling candidates: a scoring mechanism is introduced to evaluate and compare the feasible carpool sequences. It is based on following scoring functions: (1) cost, (2) time-of-day, (3) time loss and (4) degree of flexibility.

For each employee, the multiple parallel carpools that depend on the day of the week are proposed.

The proposed framework consumes a personnel database. As a proof of concept matching is applied to the dataset of attendants of adult courses organized by the Doppahuis[1] in Hasselt.

[1] http://www.doppahuis.be/het-doppahuis/welkom-in-het-doppahuis

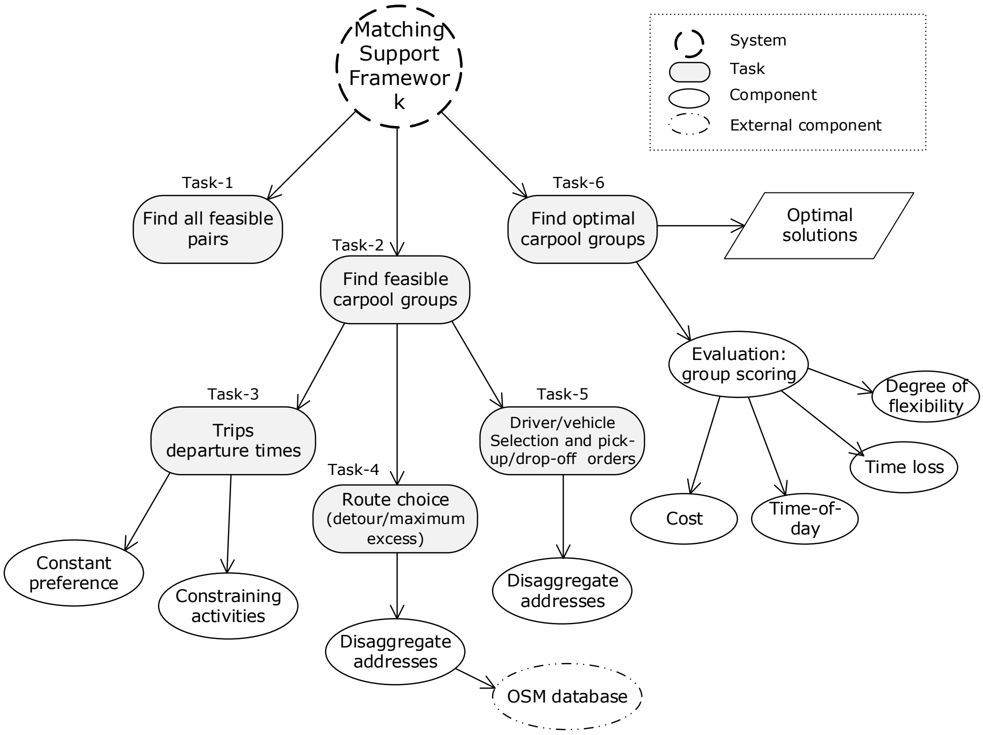


Figure 1.3. Tasks covered in the matching support framework.

1.6 Approach

Since traditional modeling tools have difficulties for handling the complexity of communication and negotiation that are required in carpooling simulations we opted for a method that is more suited for the interaction of autonomous entities: agent-based modeling (ABM). An agent-based approach is used for assessing the effects of individual's decision-making and for simulating the interactions of autonomous agents. An agent-based model (ABM) allows one to understand the interactions of physical particles, and to describe many problems of astronomy, biology, ecology and social sciences. The ABMs can provide valuable information on the society and on the outcome of social actions or phenomena. 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.

An ABM is essentially distributed and individual-centric and is appropriate for the systems (1) which require modeling complex, nonlinear, discontinuous or discrete 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 (Bonabeau, 2002; Hussain et *al.*, 2016).

Such systems may be complex to design. "A particular interest has been given to the use of organizational concepts where the concepts of *organizations*, *groups*, *communities*, *roles*, *functions*, etc. play an important role" (Ferber, et *al.*, 2004). From an organizational point of view, a Multi-agent System (MAS) can naturally be considered and designed as a computational organization (Zambonelli, et *al.*, 2003) that defines a framework for agent activities, i.e. the organization imposes a set of constrains for the behavior of agents, and offers a set of facilities and services that agents may use. According to (Ferber et *al.*, 2004), "the organization acts (1) as a "dynamic framework" where agents may enter and leave organizations at will, and (2) as an environment for resources, services, communications and tasks, through the concepts of both groups and roles" (Weyns, et *al.*, 2005). The Capacity, Role, Interaction and Organization[2] (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. 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 fulfil 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''.

According to Manzini & Pareschi, (2012) and Jennings, (2000), this approach is appropriate because the carpooling individuals are dynamically changing their role in the carpooling social network. Adopting an organizational approach enables the agents to dynamically change their behaviors without changing their internal architecture. 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 Janus[3] (Gaud, et *al.*, 2009), multi-agent based platform is used for simulating the interactions of autonomous individuals: it provides an efficient implementation of agent-based and organizational-based concepts.

---

[2] http://www.aspecs.org/CRIO

[3] http://janus-project.org/Home

The second part of the thesis is accomplished by developing a comprehensive matching advisory framework for employees who are candidates for carpooling. IMOB has specified an advisor tool aimed to support recurrent commuter carpooling in closed groups. People specify their day-specific constraints in a periodic scheme of fixed length (couple of weeks, group specific). The main constraints are time windows. Each individual can act as a driver and/or a passenger on any particular day. Individuals register their availability as a driver as well as the car capacity for each day in the periodic scheme. The carpool requirements for an individual apply for a personal specified period of time. The tool determines the sets of drivers and passengers along with the particular individual constraints for every day in the periodic scheme. The matching component described in this thesis, looks for groups of people who can drive together while fulfilling all constraints related to time windows, detour time loss and detour distance. The purpose is to propose carpool solutions (groups) to individuals who shall negotiate about cooperation. A large number of groups can be found for a particular individual and not all of those can be presented to the user. Therefore, scoring functions are used to qualify the solutions. A small set of groups having the highest scores is presented to the candidates who start a negotiation and take the final decision.

1.7 Thesis Outline

This dissertation has two parts and each part contains several chapters. The first part, an *agent-based simulation model for carpooling* (from chapter 2 to chapter 5) is divided into a couple of incremental research efforts modeling carpooling commuters interaction behavior and the negotiation mechanisms. The second part (chapter 6) is all about the application of *the carpooling matching support service for large employers*. The table 1.1 shows how the components we developed incrementally are integrated in the successive models. It provides a synthetic view of the contributions over the different chapters. Each of the chapters covers a particular step in the development.

Table 1.1. Checklist of the features (components).

Features	**Ch.2**	**Ch.3**	**Ch.4**	**Ch.5**	**Ch.6**
Exploration & Interaction					
HW-TAZ-pairs only	√	-	-	-	-
Similar Work-TAZ	-	√	√	-	-
Same company	-	-	-	√	√
Time preference					
Constant preference	-	√	-	√	√

Hendrickson's PF	√	-	√	-	-
Path similarity					
home-work TAZs	√	-	-	-	-
Multiple home-TAZs	-	√	√	-	-
Disaggregate addresses	-	-	-	√	√
Driver & vehicle selection, pick-up & drop-off order					
home-work TAZs	√	-	-	-	-
Multiple home-TAZs	-	√	√	-	-
Disaggregate addresses	-	-	-	√	√
Scoring functions					
Time loss	-	-	√	√	√
Degree of flexibility	-	√	√	√	√
Time of day	-	-	√	-	√
Cost	-	-	-	-	√
Long-term carpooling					
With multiple carpools successive in time	√	√	√	√	-
With multiple parallel carpools that depend on the day of the week	-	-	-	-	√
General					
Constraining activities	√	√	√	√	-
Multiple trips (HW&WH)	√	√	√	√	√
Dataset used					
FEATHERS	√	√	√	√	-
Doppahuis	-	-	-	-	√
Travel times used					
FEATHERS	√	-	-	-	-
WIDRS tool	-	√	√	-	-
OSM database	-	-	-	√	√

Chapter 1 is the introductory chapter which explains the research background and motivation, and contributions and objectives of the research.

Chapter 2 presents an agent based framework and simulation setup to evaluate the evolution of aggregate behavior of the carpooling society under several conditions. The base model presented in this chapter is used to measure the carpool potential on similar trips and without taking into account the pick-up and drop-off orders of the passengers. The concept of communication, negotiation, and coordination in the carpooling process are covered on the long-term basis. The direct interaction between agents is modeled to restricted carpooling social groups (CPSG) and the CPSG are formed by considering their home and work TAZs. A negotiation model for carpooling (combining the forward and backward commuting trips for a day in a single negotiation) on the trips departure times and also on driver assignment is presented. The time preference function is proposed which is partly derived from an existing departure time study presented in Hendrickson & Plank, (1984). The implementation also applies constraining activities by considering the personal daily schedule of each individual.

Chapter 3 presents the design of an organizational model using the CRIO organizational meta-model that is mapped to an agent-based simulation model and a proof of concept implementation. It has been setup to simulate the emergence of carpooling and analyzes various effects of agent interaction and behavior adaptation for sets of candidate carpoolers. Agents' communication, negotiation and coordination in a multiple trip and for long-term carpooling is investigated. The interaction mechanism of agents presented in chapter 2 is extended to allow individuals living in different zones and heading to the same work area to negotiate for carpooling. The amount of interaction between agents is minimized by establishing CPSGs consisting of people whose work locations are belonging to the same TAZ. A multiple-trips negotiation outcome model based on constant preference function for the trips departure times, driver and vehicle selection and pick-up and drop-off orders of the carpoolers is presented. The evaluation process is introduced using degree of flexibility (degree of freedom) scoring function to find the optimal sequence of the participants.

Chapter 4 presents the extension of the work presented in chapter 2 where cooperating carpoolers were restricted to share the respective home and work areas and in chapter 3 where the constant preferences for the trips start times are used. The presented carpooling simulation model analyzes various effects of multi-zonal individuals' interaction and behavior adaptation for sets of candidate carpoolers. The multiple trips negotiation model is extended and highly depends on the factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. The selection of the most preferred trip departure time partly derived from existing departure time studies (Hendrickson & Plank, 1984; Hussain et *al.*, 2015). In order to cooperate, the individuals adapt their agenda according to personal preferences and limitations. The driver and vehicle selection, pick-up and drop-off order, and the preferred trip start time intervals of the optimal carpool group are evaluated by using scoring functions i.e. time of day, degree of flexibility and the time loss. The model presented in this chapter is considered to be final when the (i) aggregate behavior of the carpooling social network and (ii) personal preferences for the trips departure time are taken into account.

Chapter 5 further extends the agent-based carpooling simulation model by the use of disaggregate behavior of the carpooling social network (carpoolers behavior and network information) so that the complete carpooling problem can be examined. It presents a mechanism to model the interactions of autonomous agents which enables communication within CPSGs that coincide with the sets of agents working at a particular company or institution. The street addresses of the individuals are used to extract the actual trip duration information on the road network from the OSM dataset directly using the GraphHopper API. A GraphHopper server was set up to that end. A multiple trip negotiation model for work trips (HW and WH) is also presented which enables agents' matching. The driver and vehicle selection, pick-up and drop-off order and the preferred trip start times of feasible carpool groups are evaluated by means of scoring functions: (i) degree of flexibility and (ii) the time loss. The actual trips execution (carpooling) is considered where the trips are executed on long-term basis. The purpose of the research reported in this chapter is to investigate the computational performance of the model that contains all features described in this and previous chapters with the exception of the optimal trip start time determination using non-constant preference functions. The model presented in this chapter is considered to be final and can be chosen for a specific company or institution when the disaggregate behavior of the carpooling social network is taken into account.

Chapter 6 presents a matching support framework for employees who are candidates for carpooling and is based on the agent-based carpooling simulation model presented in chapter 5 of this dissertation. It aims to support large companies and institutions located in congested areas where parking space is expensive or scarce. The core objective is to show the feasibility of matching for recurrent travel demand. The goal is to notify people about new opportunities to find partners belonging to a closed managed group and interested in carpooling. The framework accounts for dynamic evolution of the extracted personnel database in order to minimize burden on the users. It matches candidates based on source and target locations as well as on the time windows specified by the interested candidates. The proposed framework finds suitable groups of people to carpool. For a given group, the timely feasible pick-up and drop-off orders are evaluated. Those are scored at the carpool level. The best groups are kept and presented to the group members who in turn evaluate them using their own individual scoring criteria and start negotiation to take the final decision. As a proof-of-concept of the proposed framework, experiments were conducted at the scale of the Doppahuis database. Supporting carpooling by personnel contributes to the mobility plan to be established by the company.

The **conclusions and recommendations** for the future research studies are presented after each part of the dissertation. This section discusses the main findings and implications of the different studies and concludes with some recommendations for future research possibilities.

1.8 References

Agatz, N., Erera, A., Savelsbergh, M., & Wang, X. (2012). Optimization for dynamic ride-sharing: A review. *European Journal of Operational Research*, *223*(2), 295–303. https://doi.org/10.1016/j.ejor.2012.05.028

Amey, A. M., Attanucci, J. P., Veneziano, D., & Ferreira, J. (2010). Real-Time Ridesharing: Exploring the Opportunities and Challenges of Designing a Technology-based Rideshare Trial for the MIT Community.

Bellemans, T., Kochan, B., Janssens, D., Wets, G., Arentze, T., & Timmermans, H. (2010). Implementation framework and development trajectory of FEATHERS activity-based simulation platform. *Transportation Research Record: Journal of the Transportation Research Board*, (2175), 111–119.

Belz, N., & Lee, B. (2012). Composition of Vehicle Occupancy for Journey-to-Work Trips. *Transportation Research Record: Journal of the Transportation Research Board, 2322, 1–9. https://doi.org/10.3141/2322-01*

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(Suppl 3), 7280–7287. http://doi.org/10.1073/pnas.082080899

Carpool. (n.d.). In Wikipedia. Retrieved August 31, 2017, from https://en.wikipedia.org/wiki/Carpool#cite_note-4

Carpooling.com. (n.d.). In Wikipedia. Retrieved August 31, 2017, from https://en.wikipedia.org/wiki/Carpooling.com

Cossentino, M., Gaud, N., Hilaire, V., Galland, S., & Koukam, A. (2010). ASPECS: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent Systems*, *20*(2), 260–304. https://doi.org/10.1007/s10458-009-9099-4

Dubernet, T., Rieser-Schüssler, N., & Axhausen, K. W. (2013). Using a Multi-agent Simulation Tool to Estimate the Carpooling Potential. Presented at the Transportation Research Board 92nd Annual Meeting.

Ferber, J., Gutknecht, O., & Michel, F. (2004). From Agents to Organizations: An Organizational View of Multi-agent Systems. In P. Giorgini, J. P. Müller, & J. Odell (Eds.), *Agent-Oriented Software Engineering IV: 4th InternationalWorkshop, AOSE 2003, Melbourne, Australia, July 15, 2003. Revised Papers* (pp. 214–230). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-24620-6_15

Furuhata, M., Dessouky, M., Ordóñez, F., Brunet, M.-E., Wang, X., & Koenig, S. (2013). Ridesharing: The state-of-the-art and future directions. *Transportation Research Part B: Methodological*, *57*, 28–46. https://doi.org/10.1016/j.trb.2013.08.012

Eva Kesternich, (2015), What factors explain carpoolers' decision to use carpooling matching platforms? : A survey-based observation of carpooling matching platforms in Europe, *master thesis report*, URL: http://essay.utwente.nl/66952/1/Kesternich_MA_BMS.pdf.

Gaud, N., Galland, S., Hilaire, V., & Koukam, A. (2009). An Organisational Platform for Holonic and Multiagent Systems. In K. V. Hindriks, A. Pokahr, & S. Sardina (Eds.), *Programming Multi-Agent Systems: 6th International Workshop, ProMAS 2008, Estoril, Portugal, May 13, 2008.* pp. 104–119, Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-03278-3_7

Hagan, M., & Dowd, B. (2013). Introduction and Commentary for Special Issue Simulation Techniques in Health Services Research. *Health Services Research*, *48*(2 Pt 2), 683–685. https://doi.org/10.1111/1475-6773.12053

Hartman, I. B.-A., Keren, D., Dbai, A. A., Cohen, E., Knapen, L., Yasar, A.-U.-H., & Janssens, D. (2014). Theory and Practice in Large Carpooling Problems. *The 5th International Conference on Ambient Systems, Networks and Technologies (ANT-2014), the 4th International Conference on Sustainable Energy Information Technology (SEIT-2014)*, *32*, 339–347. https://doi.org/10.1016/j.procs.2014.05.433

Hendrickson, C., & Plank, E. (1984). The flexibility of departure times for work trips. *Transportation Research Part A: General*, *18*(1), 25–36. https://doi.org/10.1016/0191-2607(84)90091-8

Hussain, I., Knapen, L., Galland, S., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016). Organizational-based model and agent-based simulation for long-term carpooling. *Future Generation Computer Systems*, *64*, 125–139. https://doi.org/10.1016/j.future.2016.02.019

Jennings, N. R. (2000). On agent-based software engineering. *Artificial Intelligence*, *117*(2), 277–296. https://doi.org/10.1016/S0004-3702(99)00107-1

Knapen, L., Cho, S., & Bellemans, T. (2013). Agent-based modeling for carpooling. *Data Science and Simulation in Transportation Research*, 232.

Knapen, L., Yasar, A., Cho, S., Keren, D., Dbai, A. A., Bellemans, T., … Bhaduri, K. (2014(a)). Exploiting graph-theoretic tools for matching in carpooling applications. *Journal of Ambient Intelligence and Humanized Computing*, *5*(3), 393–407. https://doi.org/10.1007/s12652-013-0197-4

Knapen, L., Bellemans, T., Usman, M., Janssens, D., & Wets, G. (2014(b)). Within day rescheduling microsimulation combined with macrosimulated traffic. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, 45, 99–118. https://doi.org/10.1016/j.trc.2014.04.012

Manzini R. and Pareschi, A., (2012), A Decision-Support System for the Car Pooling Problem, *Journal of Transportation Technologies,* Vol. 2 No. 2, pp. 85-101. doi: 10.4236/jtts.2012.22011.

Sm, S. (2005). Carpool Incentive Programs: Implementing Commuter Benefits as One of the Nation's Best Workplaces for Commuters.

Wauters R., (2014), Ride-sharing has arrived in Europe, and the race is on between BlaBlaCar and Carpooling.com*, Updated: February 7th, 2014, Retrieved: August 2017, http://tech.eu/features/481/ride-sharing-europe-carpooling-blablacar/*

Weyns, D., Van Dyke Parunak, H., Michel, F., Holvoet, T., & Ferber, J. (2005). Environments for Multiagent Systems State-of-the-Art and Research Challenges. In D. Weyns, H. Van Dyke Parunak, & F. Michel (Eds.), *Environments for Multi-Agent Systems: First International Workshop, E4MAS 2004, New York, NY, July 19, 2004, Revised Selected Papers* (pp. 1–47). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-32259-7_1

Zambonelli, F., Jennings, N. R., & Wooldridge, M. (2003). Developing Multiagent Systems: The Gaia Methodology. *ACM Trans. Softw. Eng. Methodol.*, *12*(3), 317–370. https://doi.org/10.1145/958961.958963

Part I

Agent-based Simulation Model for Carpooling

Chapter 2

TAZ-based Case Requiring Complete Path Matching

This chapter consists of following published paper

Hussain, I., et *al.* (2016(a)). Negotiation and Coordination in Carpooling. *Transportation Research Record: Journal of the Transportation Research Board*, 2542, 92–101. https://doi.org/10.3141/2542-11

Which is based on following conference papers

Hussain, I., et *al.* (2015a). An agent-based negotiation model for carpooling: A case study for Flanders (Belgium), *Transportation Research Board 94th Annual Meeting*, Location: Washington DC, United States, Date: 2015-1-11 to 2015-1-15.

Hussain, I., et *al.* (2015b). Agent-based negotiation model for long-term carpooling: A flexible mechanism for trip departure times. *Urban Transport XXI*, *146*, 461.

2.1 Overview

This chapter presents an agent based framework, set up to evaluate the evolution of a carpooling society under several conditions. It focuses on a simulation of a network of carpooling candidates. This chapter contributes to the PhD thesis by (1) enabling the interaction between individuals (agents) to restricted groups on the basis of their home and work TAZs (so that their trips are similar), (2) presenting a multiple-trip negotiation model based on the lifestyle factors that influence the departure time decision, on the profile of the individuals, and on the effect of constraining activities, (3) providing negotiation on trips (HW and WH) departure times and also on driver assignment and (4) covering the concept of communication, negotiation, and coordination for the long-term carpooling. It differs from the other chapters by (1) enabling interaction to restricted groups: only agents sharing home and work TAZ-locations can interact with each other and (2) the time preference function is based on an existing (Hendrickson and

Plank, 1984) study. The constraint that restricts cooperating carpoolers to share the respective home and work TAZs was removed in chapter 3, where sets of agents working in a particular TAZ and living in spatially dispersed TAZs are considered for co-traveling. In this chapter the evaluation process is not aimed to find the optimal passenger pick-up sequence. The base model presented in this chapter is used to measure the carpool potential on similar trips (the individuals share the *home* and *work* locations TAZ's respectively) and without taking into account the pick-up and drop-off orders of the passengers. The negotiation *outcome* is determined by a deterministic function based on the candidates profiles and time windows. The actual negotiation *process* is not simulated in detail.

2.2 Abstract

Carpooling enables commuters to share travel expenses, save costs, and improve their mobility options and reduces emission and traffic congestion. To commute by carpooling, individuals need to communicate, negotiate, and coordinate, and in most cases they need to adapt their schedule to enable cooperation. This paper presents the design of an agent-based model by defining phases and steps that may be taken to move from solo driving to carpooling. The paper analyzes the various effects of agent interaction and behavior adaptation for a set of candidate carpoolers. The start of the carpooling process depends on the individuals' objectives and intention to carpool. Through negotiation and coordination, individuals can reach complex agreements in an iterative way. The success of negotiation highly depends on the lifestyle factors that influence the departure time decision, on the profile of the individuals, and on the effect of constraining activities. The carpooling social network was established by use of the results predicted by FEATHERS, an operational activity based model for Flanders, Belgium. From the simulation's discussions, it is possible to portray the true picture of potential carpoolers throughout their carpooling period. The simulation results show that 9.33% of the commuters started to carpool when the time window was ±30 min and the average occupancy per car was 2.4 persons. When the time window was larger, the chances for negotiation success were greater than those when a smaller time window was used. Hence, carpooling requires time flexibility. The Janus (multi-agent) platform was used to simulate the interactions of autonomous agents.

Keywords: Commuting, carpooling, coordination and negotiation, trip start time, schedule adaptation, agent-based modeling.

2.3 Introduction

Carpooling is considered to be an effective alternative transportation mode that is ecologically friendly and sustainable. It enables commuters to share travel expenses, save on fuel and parking costs, and improve their mobility options. It also reduces emissions and traffic congestion. To commute by carpooling, individuals need to communicate, negotiate, and coordinate, and in most cases they need to adapt their schedule to enable cooperation. Furthermore, socioeconomic characteristics (SECs), including age, gender, income, education, relationship, job, and ownership of a vehicle and a driver's license, can play a vital role to find individuals favorable for carpooling. Each negotiation involves a small number of participants, but the schedules can be interconnected by cooperation (Knapen et al., 2014; Horvitz, et al., 2005). Although traditional modeling tools cannot handle the complexity of communication and negotiation for carpooling, agent-based models (ABMs) are able to do so through modeling of the interaction of agents. ABMs can provide valuable information on society and on the outcomes of social actions or phenomena. Many areas of research, including research on transportation behavior, need to analyze and model complex interactions between autonomous entities (Cho et al., 2013).

The aim of the research described here was to investigate the effect of communication, negotiation, and coordination for carpooling by taking into account the possibility of flexible activity scheduling. It also focused on a simulation aimed at the setting up of the framework and establishment of a network of carpooling candidates. To perceive the results, the carpooling-related actions performed by each individual were divided into the following steps: (a) social network identification, (b) exploration and communication, (c) negotiation, (d) coordination and schedule adaptation, and (e) trip execution (carpooling). These steps exemplify a model that represents an extension of the simple but analytically tractable model for carpooling (Hussain, et al., 2015; Hussain et al., 2014). During the exploration step, the agent looks for other individuals with whom to cooperate on commuting trips. The success of negotiation highly depends on lifestyle factors and on the effect of constraining activities that influence the departure time decision. The driver selection decision is based on the individual profile (ownership of a vehicle and a driver's license). For trip execution, carpoolers need to coordinate for long-term carpooling. The daily schedule of each individual, which repeats over the specified period, is considered.

The model is based on an agent- and organization-based metamodel, in which the role and organization are first-class entities (Cossentino, et al., 2010). The agents (individuals) can communicate with individuals within a small group sharing the same home and work travel analysis zones (TAZs) by taking SECs into account. Furthermore, they negotiate about the timing of trips [home to work (HW) and work to home (WH)] to adapt their schedules. The Janus multiagent-based platform, which provides an efficient means of implementation of agent- and organization-based concepts, was used (Gaud, et al., 2009).

This paper is organized as follows: first, related work on carpooling and agent-based modeling is briefly described. The first part of the description of the model covers practical concepts, and the second part explains the technical part of the carpooling model. Finally, simulation results, followed by conclusions and suggestions for future work, are presented.

2.4 Related Work

In recent years, agent-based simulation has come into use in the field of transportation science because of its ability to analyze the aggregated consequences of individual-specific variations in behavior. ABM can provide valuable information about society and the outcomes of social actions or phenomena. Existing work on the different types of negotiation techniques and models, joint activity and joint trip execution, long-term carpooling, and the trip start time in shared transport is described in this section.

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

In the context of travel demand, cooperation aspects apply to joint activity and joint trip execution. Ronald, et al., (2009) presented an ABM that focused on the negotiation methodology. The proposed model included a well-defined and structured interaction protocol: integration of the transport and social layers. A utility function based on individual and combined attributes was presented. The agents negotiate the type, location, and start time of a social activity. Lützenberger et al., (2011) introduced an approach that considers a driver's mind and examines the effect of environmental conditions. The authors planned to integrate the agent interactions necessary when carpooling. Kamar & Horvitz, (2009) described an ABM aiming to combine demand and supply in an optimal manner in an advisory system for frequent ridesharing. The authors focused on the mechanisms required to model users cooperating on joint plans and focused on the economic value of the shared plans. Knapen et al., (2014) presented an advisory automated, global carpooling matching service to match commuting trips for carpooling. The probability of successful negotiation was calculated by means of a learning mechanism. The matcher needs to deal with a dynamically changing graph with respect to topology and edge weights.

Varrentrapp, et al., (2002) provided an informal and formal declaration for the long-term carpooling problem. The soundness of the problem formulation was discussed, and some properties were verified. Finally, the problem proved to be NP-complete (where NP indicates nondeterministic polynomial time). This research assumed that carpools are stable in time and that every member in turn acts as the driver. Manzini & Pareschi, (2012) described an interactive system to support the mobility manager (officer) operating on the long-term carpooling problem. The proposed methods and models made use of clustering analysis. The basic hypothesis was that in a given generic group, the participants in the group take turns being the driver of the shared car. Clustering procedures that use methods available in standard decision support systems were proposed. After clustering, for each driver a traveling salesman problem was solved.

Hendrickson and Plank studied the flexibility in trip departure times of individuals, focusing on fixed HW trips (Hendrickson & Plank, 1984). The authors developed a multinomial logit (MNL) model to estimate the relation and significance of different attributes influencing the choice of transport mode and trip departure time. The authors proposed an equation to define the personal utility or preferences for a given set of departure times for the work trip. For the departure time choices, Hussain, et al., (2015) acquired the MNL model of Hendrickson & Plank, (1984) for work trips. The authors used coefficients for the shared mode only and made it continuous by taking different departure time intervals of 1 min instead of 10 min.

2.5 Agent-based Model for Carpooling

An ABM for cooperative travel was simulated to account for individual-specific behavior during the carpooling process. The purpose was to find out how much people need to adapt their daily schedule to enable cooperation in a given area and how participation in carpooling evolves over time. The agents can interact with each other autonomously to find matching partners to co-travel in several different consecutive carpools, each of which corresponds to a multiday period. The aim of the simulation is to find out how carpool groups are formed and the share of carpooling among the available transportation modes, given behavioral constraints with respect to timing.

In this simulation model of the evolution of carpooling, the commuting trips in daily schedules (HW and WH) are specifically detailed and discussed as they relate to long-term carpooling. The set of other activities, including pickup and drop-off activities and shopping, are also considered to measure the effect of their presence on carpooling for commuting trips. Home and work locations, trip start times (HW and WH), trip durations, activity duration, and SECs (including ownership of a vehicle and a driver's license) are used as input data. The selection of a driver is based on inspection of the individuals' profiles (ownership of a vehicle and a driver's license). The preference time function is used to adapt the trip start times of an individual. The selection of the most preferred trip departure time, partly derived from existing departure time studies, is based on a number of factors, namely, (a) traveling factors, (b) socioeconomic factors, and (c) time pressure factors. For the departure time choices, the authors acquired the MNL model of Hendrickson & Plank, (1984) for the work trips and also extended the work presented elsewhere Hussain, et al., (2015) by applying constraining activities before or after the trips.

For the experiments described in this paper, the operational activity-based model for the region of Flanders, Belgium, FEATHERS, was used to generate a planned agenda for each member of the synthetic population (Bellemans et al., 2010). Those schedules represent the planned agendas for mutually independent individuals using an undisturbed transportation network. The initial daily plans are assumed to be optimal, that is, to generate maximal utility and, hence, to reflect each owner's preferences.

The agent is someone who lives in the study area and executes his or her daily schedule to satisfy his or her needs. A daily schedule is a combination of activities and trips with a specified start time and duration of each activity and trip. The modeling structure claims that individuals spend the day taking part in activities and traveling between activity locations.

Microscopic routing and rerouting and traffic simulation are not required in this model because the main focus of the model is on negotiation about future trips. The proposed model has no information about carpool parking; therefore, it is assumed that people board and alight at home and work locations only. The framework is based on estimated travel times for traffic flows between TAZs.

Those travel times are assumed to be common knowledge owned by the participating agents. Each agent follows a number of steps, including goal setting, exploration, schedule adaptation through negotiation, and execution of the agent's schedule. These steps are modeled for a specified time period (e.g., number of years) according to the activity diagram shown in Figure 2.1.

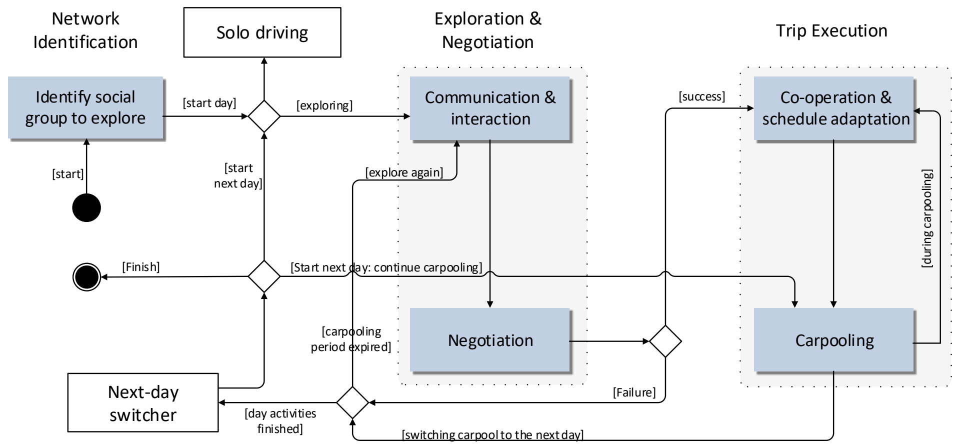


Figure 2.1. Activity diagram of an agent. Agents may repeat their activities in the exploration and negotiation phases and in the trip execution phase during the simulation period.

2.5.1 Network Identification: Carpooling Social Network

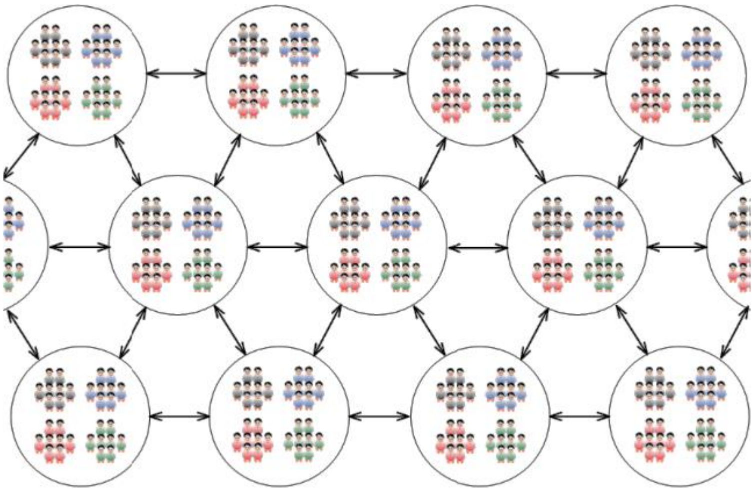
The carpooling social network is made up of nodes representing individuals and links defined by one or more specific types of interdependency. It slightly differs from general social networks:

1. First, the carpooling social network considers not only sociodemographic attributes but also spatiotemporal attributes, that is, activity or trip start times and home and work locations.
2. Second, a carpooling social network is specifically aimed at carpool partner selection and the interaction between participants.

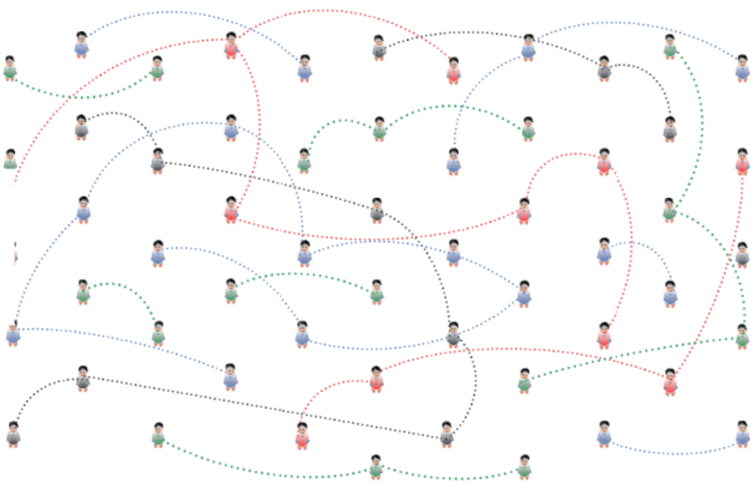
The authors assumed that if individuals have any features similar to those of other individuals, such as job, age, education, or home or work locations, then they have a relationship with each other. In this model, the strength of the relationship can be measured by calculation of the number of similar attributes for the agents. It is difficult to find an ideal carpool partner from a large network space. The authors first segmented the partial area into TAZs and then divided the population into different groups on the basis of trip similarity (same origin and destination) relationships (Figure 2.2*a*). The authors assumed that the individuals who live closer to each other have a strong relationship for carpooling. Within these social groups, individuals can interact and negotiate with each other to enable carpooling (Figure 2.2*b*).

The social network is subdivided into disconnected components, each one of which corresponds to a particular TAZ pair (*A*,*B*). An agent joins the group for (*A*,*B*) if and only if she or he lives in *A* and works in *B.*

If n locations exist, the social network contains at most $n(n-1)$ components.



(a)



(b)

Figure 2.2. Segmentation of a carpooling social network : (a) social network segmented into TAZs and further segmented into components (groups) according to trip similarity and (b) interaction of agents in given zone (agents and lines identifying their relationships are shown in the same color).

2.5.2 Interaction and Communication

Each agent looks for other individuals to cooperate with while executing its periodic trips by exploring the carpooling social network. Only agents sharing home and work locations (so that their trips are similar) can interact with each other. This constraint was removed in the new model, which was being evaluated at the time of writing of this paper.

The relationship information for the carpoolers can provide the path, profile, and time interval similarities. Each agent initially has a basic set of communication characteristics, such as common interests and requirements. To interact, the interests and requirements for the respective agents need to match sufficiently well. Interests and requirements are conveyed by means of a *CarpoolInvitation* message:

CarpoolInvitation = {interest, requirements}

where interests is the common interest in the intention to carpool, and requirements are the traveling route, time, and travel cost.

2.5.3 Negotiation

The matching is applied in the negotiation phase, where final decisions to carpool are taken. The agents negotiate on trip (HW and WH) departure times and also about who will become the driver. The schedule adaptation depends on the preferences among the feasible schedules of the individuals. The negotiation for both trips (HW and WH) becomes successful only when the preferred trip start times are compatible among all candidates within the carpool.

This model comprises symmetrical commuting trips and is assumed to be realistic; although it induces more stringent timing constraints, it avoids multiparty negotiations, which require a large mental effort.

2.5.3.1 Negotiation for Driver and Vehicle Selection

Driver and vehicle selection is based on inspection of the individuals' profiles. Each agent who owns a car and a driver's license may become the driver when carpooling.

2.5.3.2 Negotiation for Trips Departure Time

2.5.3.2.1 Preference Time Function

Two factors affect the preference function for the trip departure time of an agent:

1. the SEC, consisting of the ratio of travel cost to annual income, helps to quantify the concept of the value of time for departure at a particular time in the given time interval, and
2. the individuals' levels of tolerance for arriving late or early for a specific activity indicate the level of rigidity of the starting times of different activities.

To construct a behaviorally accurate method for trip start times, the departure time choice MNL model of (Hendrickson & Plank, 1984) for work trips was used. Hendrickson and Plank used a set of data gathered in Pittsburgh, Pennsylvania, for the express purpose of analysis of dynamic level-of-service variations and departure time decisions. Collection of the data for that dataset involved independent measurement of travel times and transit wait times for travel to the Pittsburgh central business district. The base model of Hendrickson and Plank included up to 28 alternatives, indicating combinations of four modes (drive alone, shared ride, transit with walk access, and transit with auto access) and seven different departure time intervals of 10 min each. People do not have a constant level of preference for every moment in the entire feasible time interval for many reasons (e.g., time pressure).

Equation 1 was used to determine the actual utility value of a particular agent to depart at a specific time in its available time window.

Consider N agents a_1, a_2, . . . , a_N and consider departure times $t_1, t_2, t_3 \ldots, t_T$ available among the set of departure times T. The utility or preference for a particular time t_j of an agent a_i ($V_{a_i t_j}$) is specified to be:

$$
\begin{aligned}
V_{a_i t_j} = -2.09 - 0.008(FFTT_{a_i}) - 0.021\left(CONG_{t_j}\right) - 0.699\left(\frac{COST}{INCOME}\right)_{a_i t_j} \\
- 0.095\left(ACC_{a_i t_j}\right) - 0.088\left(WAIT_{a_i t_j}\right) - 0.148\left(LATE_{a_i t_j}\right) \\
+ 0.0014\left(LATE_{a_i t_j}\right)^2 - 0.01\left(EARLY_{a_i t_j}\right) \\
- 0.00042\left(EARLY_{a_i t_j}\right)^2
\end{aligned}
\tag{1}
$$

where the coefficients are taken from the study of Hendrickson & Plank, (1984) for the specific mode (shared transport) and the variables are defined as follows for a_i:

$FFTT_{a_i}$: free-flow travel time in the carpool vehicle (i.e., 75% of the travel time during the peak period and 90% otherwise; a negative coefficient is expected because an increase in the travel time would discourage carpooling);

$CONG_{\ t_j}$: portion of the travel time associated with congestion at the departure time (i.e., 25% of the travel time during the peak time and 10% otherwise);

$(\frac{COST}{INCOME})_{a_i t_j}$: ratio of annual cost of carpooling to income level per annum, which depends on the time of day because toll and parking charges are included and those can be dependent on the time of day;

$ACC_{\ a_i t_j}$: walking time at the end of a transit trip associated with departure time ($ACC_{\ a_i t_j}$ provides a measure of the accessibility of transit service to the traveler and is included for the transit with walk access mode; the subscript t_j allows variations in access time associated with different departure times);

$WAIT_{\ a_i t_j}$: waiting time with respect to the individual's most preferred time to depart;

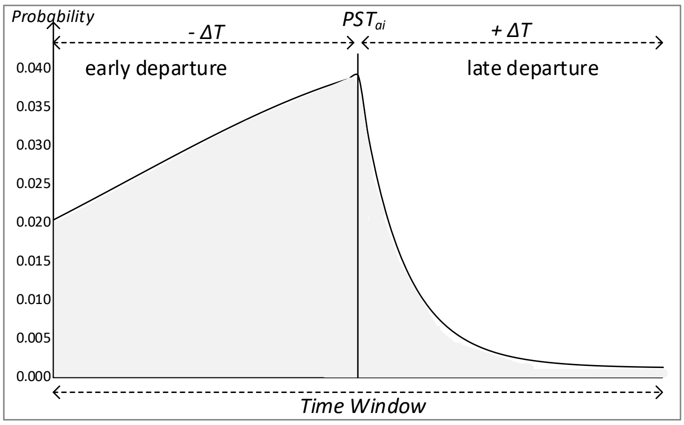
$LATE_{\ a_i t_j}$: number of minutes of late arrival at work associated with the departure time; [$\left(LATE_{\ a_i t_j}\right)^2$ is used to represent more accurately individual perceptions of a late arrival at work]; and.

$EARLY_{\ a_i t_j}$: number of minutes of early arrival at work associated with the departure time [the magnitude for the coefficient $EARLY_{\ a_i t_j}$ (.01 was used here) was smaller than that for the coefficient $LATE_{\ a_i t_j}$: this was done because a late arrival at work is believed to be more onerous than an early arrival; as with $\left(LATE_{\ a_i t_j}\right)^2$, $\left(EARLY_{\ a_i t_j}\right)^2$ is used to represent more accurately individual perceptions of an early arrival at work, but a negative coefficient is anticipated to reflect the increasing disutility associated with earlier arrivals at the workplace].

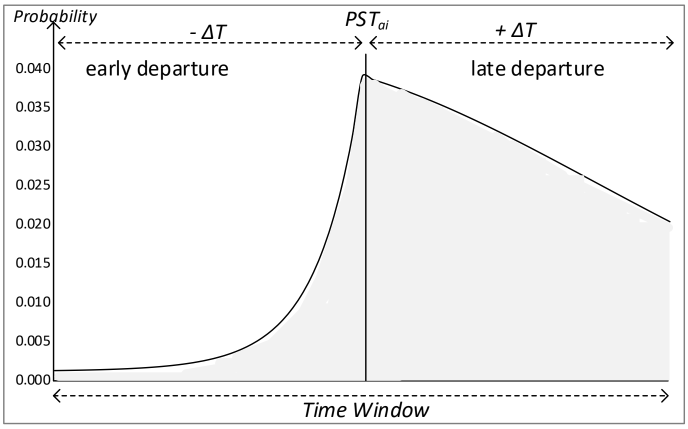
The departure time choices are treated as a simultaneous interactive decision on the basis of maximization of the satisfaction of individual travelers with each departure time combination. The probability that an individual will select departure time alternative $P_{a_i t_j}$ of the carpool is given by Equation 2:

$$P_{a_i t_j} = \frac{exp(V_{\ a_i t_j})}{\sum_T exp(V_{\ a_i T})} \tag{2}$$

The probability can be calculated for the discrete cases mentioned by (Hendrickson & Plank, 1984). The results were used to construct the continuous preference function for the morning case (Figure 2.3*a*) because, for the simulation, the individual probability value for each possible trip start time in the candidate specific time window [e.g., the optimal time window $\pm\Delta t$) of 30 min] needs to be calculated. The preference function for the evening case (WH trip) was created by mirroring of the function for the HW trip around the time value for which the maximum probability was reached (Figure 2.3*b*).



(a)



(b)

Figure 2.3. Departure time probability curves for an agent a_i: (a) for morning and (b) evening trips.

2.5.3.2.2 Time Intervals Similarities

After the assignment of an individual preference function on the basis of the factors elaborated above for each agent, a negotiation mechanism was used to determine the carpool trip departure time.

For agent a_i, the earliest and latest departure times for the trip are TW_{L,a_i} and TW_{U,a_i}, respectively (i.e., the lower and upper bounds for the time window, respectively). The preferred trip start time of agent a_i is PST_{Trip,a_i}.

In the simplest case, the individual is assumed to accept a symmetric maximum deviation ($\pm\Delta T$) of the preferred trip start time. In general, this is not necessarily true, because preceding or succeeding activities can induce timing constraints. The possible cases for the constraining activities are as follows:

1. The possible lower and upper bounds for the preferences of a_i for both trips (HW and WH) without any constraining activities are given by Equation 3:

$$\begin{aligned} TW_{L,a_i} &= PST_{Trip,a_i} - \Delta T \\ TW_{U,a_i} &= PST_{Trip,a_i} + \Delta T \end{aligned} \tag{3}$$

2. Equation 4 helps to determine the lower and upper limits of the departure time window for the morning trip of agent a_i who has certain fixed constraining activities before the morning trip. CA_{fTime,a_i} is the finishing time of a constraining activity.

$$\overline{\Delta T} = PST_{HWTrip,a_i} - CA_{fTime,a_i}$$

$$\begin{aligned} TW_{HWLower,a_i} &= PST_{HWTrip,a_i} - \overline{\Delta T} \\ TW_{HWUpper,a_i} &= PST_{HWTrip,a_i} + \Delta T \end{aligned} \tag{4}$$

3. When a constraining activity is scheduled immediately after the work activity at the work location, then the lower bound for the WH trip departure time for agent a_i is CA_{fTime,a_i}, as in Equation 5:

$$\begin{aligned} TW_{WHLower,a_i} &= CA_{fTime,a_i} \\ TW_{WHUpper,a_i} &= PST_{WHTrip,a_i} + \Delta T \end{aligned} \tag{5}$$

4. When the constraining activity scheduled after the work activity is at any location different from the work location and if timely arrival for that activity is compulsory, then the upper bound of the time window for a_i depends on the start time of constraining activity $CA_{startTime,a_i}$, as in Equation 6:

$$\overline{\Delta T} = CA_{startTime,a_i} - PST_{WHTrip,a_i}$$

$$\begin{aligned} TW_{WHLower,a_i} &= PST_{WHTrip,a_i} - \Delta T \\ TW_{WHUpper,a_i} &= PST_{WHTrip,a_i} + \overline{\Delta T} \end{aligned} \tag{6}$$

The negotiation outcome needs to be within the intersection of the time intervals of the individuals. The time intervals are proposed by consideration of all possible constraining activities (Figure 2.4). Equation 7 shows the lower and upper bounds for the trip of the carpool; the indices used for the maximization function range over the set of candidate participants.

The available time intervals for the carpool are given by Equation 7, where the index j identifies the carpool participant candidate.

$$TW_{L,carpool} = \max_{j=1...N}(TW_{L,j})$$
$$TW_{U,carpool} = \min_{j=1...N}(TW_{U,j}) \quad (7)$$

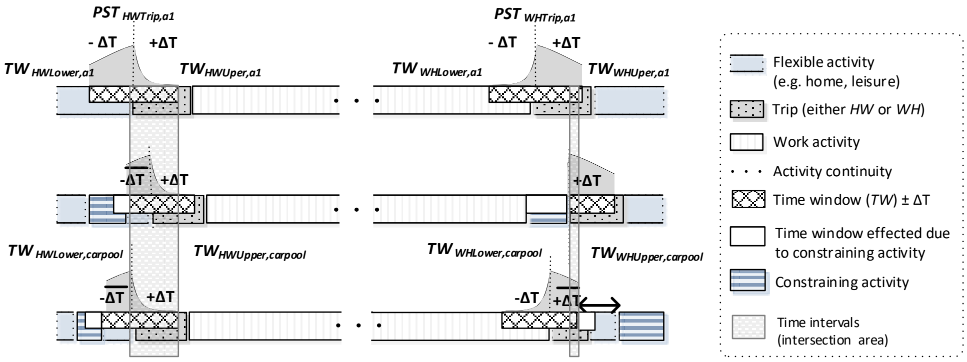


Figure 2.4. Negotiation success on trips (HW and WH) departure times for agents in a carpool by consideration of all possible constraining activities.

The probability density for the trip start time for an individual is determined by normalization of the preference function so that its integral equals 1. The probability that a start time can be found for a particular agent in the period of time that suits every candidate is given by the integral of the probability density for that participant over the intersection of all feasible intervals. For practical reasons, integration is done numerically under the assumption that the probability is constant in every 1-min period. The probability that a trip start time that suits everyone will be found ($P_{carpool}$) is given by the product probabilities to find a suitable solution for each carpool participant in the intersection of the time intervals:

$$P_{carpool} = \prod_{i=0}^{n} \sum_{j=TW_{L,carpool}}^{TW_{U,carpool}} \left(P_{a_i t_j}\right) \quad (8)$$

The negotiation is assumed to succeed if and only if

$$P_{carpool} > threshold \quad (9)$$

As soon as it becomes clear that candidates will carpool, the trip start time needs to be determined. Therefore, the preference function is used. For every agent, the preference for a given departure time is proportional to the probability that the person will select that time (because of the normalization mentioned above).

$$V_{a_i t_j} = k(P_{a_i t_j}) \quad (10)$$

where k is a proportionality constant.

The authors assumed that the combined preference for all carpoolers is the product of the preference values.

$$V_{carpool,t_j} = \prod_{i \in carpool} (V_{a_i t_j}) \tag{11}$$

The effective trip start time of the carpool ($TST_{carpool}$) is the point in time resulting in the largest collective preference value; it is given by

$$TST_{carpool} = \underset{j=TW_{L,carpool} \, to \, TW_{U,carpool}}{arg\,max} (V_{carpool,t_j}) \tag{12}$$

For the evening (WH) trip, the probabilities of the departure time alternatives of the morning trip (HW) were taken, but they were mirrored in time.

In the simulation, for the start time of HW and WH trips, the negotiation succeeds if and only if

$$\prod_{i=0}^{n} \sum_{j=TW_{HWL,carpool}}^{TW_{HWU,carpool}} (P_{a_i t_j}) > \ threshold$$
$$AND \tag{13}$$
$$\prod_{i=0}^{n} \sum_{j=TW_{WHL,carpool}}^{TW_{WHU,carpool}} (P_{a_i t_j}) > \ threshold$$

The effective trip start times of the carpooling trips (HW and WH) are given by Equation 14:

$$\underset{j=TW_{HWL,carpool} \, to \, TW_{HWU,carpool}}{arg\,max} (V_{carpool,t_j})$$
$$AND \tag{14}$$
$$\underset{j=TW_{WHL,carpool} \, to \, TW_{WHU,carpool}}{arg\,max} (V_{carpool,t_j})$$

After successful negotiation, the carpool participants adjust their schedule. The individual's resulting schedule applies to every working day during the period of carpooling.

2.5.4 Cooperation and Schedule Adaptation

The negotiation becomes successful when the negotiators adapt their daily schedule to enable cooperation. In general, during this step the carpoolers agree on pickup times, the pickup and drop-off order, and the trip start times (for HW and WH) of the carpool, taking into account the constraints imposed by their agendas. During the negotiation, each individual specifies the period (number of days) during which he or she will carpool for the trip.

During carpooling, when someone leaves the carpool permanently or a new individual joins the carpool, then the remaining carpoolers may renegotiate and adapt their carpool trip start times for both trips. Note that this negotiation does not necessarily succeed. When the driver decides to leave the carpool, she or he will assign the driving responsibilities to the passenger with a vehicle and a driver's license.

2.5.5 Trip Execution or Carpooling

The carpooling activity corresponds to the execution of the trips (HW and WH) over multiple 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 locations have been computed a priori and are assumed to be time independent. This feature is to be refined by making the negotiation aware of the time-dependent travel time.

During the carpooling trips, the carpoolers need to communicate and negotiate with each other when someone wants to join the carpool or decides to leave the carpool. Either the driver or a passenger may leave the carpool, which requires renegotiation of the start time of both trips (HW and WH). The handling of incoming invitations during the carpool lifetime requires additional negotiation between the carpoolers and the new candidates that will join the carpool. An individual who once left the carpool can again interact with the individuals in the carpool of his or her interest to enable carpooling.

2.6 Simulation Results and Discussions

The proposed model was run for data created by the FEATHERS activity-based model for the Flanders region. The Flanders region has about 6 million inhabitants. The area is subdivided into 2,386 zones. People working in the zone in which they live are not considered to be carpooling candidates since a zone covers only 5 km^2. According to the data, some individuals performed more than one work activity in a day at either the same work location or different work locations. Each individual considers the full schedule, including the constraining activities (before or after the commuting trips, or both). The negotiation is successful only when the individuals' preferred trip start times are compatible within the carpool for both commuting trips (HW and WH).

For the experiment, the sorted data file created by FEATHERS was used to obtain the following data and constraints according to home and work combinations:

No. of individuals:	30,000 individuals from a set of selected zones;
Network exploration:	five other people at most during every simulated day (i.e., an exploring individual is allowed to contact at most five other people during every simulated day);
Probability of invitation:	if the probability is 100%, carpooling requests must be sent; otherwise, no requests may be sent;
Carpool period:	random selection by a carpooler of a number ranging from 30 to 60 to determine the number of working days to carpool;
Carpool size:	four people at most (the driver included);
Threshold value:	probability threshold with constraining activities of .8, .7, .6, .5, .4, .3, and .2 by use of a constant time window ($\pm\Delta T$) of 30 min;
Time window ($\pm\Delta T$):	time window with constraining activities of 5, 10, 15, 20, 25, and 30 min with a probability threshold of 0.3; and
Simulation period:	150 working days.

Data from Flanders were used (Figure 2.5*a*). The commuting trips for carpooling could be taken throughout or outside of the Flanders region. According to the selected data, the 61 HW combinations (social groups) created by the simulation and each agent were assigned to exactly one such group. Within these social groups, individuals could interact and negotiate with each other to enable carpooling. The value of the probability of success was determined by the level of flexibility in adaptation to trip start times. These probabilities were termed threshold points and served as success criteria that determined the fate of the negotiation process (Figure 2.5*b*).

Figure 2.5*c* represents the active carpool groups throughout the simulation period for time windows of 5, 10, 15, 20, 25, and 30 min with a constant probability threshold of .3. The horizontal axis shows the number of working days, and the vertical axis represents the number of active carpool groups for each day. For each curve, active carpool groups existed on the initial day of the simulation because carpool groups are always created up to 30 days in advance. Starting on the simulated day, the curves show a dramatic decrease before stabilization because new carpoolers seem to join existing groups rather than create new ones. It seems to be easier to join an existing group than to create a new one. The gradual increase occurring after 45 days is explained by the decreasing possibility that an individual may join an existing carpool because of the limited car capacity. After the initial period, the remaining part of the curves levels off with minor fluctuations to the end of the simulation.

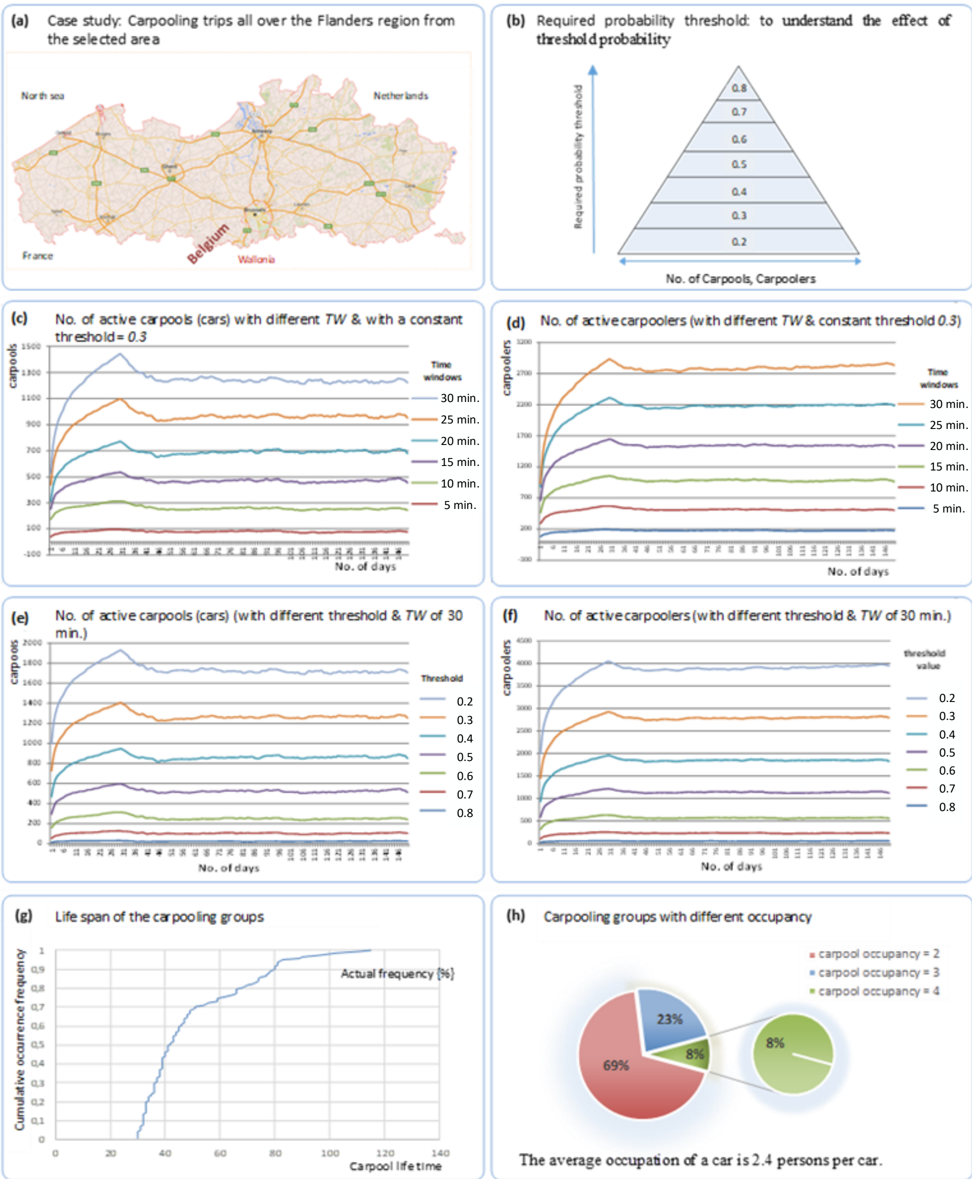


Figure 2.5. Results of the experiments (a) Map of Flanders region (study area), (b) threshold points that serve as success criteria to determine fate of negotiation process, (c) number of active cars and (d) number of active carpoolers determined by use by time window, (e) number of active cars and (f) number of active carpoolers determined by use by probability threshold point, (g) life span of carpools, and (h) carpool occupancy (average occupation of a car = 2.4 persons).

In Figure 2.5*d,* the line graph shows the number of active carpoolers over the 150 working days of the simulation. The graph contains six lines, representing active carpoolers for time windows of 5, 10, 15, 20, 25, and 30 min, respectively, each one with a constant probability threshold of .3. For each time window, the number of active carpoolers rapidly increases at the start of the simulation up to 30 days because every noncarpooling individual tries to join a carpool and nobody leaves a carpool. After 30 days, some participants decide to leave a carpool and the increase in the rate is lower to the end of the simulation. Figure 5*d* shows that the chances for negotiation success are greater when the time window is larger than when it is smaller.

The graphs in Figure 2.5*e* and 2.5*f,* represent the active carpool groups and active carpoolers for probability threshold values of .8, .7, .6, .5, .4, .3, and .2 with a constant time window of 30 min. The pattern of each curve for the graphs in Figure 5, *e* and *f,* is related to the graphs in Figure 5, *c* and *d,* respectively. Figure 5*f* shows that large numbers of people get involved in carpooling when the threshold probability value is set lower (i.e., at .2). For a higher threshold probability (i.e., .8) the criterion becomes very strict and, hence, the number of carpoolers is significantly reduced.

Figure 2.5*g* and 2.5*h*, shows the life span of the carpools according to carpool occupancy. Data for 1,000 individuals were used as the input. A total of 141 carpools were created: 12 of them had an occupancy of four agents in each carpool, 32 carpools had an occupancy of three agents, and the remaining 97 carpools contained two agents each. The average life spans of the carpools with two, three, and four people were 38.5, 69.8, and 91.3 days, respectively. Figure 5*g* shows the actual frequency of occurrence of carpools, with the cumulative frequency of occurrence being shown on the *y*-axis and the carpool lifetime being shown on the *x*-axis. The diagram shows that the life span grows with a higher occupancy. A carpool with an occupancy of two agents is terminated as soon as one of them quits, but when the carpool has three or more members, the carpool continues to exist when a single member quits and someone else (or the same individual) may join the same carpool. These facts cause high-occupancy carpools to live longer. The pie chart in Figure 5*h* presents the percentages of carpools with different occupancies (two, three, and four people). According to the results, 69%, 23%, and 8% of the carpools with occupancies of two, three, and four people, respectively, were created.

Carpooling requires time flexibility. For time windows of 5, 10, 15, 20, 25, and 30 min and with a constant probability threshold of .3, it was observed that 0.66%, 1.66%, 3.2%, 5.13%, 7.33%, and 9.33% of the commuters, respectively, started to carpool within the simulation period. The 2012 and 2013 Flemish travel survey [Onderzoek Verplaatsingsgedrag Vlaanderen (OVG)] showed that 8.85% and 9.51% of the 1,600 respondents, respectively, carpooled for HW commuting (Declercq, et al., 2014). The average car occupancy was 2.4 persons per car in the 2013 OVG and 2.46 persons per car in the 2013 OVG. If a time window of 30 min and a probability threshold of 0.3 are used in the simulation, the results of the simulation are good according to the 2013 OVG.

The model described here requires that all carpool participants share the origin TAZ as well as the destination TAZ. The model extension that is currently used no longer suffers from this constraint; it allows the path of one participant to be a subpath of the path of another participant. The car trip (and timing for passenger boarding and alighting) therefore depends on the selection of the driver. This information is used to select the optimal driver. The additional results will be published in a follow-up paper (Hussain et al., 2016). The simulation model has scalability issues that have yet to be solved. Indeed, it is necessary to consider a sufficiently large study region.

2.7 Conclusion and Future Work

Modeling of the interaction between individual agents has become progressively more important in recent research. As a consequence, ABMs are becoming required tools in the domain of transportation. An agent-based framework was set up by use of the Janus organization-based framework to evaluate the evolution of a carpooling society under several conditions. The model aimed to analyze various effects of the interaction of agents and the adaptation of behavior. This research covered the concept of communication, negotiation, and coordination in a multiple-trip model of carpooling and took into account the possibility of scheduling of flexible activities. The experiments also tried to limit the amount of communication between agents by restricting communication to groups on the basis of their home and work locations. The agents negotiated trip (morning and evening) departure times and driver assignment.

Because of many factors, people do not have a constant level of preference for every moment in the entire feasible time interval. To construct a behaviorally accurate method for determination of trip start times, the departure time choice MNL model of Hendrickson & Plank, (1984) for work trips was used. Driver selection depends on the individual profile (ownership of a vehicle and a driver's license). The schedule (with constraining activities) for each individual was taken from data from FEATHERS, an activity-based model for the Flanders region of Belgium. The results showed that when the probabilities of the preferences of individuals with a lower threshold value were compared and when the time window was larger, the chances for a successful negotiation were greater.

Future research will mainly focus on the effect of schedule adaptation and enhancement of the mechanisms for communication and negotiation between agents. The sets of agents working in a particular TAZ and living in spatially dispersed zones will be important considerations in that future work.

2.8 Critical Reflection

1. The individuals' behavior for carpooling experience (either good or bad) and their daily feedback is not modeled and taken into account in the presented carpooling model. This is important but requires a comprehensive behavioral model and it will be considered in the future research. In this model, the carpoolers terminate carpooling in following cases: (a) when their carpooling period expires (b) when the carpooling period for someone else in the group expires and either there is no longer a driver or only one traveler remains.

2. The *network identification* step is used to breakdown the carpooling social network into carpooling social groups (CPSGs) within which the individuals can interact. The *communication and interaction* step covers the concepts of communication, negotiation and coordination for the agents. Both the steps are presented separately because the network identification step executed only once while the communication and interaction step is iterative and executes throughout the simulation period.

3. For an individual, a parameter "probabilityToInvite" is used in the presented simulation model which considered the interest or intention to invite someone for carpooling. If e.g. *probabilityToInvite* = 30%, means that 30% randomly chosen simulated (non-carpooling) individuals have the intention or interest to invite someone for carpooling. If we set this parameter to 100% then it guaranteed that everyone who fulfilled conditions is allowed to find a carpool group; in that case, this setting cannot induce an artificial upper limit to participate in carpooling.

4. The coefficients used in the Equation (1) are taken from the study of Hendrickson & Plank, (1984) for the specific mode (shared transport) to represent the effects of unspecified mode dependent characteristics. The base mode for these constants is transit (early and late arrival) with walk access. For this model estimation, the observations included 363 residents of four sub-urban areas.

   Although, there might be some concerns regarding the validity of the model coefficients of the proposed preference function for European region as originally it was designed on the basis of a survey conducted in an American State. However, the selected approach towards the construction of a close-to-reality individualized preference function for each agent in the population can eventually turn out to be helpful for future studies and only a few adjustments to the coefficients of the *multinomial logit model* will lead to a model that will be accurately representative of the actual negotiation mechanism specifically for Flanders, Belgium. However, the construction of behaviorally accurate agent based models require an extensive and detailed database in order to simulate the actual mechanism.

5. The formal schedule adaptation mechanism is not provided in this chapter because each time the negotiation *outcome* is determined by a deterministic function based on the candidates' profiles and time windows. The actual negotiation *process* is not simulated in detail. Modeling the negotiation process only makes sense in more detailed models like the one described in chapter 5.
6. There is not any related work found in the literature which demonstrated the *long-term carpooling* to which compare the final results. Some of the experimental results of this chapter are compared with the OVG dataset.

2.9 References

Bellemans, T., Kochan, B., Janssens, D., Wets, G., Arentze, T., & Timmermans, H. (2010). Implementation framework and development trajectory of FEATHERS activity-based simulation platform. *Transportation Research Record: Journal of the Transportation Research Board*, (2175), 111–119.

Cho, S., YASAR, A., Knapen, L., Patil, B., Bellemans, T., Janssens, D., & Wets, G. (2013). Social networks in agent-based models for carpooling.

Cossentino, M., Gaud, N., Hilaire, V., Galland, S., & Koukam, A. (2010). ASPECS: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent Systems*, *20*(2), 260–304. https://doi.org/10.1007/s10458-009-9099-4

Declercq, K., Janssens, D., & Wets, G. (2014). Onderzoek Verplaatsingsgedrag Vlaanderen 4.5 (2012-2013): Tabellenrapport.

Galland, S., Knapen, L., Yasar, A.-U.-H., Gaud, N., Janssens, D., Lamotte, O., … Wets, G. (2014). Multi-agent simulation of individual mobility behavior in carpooling. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, *45*, 83–98. https://doi.org/10.1016/j.trc.2013.12.012

Gaud, N., Galland, S., Hilaire, V., & Koukam, A. (2009). An Organisational Platform for Holonic and Multiagent Systems. In K. V. Hindriks, A. Pokahr, & S. Sardina (Eds.), *Programming Multi-Agent Systems: 6th International Workshop, ProMAS 2008, Estoril, Portugal, May 13, 2008. Revised Invited and Selected Papers* (pp. 104–119). Berlin, Heidelberg: Springer Berlin Heidelberg.
https://doi.org/10.1007/978-3-642-03278-3_7

Hendrickson, C., & Plank, E. (1984). The flexibility of departure times for work trips. *Transportation Research Part A: General*, *18*(1), 25–36. https://doi.org/10.1016/0191-2607(84)90091-8

Horvitz, E., Apacible, J., Sarin, R., & Liao, L. (2005). Prediction, Expectation, and Surprise: Methods, Designs, and Study of a Deployed Traffic Forecasting Service. In *Proceedings of the Twenty-First Conference on Uncertainty in Artificial Intelligence* (pp. 275–283). Arlington, Virginia, United States: AUAI Press. Retrieved from http://dl.acm.org/citation.cfm?id=3020336.3020371

Hussain, I., Knapen, L., Galland, S., Janssens, D., Bellemans, T., Yasar, A.-U.-H., & Wets, G. (2014). Organizational and Agent-based Automated Negotiation Model for Carpooling. *The 5th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2014)/ The 4th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH 2014)/ Affiliated Workshops*, *37*, 396–403. https://doi.org/10.1016/j.procs.2014.08.059

Hussain, I., Knapen, L., Bellemans, T., Janssens, D., & Wets, G. (2015a). An agent-based negotiation model for carpooling: A case study for Flanders (Belgium), Transportation Research Board 94th Annual Meeting, Location: Washington DC, United States, Date: 2015-1-11 to 2015-1-15.

Hussain, I., Knapen, L., Khan, M. A., Bellemans, T., Janssens, D., & Wets, G. (2015b). Agent-based negotiation model for long-term carpooling: A flexible mechanism for trip departure times. *Urban Transport XXI*, *146*, 461.

Hussain, I., Knapen, L., Galland, S., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016). Organizational-based model and agent-based simulation for long-term carpooling. *Future Generation Computer Systems*, *64*, 125–139. https://doi.org/10.1016/j.future.2016.02.019

Kamar, E., & Horvitz, E. (2009). Collaboration and Shared Plans in the Open World: Studies of Ridesharing. In *Proceedings of the 21st International Jont Conference on Artifical Intelligence* (pp. 187–194). San Francisco, CA, USA: Morgan Kaufmann Publishers Inc. Retrieved from http://dl.acm.org/citation.cfm?id=1661445.1661476

Knapen, L., Yasar, A., Cho, S., Keren, D., Dbai, A. A., Bellemans, T., … Bhaduri, K. (2014). Exploiting graph-theoretic tools for matching in carpooling applications. *Journal of Ambient Intelligence and Humanized Computing*, *5*(3), 393–407.

https://doi.org/10.1007/s12652-013-0197-4

Lützenberger, M., Masuch, N., Hirsch, B., Ahrndt, S., Heßler, A., & Albayrak, S. (2011). Strategic Behavior in Dynamic Cities. In *Proceedings of the 2011 Summer Computer Simulation Conference* (pp. 194–201). Vista, CA: Society for Modeling & Simulation International. Retrieved from http://dl.acm.org/citation.cfm?id=2348196.2348223

Manzini, R., & Pareschi, A. (2012). A decision-support system for the car pooling problem. *Journal of Transportation Technologies*, *2*(02), 85.

Ronald, N., Arentze, T., & Timmermans, H. (2009). An agent-based framework for modelling social influence on travel behaviour (pp. 2955–2961). Presented at the Proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation.

Varrentrapp, K., Maniezzo, V., & Stützle, T. (2002). The Long Term Car Pooling Problem–On the soundness of the problem formulation and proof of NP-completeness. *Technische Universitat Darmstadt*.

Chapter 3

TAZ-based Case Requiring Partial Path Matching

This chapter consists of following published paper

Hussain, I., et *al.* (2016). Organizational-based model and agent-based simulation for long-term carpooling. *Future Generation Computer Systems*, Volume 64, Pages 125-139, ISSN 0167-739X, http://dx.doi.org/10.1016/j.future.2016.02.019.

Which is based on following conference papers

Hussain, I., et *al.* (2014). Organizational and Agent-based Automated Negotiation Model for Carpooling, *Procedia Computer Science*, Volume 37, Pages 396-403, http://dx.doi.org/10.1016/j.procs.2014.08.059, ISSN 1877-0509.

Hussain, I., et *al.* (2015). Agent-based Simulation Model for Long-term Carpooling: Effect of Activity Planning Constraints. *Procedia Computer Science*, Volume 52, Pages 412-419, ISSN 1877-0509, http://dx.doi.org/10.1016/j.procs.2015.05.006.

3.1 Overview

This chapter presents an agent-based framework for long term carpooling using the CRIO organizational meta-model that has been setup to simulate the emergence of carpooling under several conditions. It is an extension of the work presented in chapter 2 where cooperating carpoolers were restricted to share the respective home and work areas. In this chapter, sets of agents working in a particular traffic analysis zone (TAZ) and living in spatially dispersed TAZs are considered for co-traveling. The contributions of this chapter are: (1) enabling the interaction between agents by establishing the carpool social groups (CPSGs) on the basis of work TAZs (the individuals who worked at same work-TAZ location can interact with each other), (2) presenting a multiple-trip negotiation model based on constant preference function for the trips departure times, on the individuals' profile, route optimization and on the effect of constraining activities,

(3) allowing the negotiation on trips (HW and WH) departure times, on driver and vehicle selection, and pick-up and drop-off orders of the carpoolers and (4) agents' communication, negotiation and coordination in a multiple trip and for long-term carpooling is investigated. This chapter differs from the previous one by (1) enabling interaction to restricted CPSGs based on similar work TAZ, (2) the use of constant preference function for trips departure times and (3) by introducing the evaluation process to find the optimal sequence of the participants by the use of degree of flexibility (degree of freedom) scoring function. The model presented in this chapter is used to measure the evolution of carpooling potential over time by taking into account the pick-up and drop-off order of the passengers. For the experiments, the pre-computed expected travel times between TAZ for the morning peak period, generated by the WIDRS tool (Knapen, et *al.*, 2014), are used.

3.2 Abstract

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.

Keywords: Organizational model, Agent-based simulation, coordination and negotiation, travel behavior, carpooling.

3.3 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., 2014; 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., 2014), 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., 2009), multi-agent based platform is used: it provides an efficient implementation of agent-based and organizational-based concepts.

3.3.1 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.

3.3.2 Chapter's Organization

This paper is organized as follows. Section 3.4 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 3.5 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 3.5. Section 3.6 explains the experimental setup and discusses some of the results. Finally, conclusions and future work are presented in Section 3.7.

3.4 Related Work

In recent years, agent-based simulation has come into the field of transportation science because of its capability to analyze aggregated consequences of individual specific behavior 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. (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., (2015) 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; 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., (2014) 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., (2010) 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. Gupta & Vovsha, (2013) present a hybrid discrete choice-duration model for work activity scheduling with interactions between workers in a multiple-worker household. The key feature is the introduction of intra-household interactions through worker schedule synchronization mechanisms. Relative strength proved to be a function of the person characteristics and household composition.

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 & 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. Lützenberger 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 & Horvitz, (2009) describe an ABM aiming to optimally combine demand and supply in an advisory system for frequent ridesharing. The authors focus on the mechanisms required to model users cooperating on joint plans and focus on the economic value of the shared plans. Martinez, et al., (2015) present an agent-based simulation model for shared taxis in which a set of rules for space and time matching are identified. It considers that the client is only willing to accept a maximum deviation from his or her direct route. The authors establishes an objective function for selecting the best candidate taxi. Rosswog, et al., (2001) describe an algorithm designed to determine user equilibria in simulation-based traffic models and present an improved algorithm to find shortest paths in street networks.

Knapen, et al., (2014) 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. Xia, et al., (2015) propose a model for carpool matching services, and both optimal and heuristic approaches are tested to find solutions. It is demonstrated that a new formulation and associated solution procedures can permit the determination of optimal carpool teams and routes.

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 & Pareschi, (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 analyzes the effect of negotiated agenda adaptation required for carpooling (joint trip execution). In this paper, we propose a model to investigate the problem.

3.5 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); Ferber, et al., (2004), 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.

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 fulfillment 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.

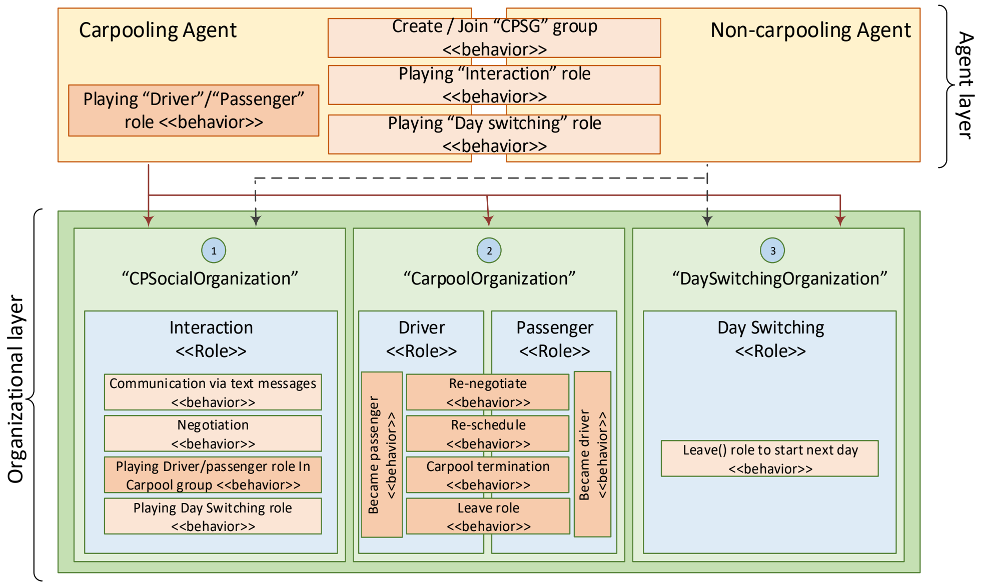


Figure 3.1. Organizational-based model that is mapped to an agent-based simulation model for the long-term carpooling.

This section presents the design of the organization-based model for our carpooling problem (Figure 3.1), 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 modeled and discussed in detail. Subsequently, the design of day switching mechanism is revealed.

3.5.1 The Problem Domain

The conceptual model for long-term carpooling is illustrated in Figure 3.2. 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.

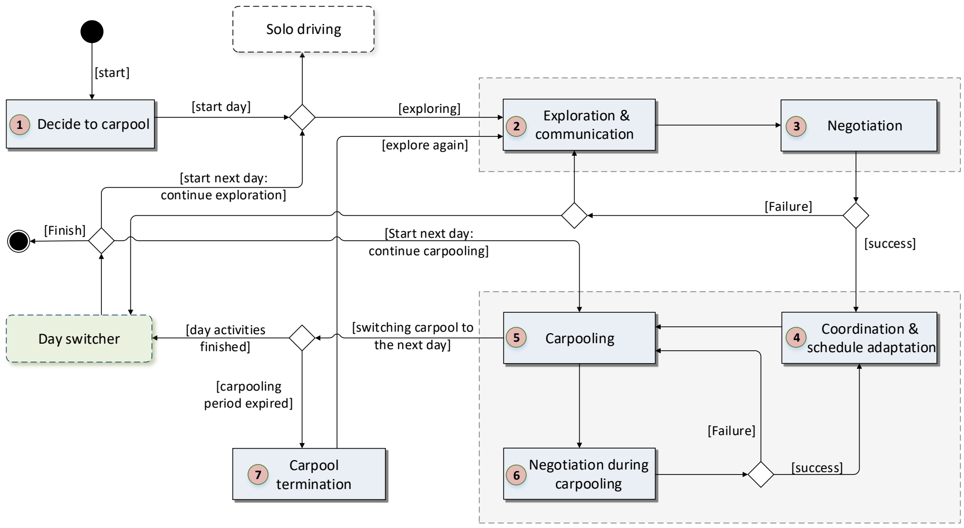


Figure 3.2. Activity-diagram of the behavior of a carpooling individual.

3.5.1.1 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 organizational approach, the individuals who are negotiating together are members of the same organization ''*CPSocialOrganization*'' (see Figure 3.3). 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.

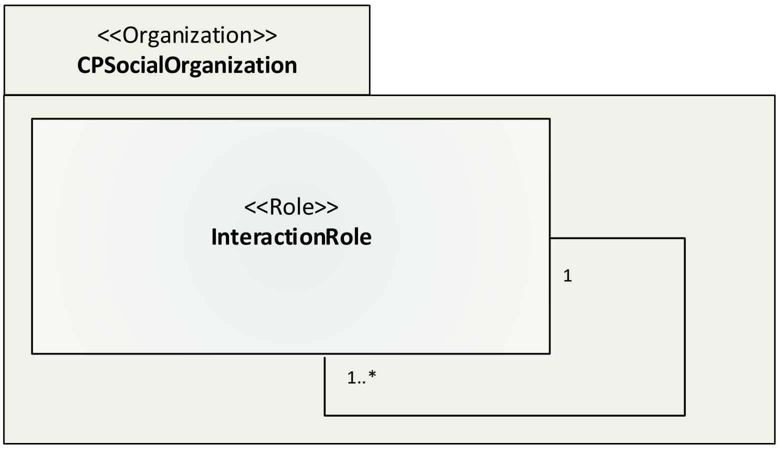


Figure 3.3. Carpooling social organization: The individuals are negotiating together, are member of the organization (CPSocialOrganization) by playing InteractionRole.

3.5.1.2 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.

3.5.1.3 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. The symbols used and their meanings are described in Table 3.1.

Table 3.1. The symbols used and their meanings.

Symbols	Meanings
$\boldsymbol{N}$	set of all individuals or agents
$\boldsymbol{a_i}$	represent an individual or agent, $a_i \in N$
$\boldsymbol{T^b_{a_i}}$, $\boldsymbol{T^e_{a_i}}$	earliest and latest possible departure time for both trips of an agent a_i
$\boldsymbol{T^b_{HW,a_i}}$ $\boldsymbol{T^e_{HW,a_i}}$	earliest and latest possible departure time for *HW* trip
$\boldsymbol{T^b_{WH,a_i}}$ $\boldsymbol{T^e_{WH,a_i}}$	earliest and latest possible departure time for *WH* trip
$\boldsymbol{t_{a_i}}$	The preferred trip start time
$\boldsymbol{t_{HW,a_i}}$ $\boldsymbol{t_{WH,a_i}}$	The preferred trip start time for *HW* and *WH*.
$\pm\Delta\boldsymbol{T}$	a symmetric deviation of time window *T* w.r.t. the preferred trip start times of an a_i.

$\overline{\Delta T}$	is the tolerance period before HW or after WH trips
C	represents the constraining activity (e. g. pick-drop or shopping)
$C_{finTime,a_i}$	Finishing time (including trip and activity) of C
$C_{startTime,a_i}$	Start time of C of an a_i.
L	Set of all locations (TAZ)
l_i	Specific TAZ location, $l_i \in L$
$T_{carpool,\, l_N}$	the arrival time window at the work zone.
$T_{carpool,l}$	the carpool time window for the l.
d_{l_i}	the duration to drive from the l_i to the destination.
T_{a_i,l_i}	time window of agent at specified l_i
$T^{e}_{carpool,\, l_k}$	the start of the feasible time window (lower bound) for the carpool at l_k
$T^{b}_{carpool,\, l_k}$	the end of the feasible time window (upper bound) for the carpool l_k
t_0	denotes the trip start time in the l_0.

3.4.1.3.1 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 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 (Figure 3.4):

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).

$$T^{b}_{a_i} = t_{a_i} - \Delta T$$
$$T^{e}_{a_i} = t_{a_i} + \Delta T \qquad (1)$$

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.

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

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).

$$
\begin{aligned}
T^{b}_{WH,a_i} &= C_{finTime,a_i} \\
T^{e}_{WH,a_i} &= t_{WH,a_i} + \Delta T
\end{aligned}
\tag{3}
$$

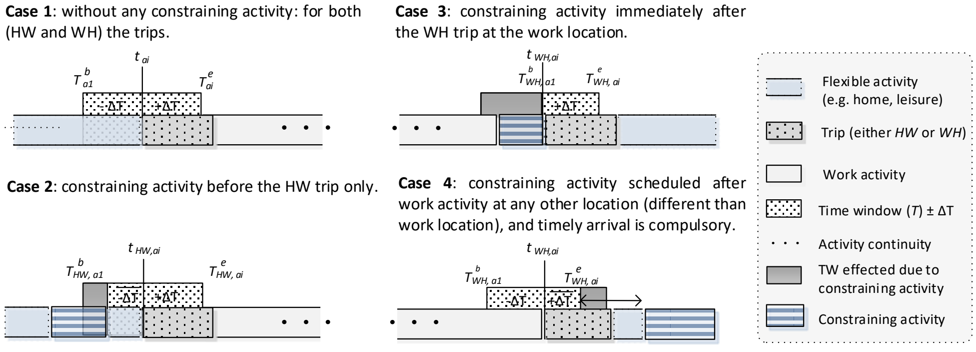


Figure 3.4. The effect of constraining activities on carpooling trips (HW and WH).

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.

$$
\begin{aligned}
\overline{\Delta T} &= C_{startTime,a_i} - t_{WH,a_i} \\
T^{b}_{WH,a_i} &= t_{WH,a_i} - \Delta T \\
T^{e}_{WH,a_i} &= t_{WH,a_i} + \overline{\Delta T}
\end{aligned}
\tag{2}
$$

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.

3.5.1.3.2 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[4] 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 Figure 3.5); and the WH case is similar.

[4] In mathematics, the notion of permutation relates to the act of arranging all the members of a set into some sequence, if the set is already ordered, rearranging its elements, a process called permuting.

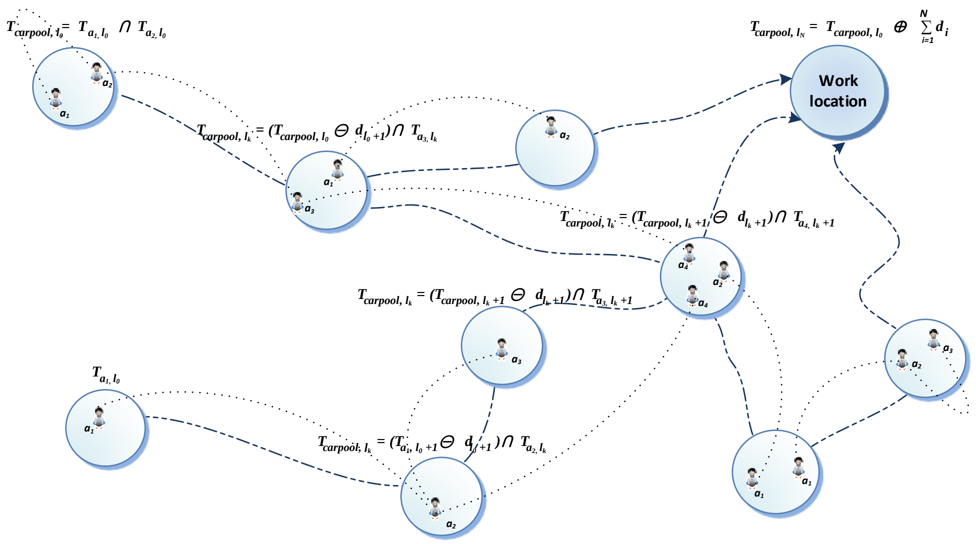


Figure 3.5. The driver assignment, pickup order and time intervals at each TAZ (where the driver can visit).

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 may be uncertain). The candidate delivering the highest score is kept. Finally, the trip start time (discussed in sub-section 3.5.1.3.3) is determined.

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

3.5.1.3.3 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:

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

The arrival time window of the carpool is:

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

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.

For the upper bound of the time window one finds

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

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

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

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

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

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

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

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).

$$T^{b}_{carpool,\, l_0} \le t_0 \le T^{e}_{carpool,\, l_0} \qquad (16)$$

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

$$\forall_k : T^{b}_{carpool,\, l_k} \le t_k \le T^{e}_{carpool,\, l_k} \qquad (17)$$

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:

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

When the negotiation becomes successful, the participants may coordinate and dynamically adapt their daily schedule in step *coordination and schedule adaptation* (section 3.5.1.4). Otherwise, the negotiation has failed, and they should continue to explore for carpool partners in *exploration and communication* (section 3.5.1.2).

3.5.1.4 Coordination and Schedule Adaptation

When the negotiation is successful according to the negotiation model discussed in this *section 3.5.1.3*, a carpooling group "*CarpoolGroups*" of the carpooling organization "*CarpoolOrganization"* is created (see Figure 3.6). 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*).

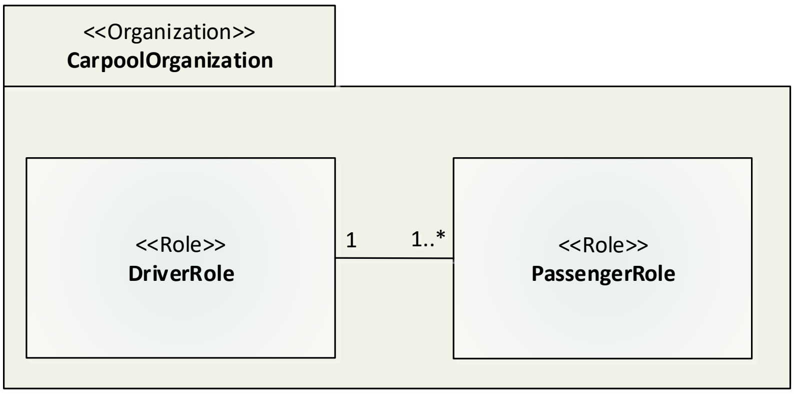


Figure 3.6. Carpool organization of the agents : The carpoolers are members of "CarpoolOrganization" by playing either driver or passenger role in the carpool group.

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.

3.5.1.5 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.

3.5.1.6 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 coordination and schedule adaptation* (section 3.5.1.4) and continue carpooling.

3.5.1.7 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 *exploration and communication* (section 3.5.1.2) of the carpooling model to find a new carpool.

3.5.2 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 Figure 3.7) 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' behavior modeling, (4) integrating agents in a certain environment and (5) establishing connections between them.

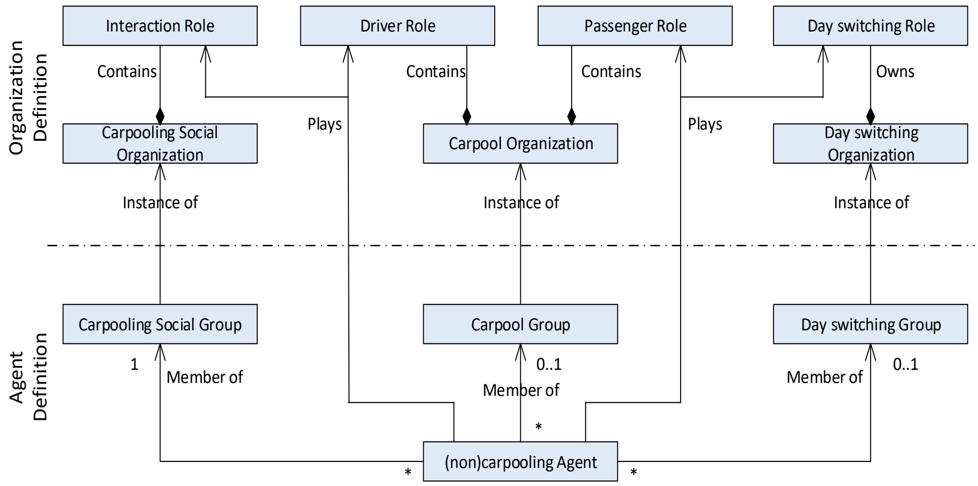


Figure 3.7. Class-diagram of the organizational model that is mapped to the agent-oriented model for long-term carpooling.

3.5.2.1 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.

In our simulation model, the agent environment[5] is established as the spatiotemporal aggregate where the agents live and conduct their own daily

[5] 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 (Ferber, et al., 2004)

schedule. Figure 3.8 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 behavior is modelled by a hierarchical finite state-machine composed of two states: GROUPING and RUNNING (see Figure 3.9 (a)).

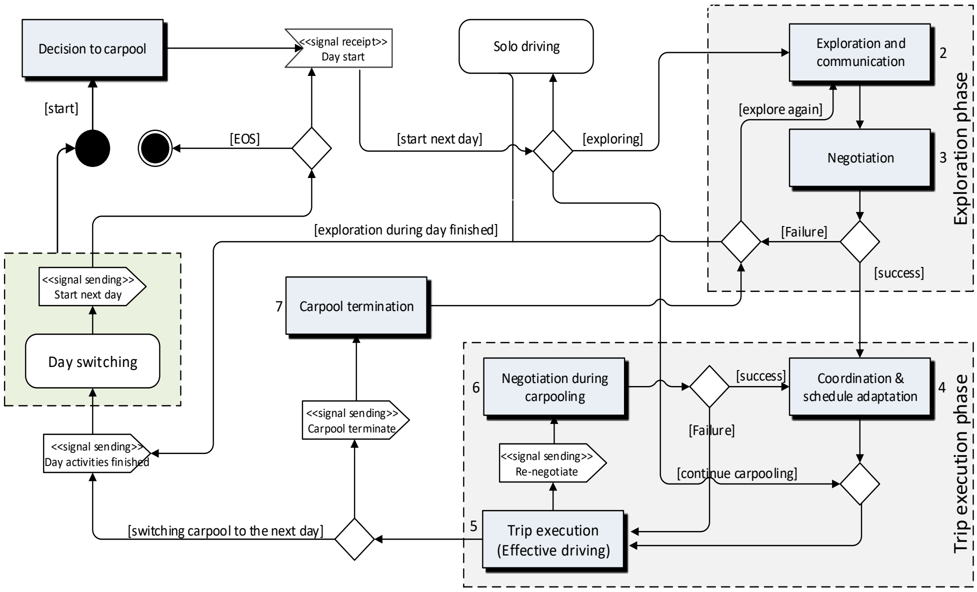


Figure 3.8. Activity-diagram of an agent of the carpooling process in the agent-based simulation model. It refines the behavior defined in the problem domain (see Figure 3.2).

3.5.2.1.1 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).

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 3.1 shows, how each agent creates or joins *CPSG* and starts the role *(InteractionRole)* using the organization *(CPSocialOrganization)*.

Algorithm 3.1: Creating/joining of CPSG & starting InteractionRole.class.

```
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
```

3.5.2.1.2 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.

3.5.2.2 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 Figure 3.9 (b) and the states are discussed below.

3.5.2.2.1 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.

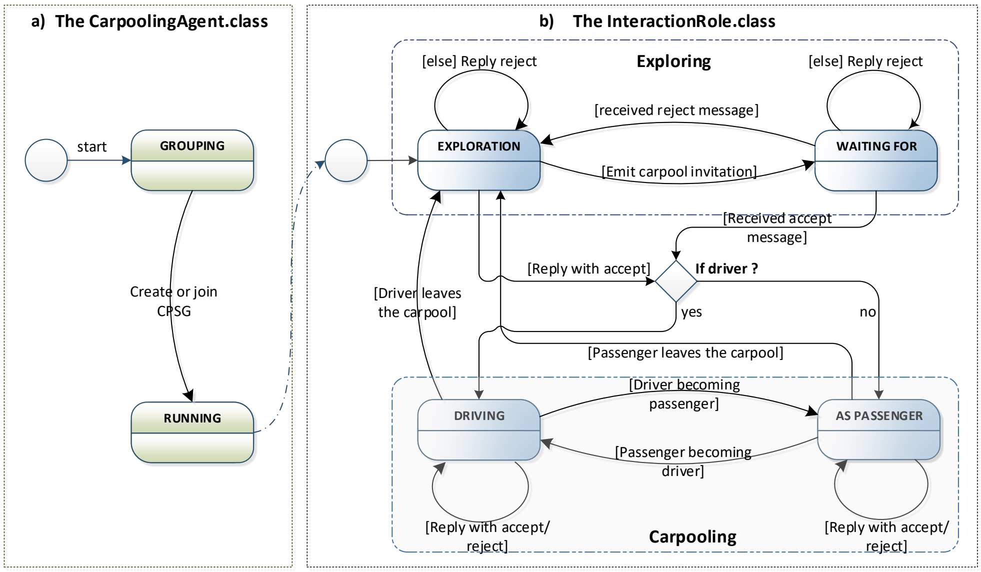


Figure 3.9. Agent's state transition machines : (a) the state-transition machine in agent's class, (2) state-transition machine in interaction role class of the *CPSocialOrganization*.

3.5.2.2.2 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*).

3.5.2.2.3 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.

3.5.2.2.4 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*.

3.5.2.3 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.

3.5.2.4 *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.

3.6 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.

3.6.1 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.

3.6.2 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.

3.6.3 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.

3.6.4 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. Figure 3.10 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 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 in a polynomial way 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.

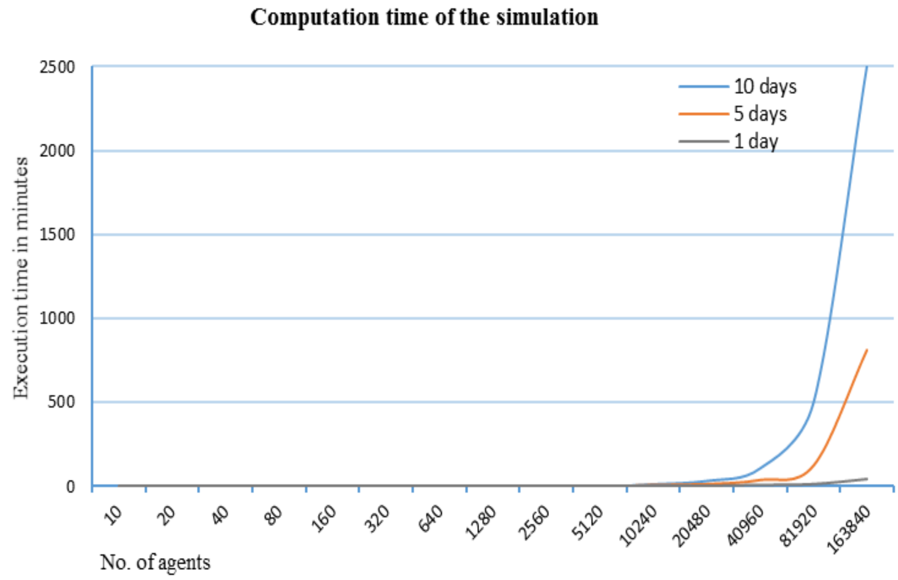


Figure 3.10. Computation time of the simulation by running different amount of agents.

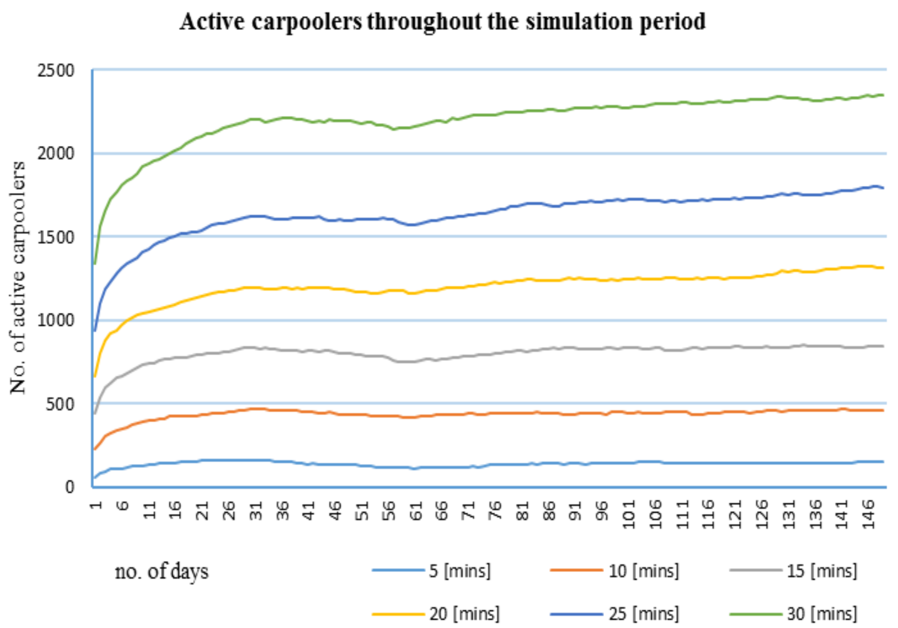


Figure 3.11. Number of active carpoolers for different time windows throughout the simulation period.

The graph in Figure 3.11 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 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.

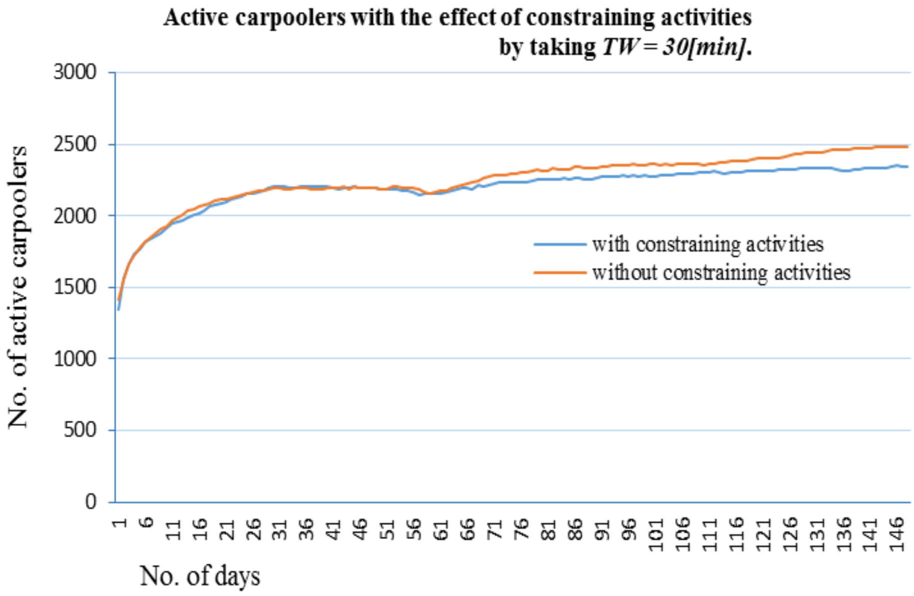


Figure 3.12. Number of active carpoolers with and without constraining activities.

Figure 3.12 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.

3.7 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 trips (*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. 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.

3.8 Critical Reflection

1. The individuals' behavior for carpooling experience (either good or bad) and their daily feedback is not modeled and taken into account in the presented carpooling model. It requires models to predict the feedback based on carpooling details (timeliness of drivers and passengers, safe driving properties etc.). These are conceptually simple phenomena. However, at least some statistical distributions derived from surveys among actual carpoolers are required in order to build a decent model. Since collecting such data may be very expensive, it is worth to investigate the sensitivity of the carpooling model to different distributions before investing in data collection.
2. In the presented carpooling simulation model, the *CPSocialOrganization* is used for the carpooling social network and CarpoolOrganization is used for the transition between the general CPSG and the CarpoolGroup. A separate organization for the carpooling negotiation groups is not used in this model because the actual negotiation *process* is not simulated in detail. In this model the negotiation *outcome* is determined by a deterministic function based on the candidates' profiles and time windows. The actual negotiation process will be modeled and simulated in detail in future. A *NegotiationOrganization* will be added to the model that will handle the further interaction and cooperation process between participants in the negotiation process (in order to come up with an optimized coordinated solution).
3. The *CPSocialOrganization* and *CarpoolOrganization* organizations are dedicated to the carpooling problem while the *DaySwitchingOrganization* organization is dedicated to the simulation execution (used for run time purpose only). It means the *DaySwitchingOrganization* is not at the same level of abstraction as the ones used for the carpooling problem. In future research work, we will model and present *DaySwitchingOrganization* separately by adding two roles (one for the agents who are executing their daily activities, one for the agents who are waiting for the next day execution).

3.9 References

Arentze, T., Pelizaro, C., & Timmermans, H. (2010). An agent-based micro-simulation framework for modelling of dynamic activity–travel rescheduling decisions. *International Journal of Geographical Information Science*, *24*(8), 1149–1170.

Bellemans, T., Kochan, B., Janssens, D., Wets, G., Arentze, T., & Timmermans, H. (2010). Implementation framework and development trajectory of FEATHERS activity-based simulation platform. *Transportation Research Record: Journal of the Transportation Research Board*, (2175), 111–119.

Chun, H. W., & Wong, R. Y. M. (2003). N∗—an agent-based negotiation algorithm for dynamic scheduling and rescheduling. *Advanced Engineering Informatics*, *17*(1), 1–22.

Cossentino, M., Gaud, N., Hilaire, V., Galland, S., & Koukam, A. (2010). ASPECS: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent Systems*, *20*(2), 260–304.

Ferber, J., Gutknecht, O., & Michel, F. (2004). From Agents to Organizations: An Organizational View of Multi-agent Systems. In P. Giorgini, J. P. Müller, & J. Odell (Eds.), *Agent-Oriented Software Engineering IV: 4th InternationalWorkshop, AOSE 2003, Melbourne, Australia, July 15, 2003.* pp. 214–230, Berlin, Heidelberg: Springer Berlin Heidelberg.

Galland, S., Knapen, L., Yasar, A.-U.-H., Gaud, N., Janssens, D., Lamotte, O., … Wets, G. (2014). Multi-agent simulation of individual mobility behavior in carpooling. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, *45*, 83–98.

Gaud, N., Galland, S., Hilaire, V., & Koukam, A. (2009). An Organisational Platform for Holonic and Multiagent Systems. In K. V. Hindriks, A. Pokahr, & S. Sardina (Eds.), *Programming Multi-Agent Systems: 6th International Workshop, ProMAS 2008, Estoril, Portugal, May 13, 2008.* pp. 104–119, Berlin, Heidelberg: Springer Berlin Heidelberg.

Guo, J., Nandam, S., & Adams, T. (n.d.). A data collection framework for exploring the dynamic adaptation of Activity-Tra vel decisions.

Gupta, S., & Vovsha, P. (2013). A model for work activity schedules with synchronization for multiple-worker households. *Transportation*, *40*(4), 827–845.

Horvitz, E., Apacible, J., Sarin, R., & Liao, L. (2005). Prediction, Expectation, and Surprise: Methods, Designs, and Study of a Deployed Traffic Forecasting Service. In *Proceedings of the Twenty-First Conference on Uncertainty in*

Artificial Intelligence (pp. 275–283). Arlington, Virginia, United States: AUAI Press.

Hussain, I., Knapen, L., Galland, S., Janssens, D., Bellemans, T., Yasar, A.-U.-H., & Wets, G. (2014). Organizational and Agent-based Automated Negotiation Model for Carpooling. *The 5th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2014)/ The 4th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH 2014)/ Affiliated Workshops*, *37*, 396–403.

Hussain, I., Knapen, L., Galland, S., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2015). Agent-based Simulation Model for Long-term Carpooling: Effect of Activity Planning Constraints. *The 6th International Conference on Ambient Systems, Networks and Technologies (ANT-2015), the 5th International Conference on Sustainable Energy Information Technology (SEIT-2015)*, *52*, 412–419.

Hussain, I., Knapen, L., Galland, S., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016). Organizational-based model and agent-based simulation for long-term carpooling. *Future Generation Computer Systems*, 64, 125–139.

Jennings, N. R. (2000). On agent-based software engineering. *Artificial Intelligence*, *117*(2), 277–296. https://doi.org/10.1016/S0004-3702(99)00107-1

Joh, C.-H. (2004). Measuring and predicting adaptation in multidimensional activity-travel patterns.

Kamar, E., & Horvitz, E. (2009). Collaboration and Shared Plans in the Open World: Studies of Ridesharing. In *Proceedings of the 21st International Jont Conference on Artifical Intelligence* (pp. 187–194). San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.

Knapen, L., Bellemans, T., Usman, M., Janssens, D., & Wets, G. (2014). Within day rescheduling microsimulation combined with macrosimulated traffic. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, *45*, 99–118.

Knapen, L., Keren, D., Yasar, A.-U.-H., Cho, S., Bellemans, T., Janssens, D., & Wets, G. (2012). Analysis of the Co-routing Problem in Agent-based Carpooling Simulation. *ANT 2012 and MobiWIS 2012*, *10*, 821–826.

Knapen, L., Yasar, A., Cho, S., Keren, D., Dbai, A. A., Bellemans, T., … Bhaduri, K. (2014). Exploiting graph-theoretic tools for matching in carpooling applications. *Journal of Ambient Intelligence and Humanized Computing*, *5*(3), 393–407.

Lützenberger, M., Masuch, N., Hirsch, B., Ahrndt, S., Heßler, A., & Albayrak, S. (2011). Strategic Behavior in Dynamic Cities. In *Proceedings of the 2011 Summer Computer Simulation Conference* (pp. 194–201). Vista, CA: Society for Modeling & Simulation International.

Manzini, R., & Pareschi, A. (2012). A decision-support system for the car pooling problem. *Journal of Transportation Technologies*, *2*(02), 85.

Martinez, L. M., Correia, G. H. A., & Viegas, J. M. (2015). An agent-based simulation model to assess the impacts of introducing a shared-taxi system: an application to Lisbon (Portugal). *Journal of Advanced Transportation*, *49*(3), 475–495.

Nijland, E. W. L., Arentze, T. A., Borgers, A. W. J., & Timmermans, H. J. P. (2009). Individuals' Activity–Travel Rescheduling Behaviour: Experiment and Model-Based Analysis. *Environment and Planning A*, *41*(6), 1511–1522.

Ronald, N., Arentze, T., & Timmermans, H. (2009). An agent-based framework for modelling social influence on travel behaviour (pp. 2955–2961). Presented at the Proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation.

Rosswog, S., Gawron, C., Hasselberg, S., Böning, R., & Wagner, P. (2001). Computational aspects in traffic simulation problems. *I: Best of Websim99. II: Traffic Simulation*, *17*(5), 659–665.

Varrentrapp, K., Maniezzo, V., & Stützle, T. (2002). The Long Term Car Pooling Problem–On the soundness of the problem formulation and proof of NP-completeness. *Technische Universitat Darmstadt*.

Xia, J., Curtin, K. M., Li, W., & Zhao, Y. (2015). A New Model for a Carpool Matching Service. *PLoS ONE*, *10*(6), e0129257.

Chapter 4

Negotiation and Matching Using Preference and Scoring Functions

This chapter consists of following paper

Hussain, I., et *al.*, (2017). Agent-based simulation of individual matching and mobility behavior in carpooling, *Transportation Research: Part C* (submitted).

4.1 Overview

This chapter presents the design of a progressive negotiation model for carpooling that is mapped to an agent-based simulation aimed at the setup of the framework and of a network of the carpooling candidates. It is an extension of the work presented in chapter 2 where cooperating carpoolers were restricted to share the respective home and work areas and in chapter 3 where the constant preferences for the trips start times are used. The contributions of this chapter are: (1) the proposed model analyzes various effects of *multi-zonal* individuals' interaction and behavior adaptation for sets of candidate carpoolers, (2) the presented multiple trip *negotiation model* enables individuals' matching: the success of negotiation depends on the factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities, (3) the selection of the most preferred trip departure time is extended by partly derived from existing departure time studies (Hendrickson & Plank, 1984; Hussain et *al.*, 2015) based on a number of factors namely; (i) travelling factors, (ii) socio-economic factors and (iii) time pressure factors and (4) the driver and vehicle selection, pick-up and drop-off order, and the preferred trip start time intervals of the optimal carpool group are evaluated by using *scoring functions*: (i) time of day, (ii) the time loss and (iii) degree of flexibility. The model presented in this chapter is superior as compared to others and can be chosen when taken into account the parameters: (i) the aggregate behavior of the carpooling social network and (ii) the personal preferences for the trips departure time.

4.2 Abstract

In order to commute by carpooling, individuals need to communicate, negotiate and coordinate, and in most cases adapt their daily schedule to enable cooperation. Through negotiation and cooperation, participants can reach complex agreements in an iterative way to find matching partners in order to co-travel. This paper presents the design of a progressive negotiation model for carpooling that is mapped to an agent-based simulation aimed at the setup of the framework and of a network of the carpooling candidates. It analyzes various effects of multi-zonal individuals' interaction and behavior adaptation for sets of candidate carpoolers. The start of the carpooling process depends on the individuals' objectives and intention to carpool. The interactions of individuals enable communication within carpooling social groups to trigger the negotiation process. The success of negotiation highly depends on the lifestyle factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. The selection of the most preferred trip departure time partly derived from existing departure time studies and based on a number of factors namely; (i) travelling factors, (ii) socio-economic factors and (iii) time pressure factors. In order to cooperate, the individuals adapt their agenda according to personal preferences and limitations. The driver and vehicle selection, pick-up and drop-off order, and the preferred trip start time intervals of the optimal carpool group are evaluated by using scoring functions for time of day, degree of flexibility and the time loss. The carpooling social network was established using results predicted by FEATHERS an 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.

Keywords: Commuting, travel behavior, carpooling, coordination and negotiation, departure time, agent technology.

4.3 Introduction

Carpooling for commuters is a specific transportation problem where cooperation between individuals is essential while executing their trips. 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 and 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. Negotiation requires that individuals effectively convey and interpret information to enable carpooling. Each negotiation involves a small number of participants but the schedules can be interconnected by cooperation. Furthermore the travelling, social economic characteristics (SEC) and time pressure factors can play a vital role to find the favorable partners for the carpooling. However, strict timing constraints in the schedule of the day reduce the options to carpool (Knapen et *al*., 2014(a); Horvitz et *al*., 2012).

Currently many research areas including transportation behavior need to analyze and model complex behavior between individuals (agents). Modeling the interaction between individual agents becomes progressively important in recent research. Traditional modeling tools have difficulties for handling the complexity of communication and negotiation 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. The ABMs can provide valuable information on the society and on the outcome of social actions or phenomena. 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.

This research presents the design of a progressive negotiation model for carpooling that is mapped to an agent-based simulation aimed at the setup of the framework and of a network of the carpooling candidates. It is an extension of the work presented in (Hussain et *al*., 2016(a)) where cooperating carpoolers were restricted to share the respective home and work areas and in (Hussain et *al*., 2016(b)) where the constant preferences for the trips start times are used. With respect to activity based modeling, research will focus on models for propagation of information, individuals' behavior, incentives an inhibitors for carpooling and on time pressure caused by cooperation. The purpose is to investigate the effect of time constraints and to model (1) how people adapt their daily schedule to enable cooperation and to analyze (2) how the consequent carpooling participation evolves over time. This is done while taking into account the constraints induced by flexible activity scheduling. 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.

In this paper, the simulated carpooling process is described by dividing it into three steps: (1) network exploration and communication (2) negotiation process and (3) trip execution (either carpooling or traveling solo). In the first step, the interactions of autonomous agents enable communication to trigger the negotiation process within *carpooling social groups* to find matching partners in order to co-travel. Sets of individuals working in a particular traffic analysis zone (TAZ) and living in spatially dispersed zones are considered for co-traveling in the same *carpooling social groups*. In the second step, a multiple trip *negotiation model* is presented which enables individuals' matching in order to co-travel. The selection of the most preferred trip departure time presented in (Hussain et *al*., 2016) is extended: the method is partly derived from an existing departure time study (Hendrickson & Plank, 1984) and is based on a number of factors namely; (i) travelling factors, (ii) socio-economic factors and (iii) time pressure factors. The success of negotiation is highly depends on the lifestyle factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. In order to cooperate, the individuals adapt their agenda according to personal preferences and limitations. The driver and vehicle selection, pick-up and drop-off order and preferred trip start times of the optimal carpool group are evaluated by using following scoring functions: (i) time of day, (ii) degree of flexibility at each intermediate stop and (iii) the time loss. In the final step, the actual trips execution (carpooling) is considered where the trips are executed on long-term basis.

For the implementation, the Janus (Gaud et *al*., 2009), multi-agent based platform is used for simulating the interactions of autonomous individuals. It provides an efficient implementation of agent-based and organizational-based concepts. For experiments, a *carpooling social network* is considered and simulated. It was established using results predicted by FEATHERS (Bellemans et *al*., 2010), an operational activity-based model for Flanders (Belgium). The expected travel times between TAZs for the morning peak period, generated by the WIDRS framework (Knapen et *al*., 2014), are used.

This paper is organized as follows. Section 4.4 summarizes the related work on coordination and negotiation techniques in carpooling, activity rescheduling and individual matching in carpooling. Section 4.5 presents the design of negotiation model for carpooling that maps to an agent-based simulation. This section is divided into three sub-sections. Firstly, the *network exploration and communication* is briefly described. Secondly, the *negotiation process* is explained in detail. Finally, the *trip execution* is presented. Section 4.6 explains the experimental setup and discusses some of the results. Finally, conclusions and future work are presented in Section 4.7.

4.4 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 behavior variations. In this section, the existing works is presented by dividing it into two subsections: (1) the different types of coordination and negotiation techniques in carpooling and (2) the rescheduling activities in the agenda for a day and individual profile matching in carpooling.

4.4.1 Coordination and Negotiation

In the first category of the research exertions, the agent-based models covering the coordination and negotiation techniques for carpooling are studied.

(Hussain et *al*., 2016(a)) proposed a multiple trip negotiation model for carpooling (combining the forward and backward commuting trips for a day in a single negotiation) which is partly derived from an existing departure time study presented in (Hendrickson & Plank, 1984). It was proposed by taking the possibility of *flexible activity scheduling* into account. The authors measured the direct interaction between agents belonging to a *carpooling social network* but limit the interaction between agents within small groups based on home and work TAZ. The implementation also applies constraining activities by considering the personal daily schedule of each individual. In (Hussain et *al*., 2016(b)), the same authors extended the interaction mechanism of agents to allow individuals living in multiple zones and heading to the same work area to negotiate for carpooling. The amount of interaction between agents is minimized by establishing carpooling social groups based on the same work TAZ. A negotiation model on trip start time and driver selection is also presented. Constant preference for the trip start time within a given interval is used in the presented negotiation model. (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. This study is basically based on (Cho et *al*., 2012) where a conceptual design of an ABM for the carpooling application is presented.

(Bellemans et *al*., 2012) introduced an agent-based simulation model to support carpooling at large manufacturing plants. The authors introduce the following services: (a) an agent-based simulation is used to investigate opportunities and inhibitors and (b) online matching is made available for matching commuter profiles. The authors argue that incorporating complex negotiations between agents is compulsory for successful carpooling, because inhibiting factors like rerouting and rescheduling have to be considered. In (Guo et *al*., 2013) a multi-agent based self-adaptive genetic algorithm is presented to solve a long-term carpooling problem efficiently with limited exploration of the search space. The system is a combination of multi-agent system and genetic paradigm, and guided by a hyper-heuristic dynamically adapted by a collective learning process. It was evaluated by simulating large scale data sets. The authors in (Armendáriz et *al*., 2011) designed and presented a multi-agent based simulation of Dynamic Carpooling System (DCS) using NetLogo. DCS optimizes the transport utilization by the ride sharing among people who usually cover the same route. The authors claim that their system provides an intelligent matching service along with a smart routing engine that can use real time information (for instance, considering weather and traffic conditions). (Cheikh & Hammadi, 2014), present a multi-agent system for the management of dynamic carpooling by proposing an original alliance between optimization and a multi agent concept to perform parallel optimized assignment of vehicles to users queries. A decomposition process intended to subdivide the global problem into several sub-problems with a reasonable search space was also presented. Authors propose to break geographic areas (global problem) into distinct zones (sub-problems) where each zone is controlled by an agent with an optimized behavior.

In the context of *travel demand*, cooperation aspects apply to joint activity execution and joint trip execution. (Ronald et *al*., 2012) 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, (Chun & 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. Lützenberger *et al.* (Lützenberger 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, (Kamar & Horvitz, 2009) describe an ABM aiming to optimally combine demand and supply in an advisory system for frequent ride-sharing. The paper focuses on the mechanisms required to model users cooperating on joint plans and on the economic value of the shared plans.

4.4.2 Rescheduling and Matching

A large body of literature (e.g. Nijland *et al.* (Nijland et *al*., 2009) and Guo *et al.* (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*., 2014(a)) 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 et *al.* (Joh et *al*., 2006) 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*,. (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 (Gan & Recker, 2008), authors presented a mixed integer linear program model of household activity rescheduling behavior. It comprised of such complicated human decisions as activity cancellation, insertion, and duration adjustment and formulated as a Mixed Integer Linear Program, called HARP. The model differs from existing rescheduling models in a number of important aspects: (1) rescheduling is driven by similarity maximization, (2) the model output structure is defined in terms of a similarity/difference measurement scheme and (3) the model accommodates rescheduling processes that are not only strictly driven by the similarity-maximization principle but also those based on utility maximization. Gupta and Vovsha, (Gupta & Vovsha, 2013) present a hybrid discrete choice-duration model for work activity scheduling with interactions between workers in a multiple-worker household. The key feature is the introduction of intra-household interactions through worker schedule synchronization mechanisms.

Xia et *al*., (Xia et *al*., 2015) propose a model for carpool matching services, and both optimal and heuristic approaches are tested to find solutions. It is demonstrated that a new formulation and associated solution procedures can permit the determination of optimal carpool teams and routes. Martinez et *al*., (Martinez et *al*., 2015) present an agent-based simulation model for shared taxis in which a set of rules for space and time matching are identified. It considers that the client is only willing to accept a maximum deviation from his or her direct route. The authors establishes an objective function for selecting the best candidate taxi.

Knapen *et al.*, (Knapen et *al*., 2014(b)) 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.*, (Knapen et al., 2012) study the problem of finding an optimal tree structured route for carpooling in case some participants leave their car at a carpool parking. They propose an algorithm to find the optimal solution for the join tree (i.e. the case where passengers are picked up at carpool parking places). Each individual declares the maximal time and/or distance that is acceptable to move from origin to destination.

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 that problem.

4.5 Agent-based Carpooling Model

This research specifies an agent-based model to simulate carpooling for commuting in the long term. The model shall support research on both topics in the field of large scale agent based modeling and in the field of cooperation and rescheduling in activity based models. Carpooling is a specific instance of cooperation between people. The focus is on mechanisms to simulate human behavior when decisions for cooperation are to be taken. 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. Agents' **communication, negotiation and coordination in a multiple trips** (home-to-work *HW* and work-to-home *WH)* negotiation model are investigated; this is done while taking into account the constraints induced by flexible activity scheduling.

This section presents the setup of the agent-based framework for carpooling. It starts by describing the problem context and the research methodology. After describing some preliminary concepts, the agent-based framework is designated. The iterative activities of the agent-based framework are divided into three main steps: network exploration and communication, the negotiation process and the trips execution (traveling solo or by carpooling). Before the start of the iterative activities the *carpooling social groups* are formed in order to limit the interaction requirements among the individuals. Within these *carpooling social groups,* individuals can communicate to negotiate on trip start times and on the driver selection.

4.5.1 Problem Description

A set P of identified participants $p_i \in P$ is given and for each participant the origin $o_i \in O$ and destination $d_i \in D$ locations. P'_i is the set of participants who are mutually compatible for negotiation in carpooling where $P'_i \subseteq P$. The participants who work in the same TAZ can interact and negotiate within the *carpooling social group* of the *carpooling social network* (see Figure 4.1). The negotiation applies to both the trips (HW and WH) and covers trips start times, the driver and vehicle selection and the *pick-up* and *drop-off* order of the *carpoolers*. An individual having trip duration T_{dur,p_i} also has a maximum detour time $T_{maxDetour,p_i}$ which is the upper limit for the generalized T_{dur,p_i} acceptable by p_i to travel from o_i to d_i. Individuals whose trips can be combined with respect to the detour time can picked-up by the driver.

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 commuting trips (home-to-work HW and work-to-home WH) in daily schedules are detailed and discussed related to long term carpooling.

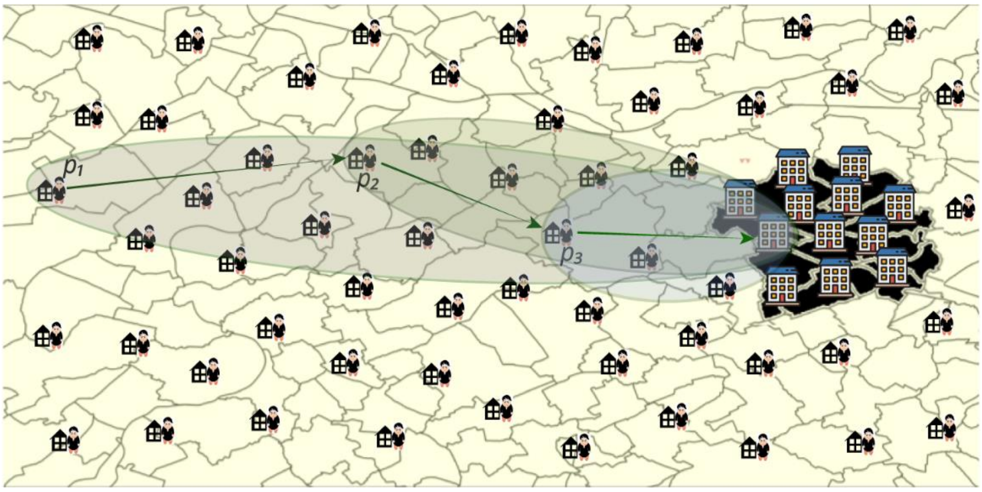


Figure 4.1: Example of distribution of the individuals over a populated area (divided by TAZs) which represents the origin-locations. The highlighted area is showing the work TAZs (final-destination). The maximum excess time for individuals (p_1, p_2 and p_3) of a carpool group is shown by the highlighted area.

4.5.2 Methodology: Agent-based Modeling

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. The agent-Based Modeling approach, which is essentially distributed and individual-centric is appropriate for systems that exhibit complex behavior. 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 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), (Ferber et *al*., 2004) 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.

For the implementation, the Janus (Gaud et *al*., 2009), multi-agent based platform is used which provides an efficient implementation of agent-based and organizational-based concepts. Janus is built upon the CRIO organizational meta-model in which the concepts of role and organization are first-class entities. 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 organization-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(a); Cossentino et *al*., 2010(b)).

4.5.3 Basic Concepts

4.5.3.1 Agent

In this study, agent is defined as 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 for each activity and trip. The modeling structure claims that individuals spend the day taking part in activities and traveling between activity locations. Each agent looks for other individuals of the same carpooling social group to cooperate while executing its periodic trips by exploring the carpooling social network.

4.5.3.2 Carpooling Social Network

The *carpooling social network (CPSN)* is made up of nodes representing individuals and social links defined by one or more specific types of interdependency. It slightly differs from general social networks in two ways: Firstly, the *carpooling social network* considers not only socio-demographic attributes but also spatiotemporal attributes i.e. activity or trip start times and home and work locations and secondly, *CPSN* is specifically aimed at carpool partner selection and interaction between participants. The strength of relationship can be measured by calculating the number of similar attributes for the agents. If an individual has either any similar features, such as the path or route, the home or work locations, with others then they seem to have any relationship with each other.

It may be difficult to find an ideal carpool partner from a large space (*carpooling social network*). The *CPSN* can be subdivided into disconnected components, so that each one of which corresponds to a *carpooling social group* $(CPSG)$. $CPSG$ concept is used to limit the interaction requirements. $CPSGs$ 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 interact and negotiate with each other in order to carpool. If there are '*n*' work locations, the carpooling social network contains '*n' carpooling social group*s.

4.5.4 Setup of the Framework

Several preliminary steps are taken, before the start of the iterative activities of the model for long term carpooling: this is illustrated in Fig. 2. Firstly, participants decide to carpool and determine their trips and schedule for long-term carpooling. Secondly, to limit the interaction requirements among the individuals in the carpooling social network, the organization concept is used to model *carpooling social groups* (*CPSG*). According to our organizational approach, the individuals who are negotiating together are members of the same *CRIO* organization. Immediately after the individual created or joined an instance (*CPSG*), (s)he starts playing the carpooling social role in that *CPSG*. Within these *CPSGs*, 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 identical or sufficiently overlapping routes (in space and time) to the destination TAZ, then they are sufficiently similar to successfully negotiate.

The iterative activities of the long-term carpooling model are illustrated in Figure 4.2. An individual can perform the following activities: (i) network exploration and communication, (ii) negotiation process and (iii) trip execution (carpooling or solo driving solo). In what follows, each of these steps is described in more detail.

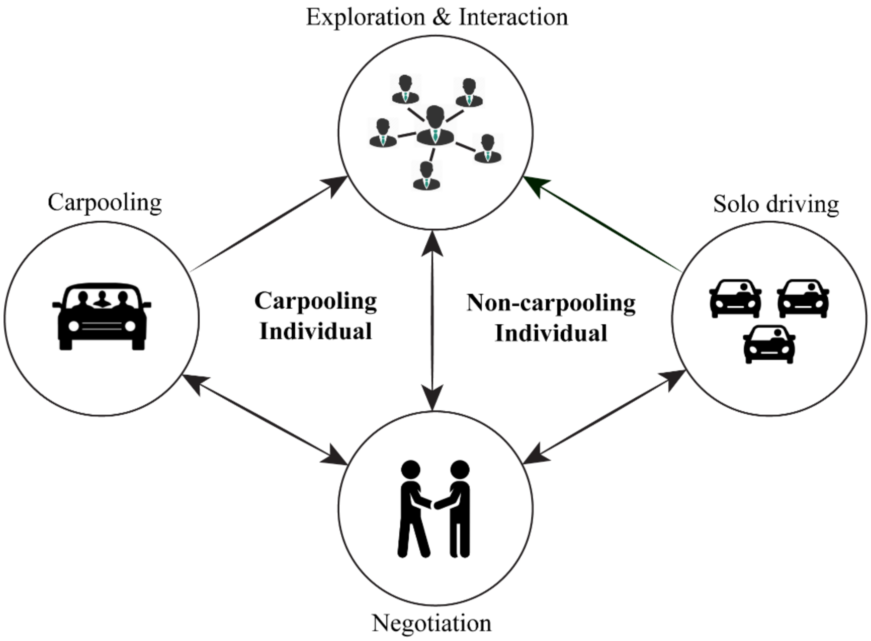


Figure 4.2: Iterative activities of an individual for his/her work trips.

4.5.4.1 Network 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 during the exploration phase throughout the period (in case (s)he is unable to find a carpool partner). In this carpooling model, the individuals 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 for communication 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, the probability value to invite someone for carpooling, specified by a parameter *probabilityToInvite* is determined by the personality and personal preferences of the traveler: some people do not like to carpool.

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

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

Each participant (*sender*) may search for a partner (*receiver*) by sending a carpool invitation. Both sender and receiver must belong to the same *CPSG*. The emission of the invitations depends on the given *probabilityToInvite* parameter (which is modeled for the carpooling intention or interest to invite someone). An individual can explore carpooling social network for multiple times in a day. The receiver individual possibly accepts the sender as a potential carpooling partner after reviewing his/her profile.

During carpooling, the carpoolers (both drivers and 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 of candidates.

4.5.4.2 Negotiation Process

The matching is applied in the negotiation phase where final decisions to carpool are revealed by finding the optimal solution that meets the conditions stated by the candidate participants. The proposed model comprises the symmetrical commuting trips and is assumed to be realistic: although it induces more stringent timing constraints. This is because it avoids multi-party negotiations which require a large mental effort. The participants negotiate on trips (*HW* and *WH*) departure times, pick-up and drop-off orders, and also on the vehicle and driver selection. Constraints induced by a flexible or fixed activity scheduling are also 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. For each individual the duration of the solo trip is known as well as the maximum acceptable detour duration and distance. The latter are used to introduce the path and time similarity concepts. Those are determined for both the *HW* and the *WH* trips. It is easily seen that the distance driven depends on driver selection; the driver needs to pick-up passengers. 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 using personal preferences (the most important are timing requirements). The schedule adaptation depends on the preferences among feasible schedules of the individuals. Details are described in the following subsections.

4.5.4.2.1 Time Preference Function

The time preference that an individual exhibits at any given moment is determined solely by their personal preferences. Several factors affect the preference function for the trip departure time of an agent: (1) The SEC (i.e. the ratio of travelling cost to annual income) helps to quantify the concept of value of time for departing at a particular time in the given time interval. (2) The individuals' tolerance level for arriving late or early for a specific activity indicates the level of rigidity in the starting times of different activities.

In order to construct a behaviorally accurate method for trip start times, Hendrickson's MNL departure time choice model (Hendrickson & Plank, 1984) for work trips is used. Hendrickson and Plank used a dataset gathered in Pittsburgh, PA for the express purpose of analyzing dynamic level of service variations and departure time decisions. Collecting the dataset involved independent measurement of travel times and transit wait times for travel to the Pittsburgh Central Business District. The Hendrickson's base model included up to twenty eight alternatives, indicating combinations of four modes (drive alone, shared ride, transit with walk access and transit with auto access) and seven different departure time intervals of 10[min.] each. People do not have a constant level of preference for every moment in the entire feasible time interval due to many factors (i.e. time pressure).

4.5.4.2.2 Actual Utility Value

The utility derived from a daily schedule depends on the timing of the activities and trips, and also on the amount of time spent traveling and in activities. A change in trips start time affects actual utility value not only through the marginal utility of travel but also through the reduction in activity participation due to the limited time available in a day. Individuals adjust their schedule optimally during negotiation to capture the impact of an exogenous change to cooperate. The equation (1) is used to determine the actual utility value of a particular agent to depart at a specific time in its available time window.

Consider N agents $a_1, a_2, \ldots, a_N$. The departure time $t_1, t_2, t_3 \ldots, t_T$ available among the set of departure times T. The utility or preference $V_{a_i t_j}$ for a particular time t_j of an agent a_i is specified to be:

$$\begin{aligned} V_{a_i t_j} = {} & -2.09 - 0.008(FFTT_{a_i}) - 0.021\left(CONG_{t_j}\right) - 0.699\left(\frac{COST}{INCOME}\right)_{a_i t_j} \\ & - 0.095\left(ACC_{a_i t_j}\right) - 0.088\left(WAIT_{a_i t_j}\right) - 0.148\left(LATE_{a_i t_j}\right) \\ & + 0.0014\left(LATE_{a_i t_j}\right)^2 - 0.01\left(EARLY_{a_i t_j}\right) - 0.00042\left(EARLY_{a_i t_j}\right)^2 \end{aligned} \tag{1}$$

where the coefficients are taken from Hendrickson's study for the specific mode (shared transport) to represent the effects of unspecified mode dependent characteristics. The variables are defined in Table 4.1 for each a_i:

Table 4.1: The parameters and their descriptions used in Eq. (1).

Symbols	**Meanings**
$\boldsymbol{FFTT}_{a_i}$	Free flow Travel Time in carpool vehicle (i.e. 75% of travel time during peak time and 90% otherwise). A negative coefficient is expected because increasing travel time would discourage carpooling.
$\boldsymbol{CONG}_{t_j}$	Portion of travel time associated with congestion at departure time (i.e. 25% of travel time during peak time and 10% otherwise).
$(\frac{\boldsymbol{COST}}{\boldsymbol{INCOME}})_{a_i t_j}$	Ratio of annual cost of carpooling to income level per annum. It depends on the time-of-day because toll and parking charges are included and those can be time-of-day dependent.
$\boldsymbol{ACC}_{a_i t_j}$	Walking time at the end of a trip associated with departure time. $ACC_{a_i t_j}$ provides a measure of the accessibility to the work desk, and is included for the transit with walk access mode. The subscript t_j allows for variation in access time associated with different departure times.
$\boldsymbol{WAIT}_{a_i t_j}$	Waiting time with respect to individual's most preferred time to depart.
$\boldsymbol{LATE}_{a_i t_j}$	Number of minutes late arrival at work associated with the departure time. $\left(LATE_{a_i t_j}\right)^2$ is used to more accurately represent individual perceptions of late arrival at work.
$\boldsymbol{EARLY}_{a_i t_j}$	Number of minutes early arrival at work associated with the departure time. For the co-efficient of $EARLY_{a_i t_j}$ (i.e. we took 0.01) a smaller magnitude than that of $LATE_{a_i t_j}$: this is done because late arrival at work is felt to be more onerous than early arrival. $\left(EARLY_{a_i t_j}\right)^2$ as with $\left(LATE_{a_i t_j}\right)^2$, but a negative coefficient is anticipated to reflect the increasing disutility associated with earlier arrivals at the work place.

4.5.4.2.3 Departure Time Choices

Departure time choice is an important component of the travel decision-making process. These are treated as a simultaneous interactive decision based upon maximization of individual travelers satisfaction with each departure time combination. The probability of an individual selecting departure time alternative $P_{a_i t_j}$ of the carpool is given by equation (2);

$$P_{a_i t_j} = \frac{exp(V_{\ a_i t_j})}{\sum_T exp(V_{\ a_i T})} \qquad (2)$$

The probability can be calculated for the discrete cases mentioned by Hendrickson. The results have been used to construct the continuous preference function for the morning case shown in Figure 4.3. This was done because, for the simulation, we need to calculate the individual probability value for each possible trip start time in the candidate specific time window. The individual is assumed to accept a symmetric deviation $\pm\Delta T$ with respect to the preferred trip start times. The area of variation of the specific time window is in between earliest and latest departure time intervals. For practical reasons integration is done numerically assuming that the probability is constant in every one-minute period. The probability density for the trip start time for an agent is determined by normalization of the preference function so that its integral equals one also given by equation (3).

$$P_{a_i} = \sum_{j\,=\,T_{a_i}^b}^{T_{a_i}^e} \left(P_{a_i t_j}\right) \;=\; 1 \qquad (3)$$

The preference function for the evening case (*WH* trip) was created by mirroring the function for the *HW* trip around the time value for which the maximum probability is reached (Figure 4.3).

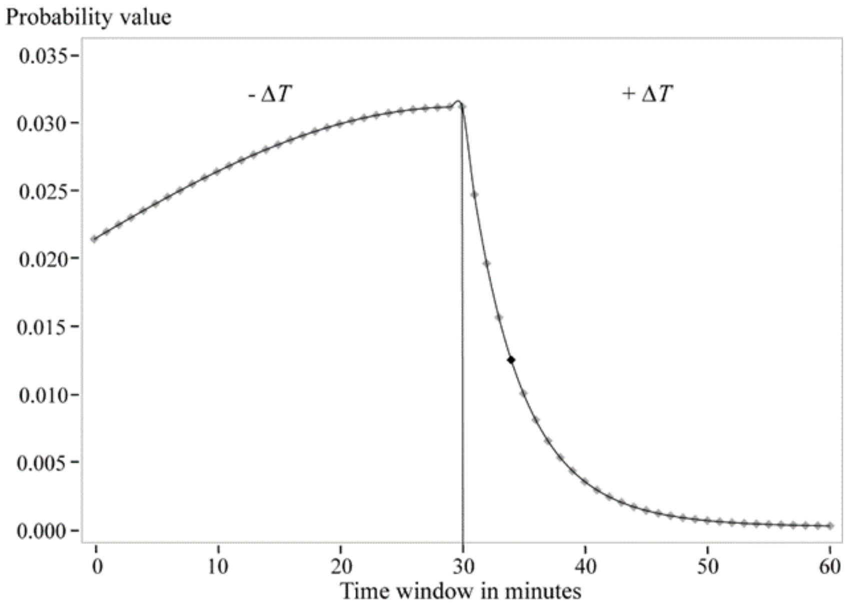


Figure 4.3: Departure time probability curves for morning trip of an individual.

Table 4.2: Symbols used and their meanings.

Symbols	Meanings
$\boldsymbol{N}$	Set of all individuals or agents
$\boldsymbol{a_i}$	Represents an individual or agent, $a_i \in N$
$\boldsymbol{T^b_{a_i}}$, $\boldsymbol{T^e_{a_i}}$	Earliest and latest possible departure time for both trips of an agent a_i. (*b* stands for begin and *e* stands for end of time window)
$\boldsymbol{T^b_{HW,\,a_i}}$ $\boldsymbol{T^e_{HW,\,a_i}}$	Earliest and latest possible departure time for *HW* trip
$\boldsymbol{T^b_{WH,\,a_i}}$ $\boldsymbol{T^e_{WH,\,a_i}}$	Earliest and latest possible departure time for *WH* trip
$\boldsymbol{t_{\,a_i}}$	The preferred trip start time
$\boldsymbol{t_{HW,a_i}}$ $\boldsymbol{t_{WH,a_i}}$	The preferred trip start time for *HW* and *WH*.
$\pm\Delta\boldsymbol{T}$	A symmetric deviation of time window *T* w.r.t. the preferred trip start times of an a_i.
$\overline{\Delta\boldsymbol{T}}$	The tolerance period before HW or after *WH* trips (induced by preceding and succeeding activities respectively)
$\boldsymbol{C}$	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
$\boldsymbol{T^e_{carpool,\,l_k}}$	Start of the feasible time window (lower bound) for the carpool at l_k
$\boldsymbol{T^b_{carpool,\,l_k}}$	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.

4.5.4.2.4 Time Intervals: Induced by the Constraining Activities

After the assignment of an individual preference function for trips start time based on the factors elaborated above for each agent, the time intervals are proposed by considering all possible constraining activities.

In the simplest case, the individual is assumed to accept a symmetric maximum deviation $\pm\Delta T$ with respect to the preferred trip start time. In general, this is not necessarily true since preceding or succeeding activities can induce timing constraints. For an agent a_i, the earliest and latest departure times for the trip are $T^b_{a_i}$, $T^e_{a_i}$ (lower and upper bounds for the time window). The preferred trip start time of a_i is t_{a_i}. The symbols used and their meanings are described in Table 4.2.

The possible cases for the constraining activities are:

5. 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. (4).

$$\begin{aligned} T^b_{a_i} &= t_{a_i} - \Delta T \\ T^e_{a_i} &= t_{a_i} + \Delta T \end{aligned} \tag{4}$$

6. Eq. (5) 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.

$$\begin{aligned} \overline{\Delta T} &= t_{HW,a_i} - C_{finTime,a_i} \\ T^b_{HW,a_i} &= t_{HW,a_i} - \overline{\Delta T} \\ T^e_{HW,a_i} &= t_{HW,a_i} + \Delta T \end{aligned} \tag{5}$$

7. 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. (6).

$$\begin{aligned} T^b_{WH,a_i} &= C_{finTime,a_i} \\ T^e_{WH,a_i} &= t_{WH,a_i} + \Delta T \end{aligned} \tag{6}$$

8. 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. (7). Here $\overline{\Delta T}$ is during the $W*$ trip. $W*$ is the trip to any TAZ from the work.

$$\begin{aligned} \overline{\Delta T} &= C_{startTime,a_i} - t_{W*,a_i} \\ T^b_{WH,a_i} &= t_{WH,a_i} - \Delta T \\ T^e_{WH,a_i} &= t_{WH,a_i} + \overline{\Delta T} \end{aligned} \tag{7}$$

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

4.5.4.2.5 Individuals' Matching

i. Departure Time Choices

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 lower and upper bounds of the intersection of the arrival time windows can be calculated as specified in equation (8); the indices used for the *max()* and *min()* functions range over the set of candidate participants.

$$\begin{aligned} T^b_{carpool,l_N} &= \max_{j=1\ldots N}(T^b_{a_j}) \\ T^e_{carpool,l_N} &= \min_{j=1\ldots N}(T^e_{a_j}) \end{aligned} \quad = \bigcap_{j=1}^{N} T_{a_j l_N} \tag{8}$$

The negotiation outcome needs to be within the intersection of the time intervals of the individuals. The probability to find a HW trip arrival time that suits everyone, is given by the product probabilities to find a suitable solution for each carpool participant in the intersection of the time intervals (between $T^b_{carpool,l_N}$ and $T^e_{carpool,l_N}$) as given in equation (9). The summation corresponds to the integration of the preference function for a particular individual over the available time interval.

$$P_{carpool,l_N} = \prod_{i=0}^{n} \sum_{j=T^b_{carpool,l_N}}^{T^e_{carpool,l_N}} \left(P_{a_i t_j}\right) \tag{9}$$

The probability for the WH (evening trip) start time window can also be created by mirroring the same function given in equation (9).

The time window $T_{carpool,l}$ for TAZ location *l* in the *HW* trip 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 d_{l_i+1} and calculating the intersection with the time window specified by the participants to be picked up at *l* (Equation (10)). The circled minus applied to a time window and a scalar, denotes a time window shift.

$$T_{carpool,l_i} = (T_{carpool,l_i+1} \ominus d_{l_i+1}) \tag{10}$$

The lower and upper bounds of the intersection of the time windows at the specific location l_i can be calculated as specified in equation (11).

$$\begin{aligned} T^b_{carpool,l_i} &= \max_{j=1\ldots N}(T^b_{a_j} \ominus d_{l_i+1}) \\ T^e_{carpool,l_i} &= \min_{j=1\ldots N}(T^e_{a_j} \ominus d_{l_i+1}) \end{aligned} \tag{11}$$

The probability to find a HW trip departure time that suits everyone, is given by the product probabilities to find a suitable solution for each carpool participant in the intersection of the time intervals (between $T^{b}_{carpool,l_i}$ and $T^{e}_{carpool,l_i}$) as given in equation (12).

$$P_{carpool,l_i} = \prod_{i=0}^{n} \sum_{j=T^{b}_{carpool,l_i}}^{T^{e}_{carpool,l_i}} \left(P_{a_i t_j}\right) \tag{12}$$

ii. Detour Duration Relative to Solo-driving Duration

An individual having a solo trip duration $d_{a_i,solo}$ has an upper limit $d_{a_i,detour}$ for the detour delay in the trip from home to work. The relative excess is handled as follows: (a) It is assumed that for short trips a larger relative detour will be considered to be acceptable than for long trips and (b) if the distance $d_{a_i,solo}$ is less than d_{min} a relative excess of 1 is accepted (i.e. the trip size can be doubled). Trips with size larger or equal to d_{max} accept a relative error r_{min}. In the interval $[d_{min}\ to\ d_{max}]$ an exponential decay is used.

$$r(d) = \begin{cases} 1 & if\ d \le d_{min} \\ e^{\left(d_{a_i,solo} - d_{min}\right).\alpha} & if\ d_{min} < d < d_{max} \\ r_{\min} & if\ d \ge d_{max} \end{cases} \tag{13}$$

Then

$$\alpha = \frac{\ln(r_{min})}{d_{max} - d_{min}} \tag{14}$$

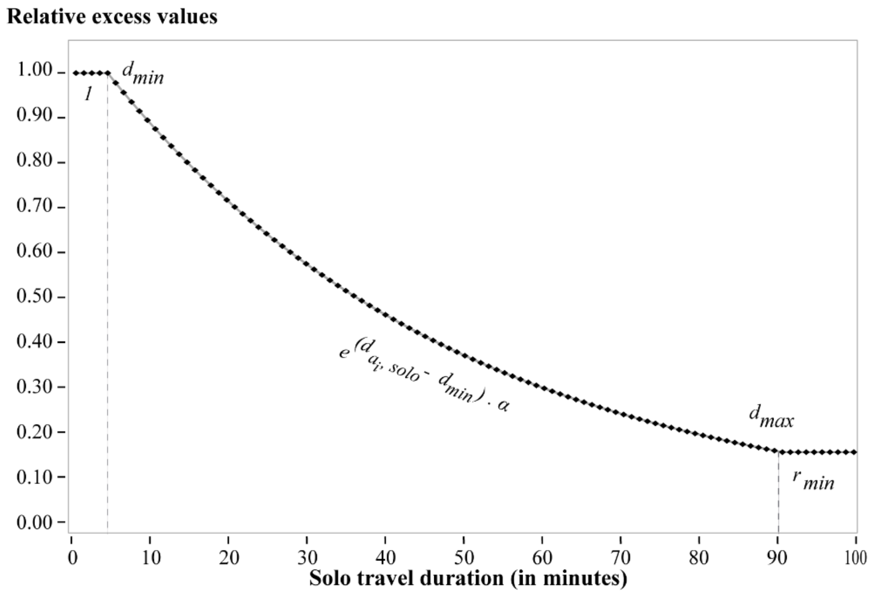


Figure 4.4: Distribution of the maximum excess overhead relative to the solo trip durations.

As an example Figure 4.4 shows the distribution of the maximum excess overhead relative to the solo trips durations. The values used for different parameters are: $d_{min} = 5mins.$, $d_{max} = 90mins$ and $r_{\min} = 0.15$ respectively.

iii. Driver and Vehicle Selection

The driver and vehicle selection is based on the inspection of the individual's profiles. Each agent who owns a car and a driving license, may become the driver when carpooling. The driver in the carpool needs to pick up every carpooler from their home TAZs and is the first one to board. Hence, driver selection and timing constraints are interrelated.

4.5.4.2.6 The Realization of Negotiation

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 and 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.

If for some l_i, 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 fails.

$$\forall_i : feasible_i \iff T_{carpool,l_i} \neq \emptyset \tag{15}$$

Additionally with the intersection of the respective *HW* and *WH* time intervals of the individuals, the combined preference for all carpoolers can be calculated by Eq. (16).

$$\forall_k : P_{carpool,l_k} = \prod_{i=0}^{n} \sum_{j=T^b_{carpool,l_i}}^{T^e_{carpool,l_i}} \left(P_{a_i t_j}\right) \tag{16}$$

For each a_i, the carpool duration must be less than or equal to the individual's maximum detour travel or maximum excess duration $d_{a_i,maxDetour}$. Since $d_{a_i,maxDetour} = d_{a_i,solo} . \left(1 + r\left(d_{a_i,solo}\right)\right)$.

$$d_{a_i,carpool} \leq d_{a_i,maxDetour} \tag{17}$$

The negotiation among individuals succeeds when all the constraints are satisfied and the final estimated value is larger than a given threshold value as shown by Eq. (18).

$$timePreference(\,).detourEffect(\,).driverAvailable(\,) > threshold \tag{18}$$

Fig. 5 characterizes the negotiation success values which have been estimated by the product of the (1) times preferences, (2) effect of detour (is the same as the time loss function, described in section 4.5.4.2.5) and (3) the driver's availability functions. The x-axis, $\bar{y}$-axis and $\bar{x}$-axis are showing the time preferences, effect of detour and the driver's availability values respectively while the y-axis represents the negotiation success values. At the $\bar{x}$-axis, when the driver's availability value is *zero* (the case when the driver is not available), the negotiation fails. On the other hand when the driver's availability value is *one* and the negotiation succeeds if and only if when the negotiation success values are achieved between *0* and *1* (also shown by bars using bar-chart in Figure 4.5). When the negotiation among the candidates succeeds then the respective sequence considered as a candidate solution.

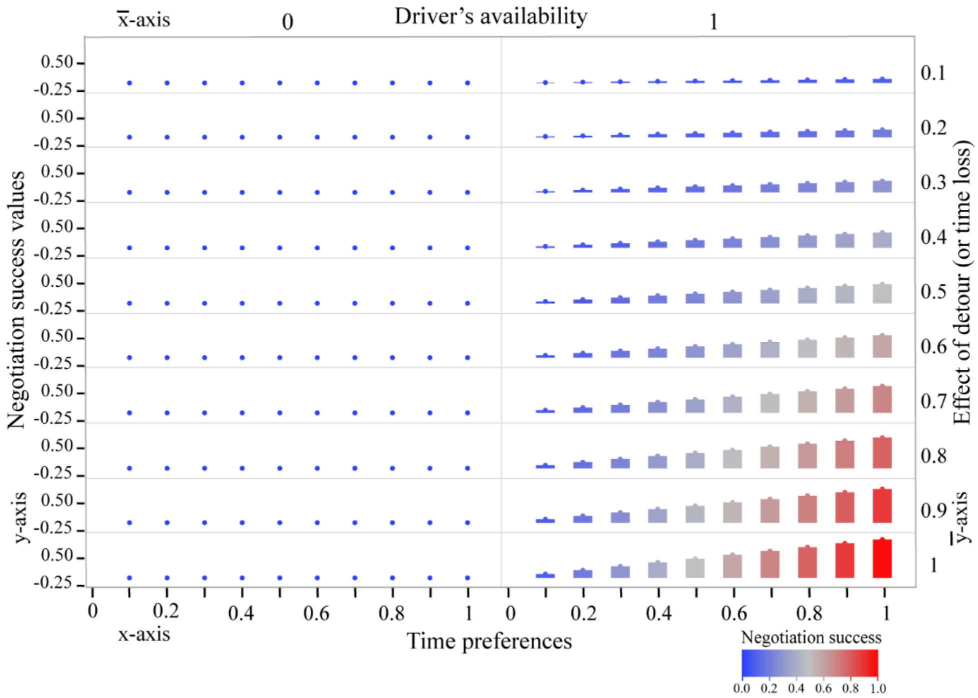


Figure 4.5: The possible negotiation success values as a function of time preference, effect of detour (the time loss) and the driver's availability.

Due to the permutation process, there can be more than one candidate solution for the same carpool participants. The difference between these solutions can be the driver and/or the pick-up and drop-off orders of the participants. To get the optimal solution from the candidate solutions, following scoring functions are used: the time of day, degree of flexibility and the detour scoring functions. Scoring functions will be described in detail below.

4.5.4.2.7 Scoring Functions: To Evaluate Candidate Sequence

i. Time of Day (Trip Start Time Determination)

As soon as it becomes clear that candidates will carpool, the trip start time needs to be determined at each TAZ location. Therefore, the preference function is used. In this paper, candidates do not have a constant level of preference for every moment (the intervals between lower and upper bounds) in the entire feasible time windows. The trip start time is calculated as follows.

Let d_k denote the duration to drive from l_{k-1} to 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:

$$T_{carpool,\, l_k} = T_{carpool,\, l_0} \oplus \sum_{i=1}^{k} d_i \tag{19}$$

The arrival time window of the carpool is:

$$T_{carpool,\, l_N} = T_{carpool,\, l_0} \oplus \sum_{i=1}^{N} d_i \tag{20}$$

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.

$$\forall_k:\ T^b_{carpool,\, l_k} \leq \ t_k = \ t_0 + \sum_{i=1}^{k} d_i \tag{21}$$

$$\forall_k:\ T^b_{carpool,\, l_k} - \sum_{i=1}^{k} d_i \leq \ t_0 \tag{22}$$

For the upper bound of the time window one finds

$$\forall_k:\ t_0 \ + \sum_{i=1}^{k} d_i \ \leq \ T^e_{carpool,\, l_k} \tag{23}$$

$$\forall_k:\ t_0 \leq T^e_{carpool,\, l_k} - \sum_{i=1}^{k} d_i \tag{24}$$

The lower and upper bounds at TAZ l_k are shown in Eq. (25) and Eq. (26) respectively.

$$T^b_{carpool,\, l_k} = \max_{j=1\ldots N}(T^b_{a_j,\, l_k} - \sum_{i=1}^{k} d_i) \tag{25}$$

$$T^{e}_{carpool,\, l_k} = \min_{j=1\ldots N}(T^{e}_{a_j,\, l_k} - \sum_{i=1}^{k} d_i) \tag{26}$$

The trip start time t_0 at TAZ l_0 shall be in between the lower and upper bounds of the time window is given by Eq. (27).

$$T^{b}_{carpool,\, l_0} \leq \quad t_0 \quad \leq T^{e}_{carpool,\, l_0} \tag{27}$$

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

$$\forall_k : T^{b}_{carpool,\, l_k} \leq \quad t_k \quad \leq T^{e}_{carpool,\, l_k} \tag{28}$$

In equation (29), the proportionality constant α is used. For every agent, the preference for a given departure time is proportional to the probability that the person will select that time (because of the normalization mentioned above).

$$V_{\ a_i t_j} = \alpha \ (P_{a_i t_j}) \tag{29}$$

The feasible trip start time at specific TAZ, is the point in time resulting in the largest collective preference value and is given by Eq. (30):

$$\forall_k : t_k = \underset{j=T^{b}_{carpool,\, l_k} \text{ to } T^{e}_{carpool,\, l_k}}{arg\, max} \prod_{i=0}^{N} \left(V_{a_i t_j}\right) \tag{30}$$

The final score for time of day for both the trips is calculated by multiplying the individual scores.

$$S_{timeOfDay} = t_{k,HW} \,.\, t_{k,WH} \tag{31}$$

ii. Degree of Flexibility

The degree of flexibility (DoF) score specified by Eq. (32) is 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 flexibility for the departure time at each location and hence for the ability to meet the schedule (because travel times may be uncertain). The candidate delivering the highest score is kept.

$$S(DoF) = 1 - \ e^{-\beta \,.\, \Delta T} \tag{32}$$

Eq. (32) is used to determine *DoF* where ΔT is the minimum interval length to set a value; e.g. for $\Delta T = 5[min]$ if we required a value 0.9 then the β can be determined by Eq. (33).

$$\beta = \frac{-\ln(0.1)}{\Delta T} \tag{33}$$

The final DoF score for trip starts times for both the trips are calculated by multiplying them.

$$S_{DoF} = S_{DoF,HW} \,.\, S_{DoF,WH} \tag{34}$$

i. Time Loss

The scoring function is used to evaluate time loss due to the detour duration relative to solo-driving duration. Let L_j^C denote the time loss for participant j by carpooling and let L_j^A denote the maximum acceptable detour duration specified by the participant j. The time loss score for the carpool is given by:

$$S_{timeLoss,trip} = \prod_{j=0}^{n} \left(1 - \frac{L_j^C}{L_j^A}\right) \tag{35}$$

The time loss score for both carpool trips is a day is the product of the individual scores.

$$S_{timeLoss} = S_{timeLoss,HW} \cdot S_{timeLoss,WH} \tag{36}$$

The optimal scoring values are estimated by taking the product of each score as shown in Eq. (37).

$$S_{optimal} = S_{timeOfDay} \cdot S_{DoF} \cdot S_{timeLoss} \tag{37}$$

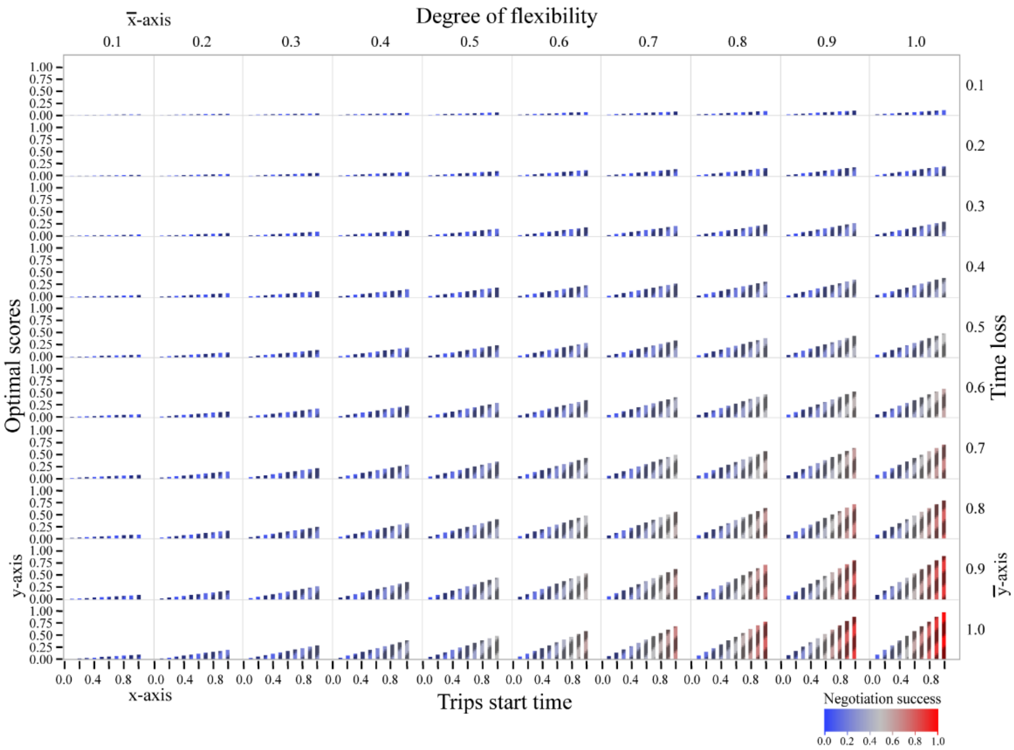


Figure 4.6: The estimated optimal scoring values using *the trips start times*, *degree of flexibility* and *the time loss* scoring functions.

Figure 4.6 represents the optimal scoring values which have been estimated by the product of (1) the trips start times, (2) degree of flexibility and (3) the time loss scoring functions. The x-axis, $\bar{x}$-axis and $\bar{y}$-axis are showing the trips start times, degree of flexibility and the time loss scoring functions respectively while the y-axis represents the optimal scores. The optimal scores are estimated between *0* and *1* (also shown by bars using bar-chart in Figure 4.6) by taking product of the scoring function values. The set of candidates exhibiting the maximum optimal score are kept and this solution should be chosen as the optimal solution.

4.5.4.2.8 Pseudocode to Determine the Candidate Pick-up Order

Algorithm 4.1 shows the pseudocode for the negotiation model described in section 4.5.4.2. The *negotiation()* function used in algorithm 4.1 takes an *ordered set of carpool candidates* (who participated in the negotiation process for a given carpool) and the *OD-based travel duration matrix* as input and returns the optimal sequence (if any) for the carpool candidates pick-up order. The list "*promising"* declared in *line 2* contains all successful pick-up / drop-off orders *(puo)* sequences of the *candidates* established by the *permuteSelector()* function. The *permuteSelector()* generates all permutations of the candidates set and finds feasible pick-up / drop-off sequences in *line 3*. In *line 4* an object *optimal* is declared to save the index of the optimal sequence (the optimized solution). Lines 6-9 scan the promising candidates, determine the composite score and keep the best solution.

The For-loop (from *lines 16-22*) in *permuteSelector()* function recursively generates all the *puo* sequences. At *line 14* of the *permuteSelector()*, the *findPUOSequence()* is used to retrieve the pick-up/drop-off sequence of the candidates. The variable "*feasibleSequence"* is used to keep track of the feasibility of the selected pick-up/drop-off order. The variable *negoScoreForPUO* keeps the negotiation score which is the sum of all individuals negotiation scores. That score will be compared with the threshold value (parameter specified by the user). The *optimalScoreForPUO* variable is used to compare different feasible sequences and to chose the optimal candidate solution. For-loop (at *lines 29-39*) iterates for each candidate of the pick-up/drop-off order list. *Line 30* checks for the feasibility of the time windows matching, the detour effect and also for the availability of the driver. The *feasibleTimeWindows()* and the *feasibleDetour()* functions are used to evaluate the time windows and the excess time for each candidate (described in *subsection 4.5.4.2.5*). A driver is assumed to be available if and only if the head of the candidates list owns a driver license and has a car available. *Line 31* calculates the negotiation score by summing the individual candidate scores for the particular pick-up / drop-off order. For each individual it is achieved by taking product of time preference, detour effect and driver's availability functions (described in *subsection 4.5.4.2.7*). Line 32 estimates the optimal score by taking sum of each candidate score and for each candidate it is calculated by taking the product of trips start times, time loss and the degree of flexibility functions. The *pickupOrder.settings()* amends information for each candidate (in case matching time windows and the detour are feasible) at *line 33.* Lines 40-43 update the optimal score and registers the solution in case it is feasible and the score is sufficiently large.

Algorithm 4.1: The pseudocode for the negotiation model (driver selection, pick-up / drop-off order and the time intervals).

```
# candidates: Set of ordered carpool candidates
# ODMatrix: Matrix of travel durations between TAZs
# promising: Set of promising pick-up orders
# optimal: The promising candidate pickup & drop-off order generating highest score
# puo: set of pick-up / drop-off order

Input: OrderedSet candidates, ODMatrix
Output: optimal: returns the optimal sequence (optimized solution)

Function negotiation(candidates, ODMatrix)
1.  Begin
2.  promising ← ∅
3.  permuteSelector (candidates, 0)      # generates 'promising'
4.  optimal ← NULL
5.  For puo in promising do
6.      If optimal is null or optimal.getOptimalScore () < puo. getOptimalScore () Then
7.          optimal ← puo
8.      End If
9.      Else            # Ignore or discard this puo from promising
10.     End For
11. End

# Generates all permutations of the candidates set and finds optimal sequences.
Function permuteSelector (candidatesList, startIndex)
12. Begin
13.     If  sizeof(candidatesList) = startIndex Then
14.         findPUOSequence(candidatesList);
15.     Else
16.         For i in  [startIndex ... sizeof(candidatesList) ) do
17.             pickupOrder ← candidatesList.clone()
18.             e ← pickupOrder [i]
19.             source [i] ← pickupOrder [startIndex]
20.             source [startIndex] ← e
```

```
            permuteSelector (pickupOrder, startIndex +1)
        End For
      End Else
End

# Evaluates pick-up order for membership of the 'promising' set using a
dynamic criterion.
Function findPUOSequence (pickupOrder)
    Begin
        feasibleSequence ← false
        negoScoreForPUO ← 0
        optimalScoreForPUO ← 0
        For ∀i in pickupOrder  do
            If timeWindowsMatched() AND feasibleDetour() AND driverAvailable()
                                          AND feasibleSequence
            negoScoreForPUO ← negoScoreForPUO +
                getNegoScoreForEachLoc ( timePref( ), detourEffect( ), driver?( ));
            optimalScoreForPUO ← optimalScoreForPUO +
                getOptimalScoreForEachLocation ( S_timeOfDay , S_DoF , S_timeLoss)
                pickupOrder.settings()
                                  #set zonal info. i.e.start time, pick-up / drop-off etc.
                feasibleSequence ← true
            End If
            Else        # not a feasible puo
                feasibleSequence ← false
            End Else
        End For
        If feasibleSequence AND negoScoreForPUO > Constants.threshold
            pickupOrder.setOptimalScore(optimalScoreForPUO)
            promising.add(pickupOrder)
        End If
    End
```

4.5.4.2.9 Joining a Carpool

After successful negotiation, the participants adapt their schedule according to the coordinated (optimal sequence) solution. At negotiation time, each individual specifies the period (number of days) during which to carpool for the trip. For the *optimal solution*, whose *optimalScore( )* is sufficiently large in the negotiation process, a *carpooling group* using organizational concepts is created. The carpoolers become members of this *carpool group* by playing their respective roles: the driver plays the *driving role*, and the passengers play the *passenger role*. 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*. Normally this occurs when someone wants to join or leave the *carpool group*. When it happens the negotiation procedure described above is executed again as long as there are at least two participants in the carpool, and one of them can act as a driver. This leads to a new trip (*TAZ* visit sequence) and timing.

4.5.4.3 Trip Execution: Traveling Solo or Carpooling

The carpooling activity corresponds to the execution of the trips (*HW* and *WH*) over multiple 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 TAZs have been computed a priori and are assumed to be time independent. This is to be refined by making the negotiation aware of time dependent travel time. The expected travel times between TAZs for the morning peak period are used. The individuals' daily schedule of a working day remains the same for all working days.

During carpooling, when someone leaves the *carpool* permanently or a new individual joins the *carpool* then the remaining carpoolers may re-negotiate and adapt their carpool trip start times for both the trips. Note that this negotiation does not necessarily succeed. When the driver decides to leave the *carpool*, a new driver is to be selected among the passengers having a vehicle and a driving license. This is realized by again executing the *permutation* procedure mentioned above. Handling incoming invitations during the carpool lifetime, requires additional negotiation between the carpoolers and the new candidates applying to join the *carpool*. An individual who once left carpooling, can again interact with the individuals of his or her interest to start carpooling.

Each participant (driver or passenger) leaves the *carpool* at the end of the individual specific participation period. A *carpool group* 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 the *CPSG* of the *carpooling social network* according to the mechanism discussed in *section 4.5.4.1* of the carpooling model to find a new *carpool*.

4.6 Simulation Experiments and Discussions

4.6.1 Dataset: CPSN and OD-based Travel Times

The carpooling social network was established by generating a population using results predicted by FEATHERS. 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 set of all schedules allows to calculate expected mode-specific traffic flows in time and space; those flows have been validated using traffic counts made available by public traffic management services. The FEATHERS model for the Flanders region is characterized by about six million inhabitants and the area is subdivided into *2386* TAZs. Hence, a TAZ covers $5[km^2]$ only.

A pre-calculated TAZ-based travel time matrix generated by the WIDRS framework (Knapen et *al*., 2014), applying to peak periods for the Flanders region is used. Those expected travel times estimate the durations of the trips. The success of the negotiation may result in reconsideration of departure and arrival times for planned trips.

In the presented framework, individuals' commuting trips (*HW* and *WH*) in their daily schedules are detailed and discussed in relation to long-term carpooling. The set of other (constraining) activities including pick-drop, shopping etc. is also considered because they can induce timing constraints to commuting trips. An individual's profile consists of the home and work TAZ, the start time and duration for each activity and trip and the socio-economic attributes (vehicle availability and driving-license ownership). The framework is based on traffic flows between TAZ. It is assumed that people board and alight at home and at work TAZ only. People working in the zone they live are not considered to be carpooling candidates.

4.6.2 Experiments and Results

Experiments were conducted at the scale of the Flanders region (Belgium). Particular TAZs from the Brussels region where people daily come to perform their work activities are considered as work area. Individuals whose transportation mode is *car* and having at least one *work activity* (daily) at one of the selected work TAZ are considered as candidate carpoolers. Note that individuals having a common destination or work TAZ can carpool with each other only. For the experiments, the *carpooling social network* characterized by number of:

Individuals: *18,218* whose travel mode is *car* only.
home zones: *2,386* TAZs
work zones: *22* TAZs

To analyze the behavior of the carpoolers, the presented framework is simulated for three years (*660 working days)* and following constraints are applied to accomplish the simulation results for an individual (see Table 4.3):

Table 4.3: Constraints and their values for the simulation experiment.

An exploring agent can contact at most	*10 people / simulated day*
The probability to invite someone	*100%*
Time window length	ΔT *= 30[min]*
Negotiation success (threshold)	*0.0*
Maximum detour ratio for short trips	*for duration ≤ 5 [min.] is 1*
Maximum detour ratio for long trips	*for duration ≥ 90[min.] is 0.15*
Car capacity (driver included)	*5*
Minimum carpool period	*30 days*
Maximum carpool period	*660 days (also the simulation period)*

A carpooler determines the number of working days to carpool by selecting a number in the [30–660] by sampling from a uniform distribution. 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. Five people at most can share a car (driver included).

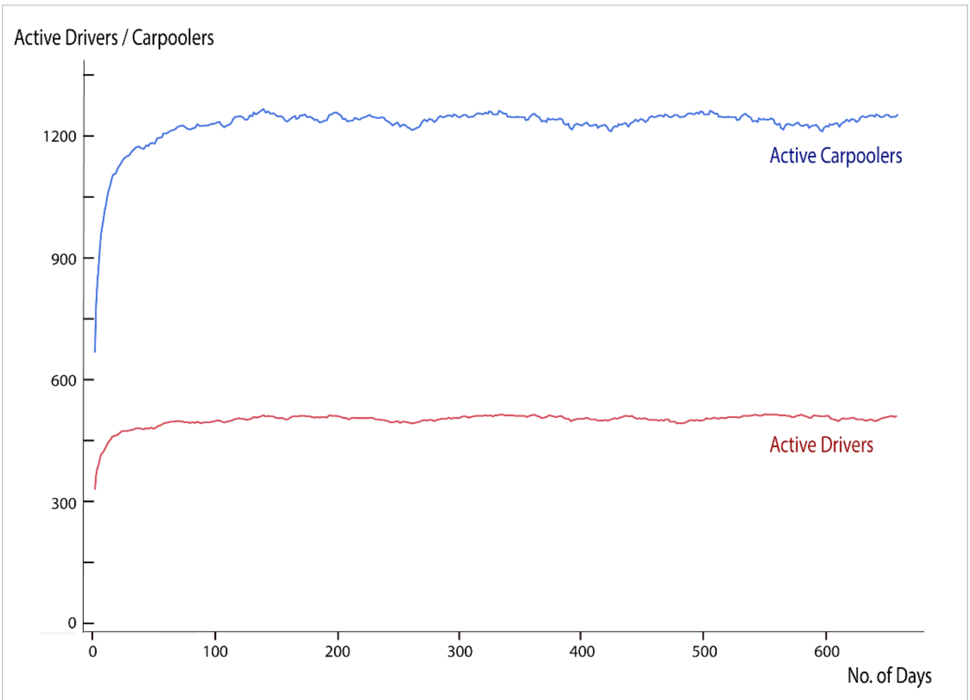


Figure 4.7. Number of active carpoolers and number of carpool drivers throughout simulated period.

Figure 4.7 shows the number of active carpoolers and also number of active drivers or carpool groups throughout the simulation period according to the constraints presented in the Table 4.3. The horizontal axis shows the number of working days, and the vertical axis represents the number of active carpoolers (with blue line) and number of active carpool groups (with red line) for each day. The number of active carpoolers and also number of drivers or carpools rapidly increases at the start of the simulation up to 30 days because every noncarpooling individual tries to join a carpool and nobody leaves a carpool. After 30 days, some participants decide to leave a carpool and the increase in the rate is lower to the end of the simulation. It seems to be easier to join an existing group than to create a new one. After the initial period, the remaining part of the curves levels off with minor fluctuations to the end of the simulation.

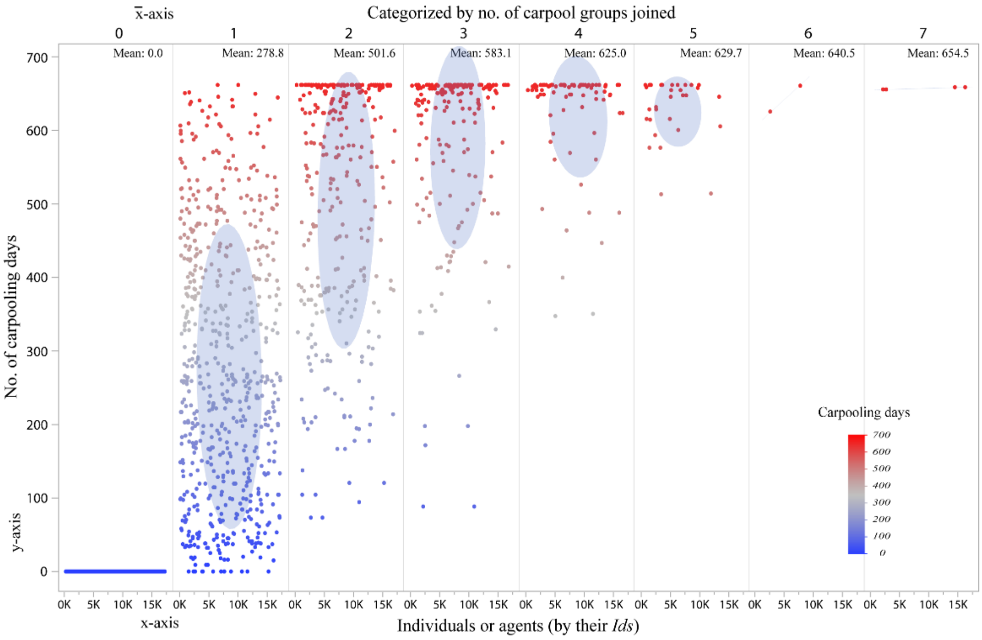


Figure 4.8: Number of carpooling days for each simulated individual. Each ellipse represents a category (the number of groups the individual participated in).

Scattered graph in Figure 4.8 shows the distribution of the carpooling days for each simulated individual. The x-axis shows all the simulated individuals (user-ids) while y-axis represents the number of carpooling days for each agent. Individuals are categorized by number of carpool groups they shared as shown at $\bar{x}$-axis (Figure 4.8). The carpooling individuals are divided into eight carpool groups (seven of them are carpooling groups while 0-group represents the individuals who traveled by driving solo: they did not find any carpool group). The specified masses of the carpooling days are shown using density ellipses for each carpool group. The density ellipsoid is computed from the bivariate normal distribution fit to the individuals and the carpooling days they traveled. The graph shows that the individuals who shared higher number of carpool groups, carpooled for longer period. The Mean value for each carpool group is also given at their particular section in the Figure 4.8 which shows how long each individual traveled by carpooling on average.

The carpoolers who carpool for less than 30 days were not able to complete the intended carpool (because of the end of the simulation or because they joined a group from which the driver resigned soon after). When the carpool group leftovers less than two persons then it will be terminated and the person who is left alone will have to stop carpooling too. Other reason can be they cannot be part of the any carpool group either with the same participants or with different participant because they carpooled with different candidates who are not compatible with this one.

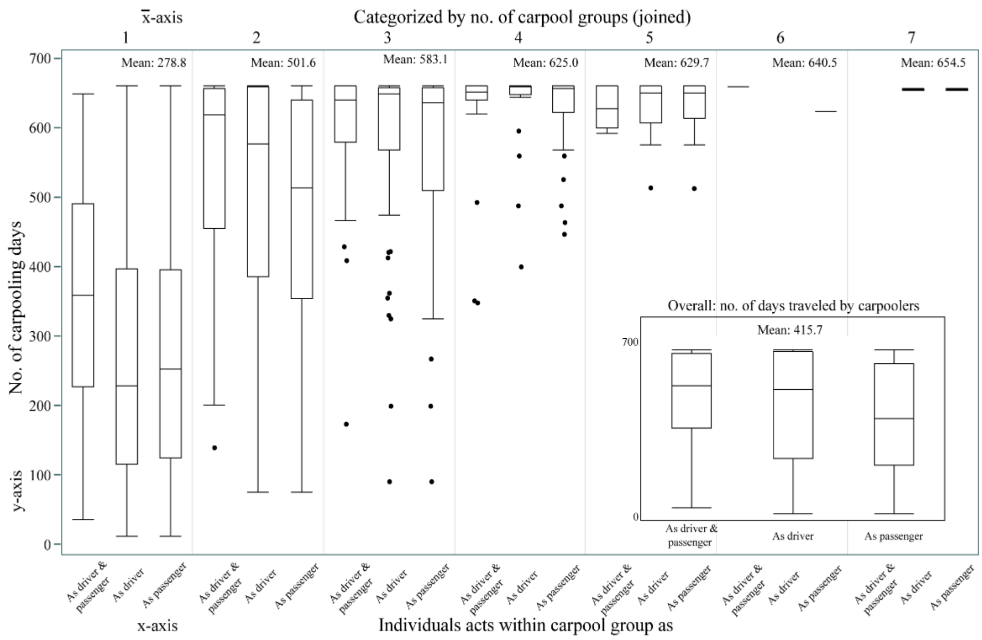


Figure 4.9: Boxplot: number of carpool days carpoolers travelled either for the number of carpool groups joined as driver, passenger or both (driver and passenger).

Boxplots in Figure 4.9 show the number of carpooling days carpoolers traveled during their carpooling period either as driver, as passenger or by both (driver and passenger) for the number of carpool groups they joined. In the presented case boxplots are useful for comparing several distributions. The Mean values for the carpool groups joined (1^{st}, 2^{nd}), carpoolers traveled for more days for as *both* (driver and passenger) than either as *driver* only or as *passenger* only. Carpoolers who joined 3^{rd} and 4^{th} carpool groups *as driver* during their carpooling period, traveled for higher number of days than traveled as passenger. The less number of carpoolers joined 6th and 7th carpool groups, and each carpooler traveled for almost full simulated period. The boxplots in the right-bottom (a separate block) of Figure 4.9 show the overall number of carpool days for all the carpool groups, the carpoolers traveled as both (driver and passenger), as driver and as passenger exclusively. The overall Mean value for these situations is *415.7* which means on average a carpooler traveled for *415* days of the simulated period. The Mean value for the carpoolers who traveled by both (driver and passenger) carpool for higher number of days than traveled as either driver or as passenger. Note that each individual can be part of a carpool group for at least 30 days or until the carpool group terminates.

Figure 4.10 shows the average size of the carpool group, the carpoolers shared. Result shows that *2.49* carpoolers shared a car on average. According to the 2012 and 2013 Flemish travel survey ["Onderzoek Verplaatsingsgedrag Vlaanderen" (OVG) means travel behavior research in Dutch], the average car occupancy was *2.4* persons per car in the 2012 OVG and *2.46* persons per car in the 2013 OVG (cools et *al.*, 2013).

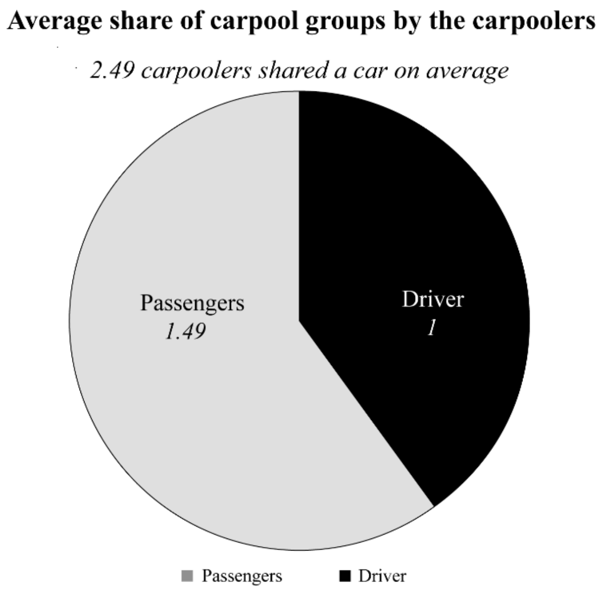


Figure 4.10: Average carpool size (on average carpoolers shared a car).

The presented results show that the current model works well according to the given constraints and parameters. Indeed, it is necessary to consider a sufficiently large region to evaluate the current model. Apart from scalability issues, future research will mainly focus on the effect of schedule adaptation and enhancing the negotiation model. Although, there might be some concerns regarding the validity of the model coefficients of the proposed preference function for European region as originally it was designed on the basis of a survey conducted in an American State. However, the selected approach towards the construction of a close-to-reality individualized preference function for each individual in the population can eventually turn out to be helpful for future studies and only a few adjustments to the coefficients of the *multinomial logit model* will lead to a model that will be accurately representative of the actual negotiation mechanism specifically for Flanders, Belgium. However, the construction of behaviorally accurate agent based models require an extensive and detailed database in order to simulate the actual mechanism.

4.7 Conclusion and Future Work

An agent-based framework for long term carpooling 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 (*HW* and *WH*) trips model and takes the possibility of flexible activity scheduling into account. The agents negotiate on trips departure times and on the driver assignment within the carpool group. In the presented model the success of negotiation depends on the factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. The selection of the most preferred trip departure time partly derived from existing departure time studies, is based on a number of factors namely; (i) travelling factors, (ii) socio-economic factors and (iii) time pressure factors. In order to cooperate, the individuals adapt their agenda according to personal preferences and limitations. The driver and vehicle selection, pick-up and drop-off order, and the preferred trip start times intervals of the optimal carpool group are evaluated by using scoring functions: trips departure time, degree of flexibility and the time loss. 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.

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. Other areas of future work include the development of a visual representation of the scenario, including the use of web services to simulate.

4.8 References

Arentze, T., Pelizaro, C., & Timmermans, H. J. P. (2005). Implementation of a model of dynamic activity-travel rescheduling decisions: an agent-based microsimulation framework. *In Proceedings of CUPUM 05* (p. paper no. 48). London. http://128.40.111.250/cupum/searchpapers/papers/paper48.pdf

Armendáriz, M., Arnould, G., & Khadraoui, D. (n.d.). (2011). Carpooling: A Multi-Agent Simulation In Netlogo. *Proceedings 25th European Conference on Modelling and Simulation* ©ECMS Tadeusz Burczynski, Joanna Kolodziej Aleksander Byrski, Marco Carvalho (Editors) ISBN: 978-0-9564944-2-9 / ISBN: 978-0-9564944-3-6 (CD)

Bellemans, T., Bothe, S., Cho, S., Giannotti, F., Janssens, D., Knapen, L., … Wets, G. (2012). An Agent-Based Model to Evaluate Carpooling at Large Manufacturing Plants. *ANT 2012 and MobiWIS 2012*, 10, 1221–1227. https://doi.org/10.1016/j.procs.2012.08.001

Bellemans, T., Kochan, B., Janssens, D., Wets, G., Arentze, T., & Timmermans, H. (2010). Implementation Framework and Development Trajectory of FEATHERS Activity-Based Simulation Platform. *Transportation Research Record: Journal of the Transportation Research Board*, 2175, 111–119. https://doi.org/10.3141/2175-13

Ben Cheikh, S., & Hammadi, S. (2014). The Alliance between Optimization and Multi-Agent System for the Management of the Dynamic Carpooling. In G. Jezic, M. Kusek, I. Lovrek, R. J. Howlett, & L. C. Jain (Eds.), Agent and Multi-Agent Systems: Technologies and Applications: *Proceedings of the 8th International Conference KES-AMSTA 2014 Chania, Greece*, June 2014 (pp. 193–202). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-07650-8_20

Cools, M., K. Declercq, D. Janssens, and G. Wets. (2013). Onderzoek Verplaatsingsgedrag Vlaanderen 4.5 (2009–2013). *Transportation Research Institute, Universiteit Hasselt, Diepenbeek, Belgium*.

Cho, S., Yasar, A.-U.-H., Knapen, L., Bellemans, T., Janssens, D., & Wets, G. (2012). A Conceptual Design of an Agent-based Interaction Model for the Carpooling Application. *ANT 2012 and MobiWIS 2012*, 10, 801–807. https://doi.org/10.1016/j.procs.2012.06.103

Chun, H. W., & Wong, R. Y. M. (2003). N∗—an agent-based negotiation algorithm for dynamic scheduling and rescheduling. *Advanced Engineering Informatics,* 17(1), 1–22. https://doi.org/10.1016/S1474-0346(03)00019-3

Cossentino, M., Galland, S., Gaud, N., Hilaire, V., & Koukam, A. (2010). An Organisational Approach to Engineer Emergence Within Holarchies. *Int. J. Agent-Oriented Softw. Eng.*, 4(3), 304–329. https://doi.org/10.1504/IJAOSE.2010.036986

Cossentino, M., Gaud, N., Hilaire, V., Galland, S., & Koukam, A. (2010). ASPECS: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent System*s, 20(2), 260–304. https://doi.org/10.1007/s10458-009-9099-4

Ferber, J., Gutknecht, O., & Michel, F. (2004). From Agents to Organizations: An Organizational View of Multi-agent Systems. In P. Giorgini, J. P. Müller, & J. Odell (Eds.), *Agent-Oriented Software Engineering* IV: 4th *InternationalWorkshop, AOSE 2003, Melbourne, Australia,* July 15, 2003. Revised Papers (pp. 214–230). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-24620-6_15

Galland, S., Knapen, L., Yasar, A.-U.-H., Gaud, N., Janssens, D., Lamotte, O., … Wets, G. (2014). Multi-agent simulation of individual mobility behavior in carpooling. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, 45, 83–98. https://doi.org/10.1016/j.trc.2013.12.012

Gan, L. P., & Recker, W. (2008). A mathematical programming formulation of the household activity rescheduling problem. *Transportation Research Part B: Methodological*, 42(6), 571–606. https://doi.org/10.1016/j.trb.2007.11.004

Gaud, N., Galland, S., Hilaire, V., & Koukam, A. (2009). An Organisational Platform for Holonic and Multiagent Systems. In K. V. Hindriks, A. Pokahr, & S. Sardina (Eds.), Programming Multi-Agent Systems: *6th International Workshop, ProMAS 2008, Estoril, Portugal*, May 13, 2008. Revised Invited and Selected Papers (pp. 104–119). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-03278-3_7

Guo, Yuhan, Goncalves, Gilles, Hsu, Tienté, 2013, A Multi-agent Based Self-adaptive Genetic Algorithm for the Long-term Car Pooling Problem, *Journal of Mathematical Modelling and Algorithms in Operations Research*, 45-66, 12(1). DOI: 10.1007/s10852-012-9175-7.

Guo, J. Y., Nandam, S., & Adams, T. (2012). A data collection framework for exploring the dynamic adaptation of Activity Travel decisions. In *Transportation Reseaarch Board*, 91st Annual Meeting. Tampa, Florida.

Gupta, S., & Vovsha, P. (2013). A model for work activity schedules with synchronization for multiple-worker households. *Transportation*, 40(4), 827–845.
https://doi.org/10.1007/s11116-013-9469-2

Hendrickson, C., & Plank, E. (1984). The flexibility of departure times for work trips. *Transportation Research Part A: General*, 18(1), 25–36.
https://doi.org/10.1016/0191-2607(84)90091-8

Horvitz, E., Apacible, J., Sarin, R., & Liao, L. (2012). Prediction, Expectation, and Surprise: Methods, Designs, and Study of a Deployed Traffic Forecasting Service. *CoRR*, abs/1207.1352.
Retrieved from http://arxiv.org/abs/1207.1352

Hussain, I., Knapen, L., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016(a)). Negotiation and Coordination in Carpooling. *Transportation Research Record: Journal of the Transportation Research Board*, 2542, 92–101.
https://doi.org/10.3141/2542-11

Hussain, I., Knapen, L., Galland, S., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016(b)). Organizational-based model and agent-based simulation for long-term carpooling. *Future Generation Computer Systems*, 64, 125–139.
https://doi.org/10.1016/j.future.2016.02.019

Jennings, N. R. (2000). On agent-based software engineering. *Artificial Intelligence*, 117(2), 277–296.
https://doi.org/10.1016/S0004-3702(99)00107-1

Joh, C.-H., Timmermans, H. J. P., & Arentze, T. A. (2006). Measuring and predicting adaptation behavior in multi-dimensional activity-travel patterns. *Transportmetrica*, 2(2), 153–173.
https://doi.org/10.1080/18128600608685659

Kamar, E., & Horvitz, E. (2009). Collaboration and Shared Plans in the Open World: Studies of Ridesharing. *In Proceedings of the 21st International Jont Conference on Artifical Intelligence* (pp. 187–194). San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.
Retrieved from http://dl.acm.org/citation.cfm?id=1661445.1661476

Knapen, L., Keren, D., Yasar, A.-U.-H., Cho, S., Bellemans, T., Janssens, D., & Wets, G. (2012). Analysis of the Co-routing Problem in Agent-based Carpooling Simulation. *ANT 2012 and MobiWIS* 2012, 10, 821–826. https://doi.org/10.1016/j.procs.2012.06.106

Knapen, L., Bellemans, T., Usman, M., Janssens, D., & Wets, G. (2014(a)). Within day rescheduling microsimulation combined with macrosimulated traffic. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, 45, 99–118. https://doi.org/10.1016/j.trc.2014.04.012

Knapen, L., Yasar, A., Cho, S., Keren, D., Dbai, A. A., Bellemans, T., … Bhaduri, K. (2014(b)). Exploiting graph-theoretic tools for matching in carpooling applications. *Journal of Ambient Intelligence and Humanized Computing*, 5(3), 393–407. https://doi.org/10.1007/s12652-013-0197-4

Lützenberger, M., Masuch, N., Hirsch, B., Ahrndt, S., Heßler, A., & Albayrak, S. (2011). Strategic Behavior in Dynamic Cities. *In Proceedings of the 2011 Summer Computer Simulation Conference* (pp. 194–201). Vista, CA: Society for Modeling & Simulation International. http://dl.acm.org/citation.cfm?id=2348196.2348223

Martinez, L. M., Correia, G. H. A., & Viegas, J. M. (2015). An agent-based simulation model to assess the impacts of introducing a shared-taxi system: an application to Lisbon (Portugal). *Journal of Advanced Transportation*, 49(3), 475–495. https://doi.org/10.1002/atr.1283

Nijland, E. W. L., Arentze, T. A., Borgers, A. W. J., & Timmermans, H. J. P. (2009). Individuals' Activity–Travel Rescheduling Behaviour: Experiment and Model-Based Analysis. *Environment and Planning A*, 41(6), 1511–1522. https://doi.org/10.1068/a4134

Ronald, N., Arentze, T., & Timmermans, H. (2012). Modeling social interactions between individuals for joint activity scheduling. *Emerging and Innovative Directions in Choice Modeling,* 46(2), 276–290. https://doi.org/10.1016/j.trb.2011.10.003

Xia, J., Curtin, K. M., Li, W., & Zhao, Y. (2015). A New Model for a Carpool Matching Service. *PLOS ONE*, 10(6), e0129257. https://doi.org/10.1371/journal.pone.0129257

Chapter 5

Case of Disaggregated Street Addresses

This chapter consists of following paper

Hussain, I., et *al.*, (2017). Agent-based carpooling model for individuals matching using disaggregated street addresses, *IEEE Transactions on Intelligent Transportation Systems* (submitted).

5.1 Overview

This chapter presents a mechanism to model the interactions of autonomous agents which enables communication within carpooling social groups (CPSGs) that coincide with the sets of agents working at a particular company or institution. The carpoolers behavior and network information are included so that the complete carpooling problem can be examined. The street addresses of the individuals are used to extract the actual trip duration information on the road network from the OSM dataset directly using the GraphHopper API. A GraphHopper server was set up to that end. A *multiple trip negotiation model* for work trips is also presented. The driver and vehicle selection, pick-up and drop-off order and the preferred trip start times of feasible carpool groups are evaluated by means of scoring functions: (i) degree of flexibility and (ii) the time loss. Long term carpooling agreements are simulated. The purpose of the research reported in this chapter is to investigate the computational performance of the model that contains all features described in previous chapters with the exception of the optimal trip start time determination using non-constant preference functions. The model presented in this chapter is considered to be final and can be chosen for a specific company or institution when the disaggregate behavior of the carpooling social network is taken into account.

5.2 Abstract

Carpooling for commuters is a specific transportation problem where cooperation between individuals is essential while executing their trips. Through negotiation and cooperation, carpooling candidates can reach complex agreements in an iterative way to find matching partners in order to co-travel. This paper presents a framework to simulate the cooperation of carpooling candidates in a network which analyzes various effects of individuals' interaction and behavior adaptation. The objective is to model the interactions of autonomous agents which enables communication within social groups that coincide with the sets of agents working at a particular company or institution. Detailed routes based on disaggregated street addresses are used. Candidates are matched taking into account the constraints to which drivers and passengers are subjected. The potential carpoolers behavior and network information are included so that the complete carpooling problem can be examined. The negotiation success highly depends on the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. In order to cooperate, the potential carpoolers adapt their daily schedule according to personal preferences and limitations. Accurate information is obtained by the use of individuals' street addresses and by computing the route length directly from the road network. The actual travel times and travel distances are taken from the OpenStreetMap database using GraphHopper. The carpooling social network was established using results predicted by FEATHERS an operational activity-based model for Flanders (Belgium). The purpose of the research reported in this chapter is to investigate the computational performance of the model that contains the features required to determine the carpooling behavior of a population using agent-based modeling.

Keywords: Agent technology, Commuting, carpooling, coordination and negotiation, departure time, travel behavior.

5.3 Introduction

Carpooling for commuters is a specific transportation problem where cooperation between individuals (agents) is essential while executing their trips. It enables commuters to share travel expenses, save on fuel and parking costs, improve mobility options for non-drivers and it also reduces emission and traffic congestion. Mutual coordination for carpooling has been found a challenging task both for the driver and for all the passengers. Negotiation is essential to cooperation both on activity and on trip execution. To enable carpooling, effective negotiation requires that agents effectively convey and interpret information. Each negotiation involves a small number of participants but the individuals' schedules can be interconnected and hence constrained by cooperation (Knapen, Yasar, et al., 2014; Horvitz, et al., 2005). Network travel information systems inform about the extent of unexpected delay and provide means to improve the consistency or dependability while traveling in the carpooling process.

Given the importance of human behavior for the outcome of cooperation in carpooling, the question arises is *how far human* behavior *is actually reflected?* To investigate the effect of communication, negotiation and coordination for carpooling one needs to answer the question *How to simulate agent interactions in the carpooling simulation?* Hence a mechanism is required to simulate human behavior when decisions for cooperation are to be taken. It is also important to find out what is the share of carpooling among the available transportation modes given behavioral constraints with respect to activity timing. The actual travel-time information of the network has been well applied in the carpooling applications and plays important role to identify the matching candidates for co-traveling. It provides travel-time information for commuters to understand the current traffic condition. The use of accurate travel times could help to reduce transport costs by avoiding congestion and may provide incentives to the individual’s mobility plans.

This research evaluates the performance of an agent-based implementation of a carpooling model. Microscopic simulation models are useful part of modeling and currently many research areas including transportation behavior need to analyze and model complex behavior of people. Traditional modeling tools have difficulties for handling the complexity of communication and negotiation that are required in carpooling simulations. A method that is more suited for the interaction of autonomous entities is agent-based modeling (ABM). The ABMs can provide valuable information on the society and on the outcome of social actions or phenomena because of its capability to analyze aggregated consequences of individual specific behavior variations.

The purpose of the research reported in this paper is to investigate the computational performance of an agent-based model that contains the features required to determine the carpooling the behavior of a population.

The framework proposed to simulate the cooperation of carpooling candidates in a network is an extension of the work presented in (Hussain, et al., 2016) and improves previous research by: (1) modeling the interactions of autonomous agents which enables communication within social groups that coincide with the sets of agents working at a particular company or institution and (2) by assigning a particular route to each trip and by determining likely carpool matches while considering constraints that apply to drivers and passengers. The accuracy is obtained by the use of individuals’ street addresses and by computing the route length directly from the network. The actual travel times and travel distances are taken from the OpenStreetMap (OSM) database using *GraphHopper* (Karich, 2014) (an Application Program Interface (API)). *GraphHopper* is a fast and memory efficient open source routing library and server. It can be used to calculate the travel duration and travel distance matrices which are then used as an input for Vehicle routing problems (Urquhart, 2015). In order to co-travel, sets of agents working at a particular company or institution (work-location) are considered to be member of the same *carpooling social group*. A multiple trip *negotiation model* for commuting trips (*home-to-work* (HW) and *work-to-home* (WH)) is presented. The success of negotiation depends on the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. In order to cooperate, agents need to adapt their daily schedule according to personal preferences and limitations. The driver and vehicle selection, pick-up and drop-off order and preferred trip start times of the carpool group are evaluated by using scoring functions (degree of flexibility and the time loss). The actual trips execution (carpooling) is considered; trips are executed on long-term basis.

In the model used for computational effort evaluation, the individuals who once joined as carpooling candidates will never stop carpooling (just to analyse the behavior of carpooling candidates without mentioning their carpooling period): they will remain in the same carpool group through the simulated period.

The implementation uses the Janus (Gaud, et al., 2009) multi-agent based platform to simulate the interactions of autonomous agents. It provides an efficient implementation of agent-based and organizational-based concepts. For experiments, a *carpooling social network* is considered and simulated. It was established using results predicted by the FEATHERS (Bellemans et al., 2010a), an operational activity-based model for Flanders (Belgium).

This paper is organized as follows. Section 5.4 summarizes the related work on coordination and negotiation techniques as well as activity rescheduling and individual matching in carpooling. Section 5.5 presents the design of a carpooling model that maps to an agent-based simulation. Section 5.6 explains the experimental setup and discusses some of the results. Finally, conclusions and future work are presented in Section 5.7.

5.4 Related Work

In this section, existing work on carpooling is presented in two subsections: (1) the different types of coordination and negotiation techniques and (2) the rescheduling activities in the agenda for a day as well as individual matching.

5.4.1 Coordination and Negotiation

In the first category of the research exertions, the agent-based models covering the coordination and negotiation techniques for carpooling are studied.

Hussain *et al.* in (Hussain, et al., 2016) proposed a multiple trip negotiation model (combining the forward and backward commuting trips for a day in a single negotiation) for carpooling which is partly derived from existing departure time study presented in (Hendrickson & Plank, 1984). It was proposed to take *flexible activity scheduling* into account. The authors measured the direct interaction between agents belonging to a *carpooling social network* and also limit the interaction between agents within small groups based on home and work travel analysis zones (TAZs). In (Hussain, et al., 2016), the same authors extended the interaction mechanism of agents by enabling it into multi TAZs based where the individuals living in different TAZ and heading to the same work TAZ are allowed to negotiate for carpooling. The amount of interaction between agents is minimized by establishing carpooling social groups based on the same work TAZ. A negotiation model on trip start time and driver selection is also presented. Constant preference for the trip start time within a given interval is used in the presented negotiation model. Galland *et al.* in (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. This study is basically based on (Cho et al., 2012) where a conceptual design of an ABM for the carpooling application is presented.

Bellemans *et al.* (Bellemans et al., 2012) introduced an agent-based simulation model to support carpooling at large manufacturing plants. Authors introduce the following services: (a) an agent-based simulation is used to investigate opportunities and inhibitors and (b) online matching is made available for matching commuter profiles. Authors argue that incorporating complex negotiations between agents is compulsory for successful carpooling, because inhibiting factors like rerouting and rescheduling have to be considered. In (Guo, Goncalves, & Hsu, 2013) a multi-agent based self-adaptive genetic algorithm is presented to solve a long-term carpooling problem efficiently with limited exploration of the search space. The system is a combination of multi-agent system and genetic paradigm, and guided by a hyper-heuristic dynamically adapted by a collective learning process. It was evaluated by simulating large scale data sets. Authors in (Armendáriz, et al., 2011) designed and presented a multi-agent based simulation of Dynamic Carpooling System (DCS) using NetLogo. DCS optimizes the transport utilization by the ride sharing among people who usually cover the same route. Authors claim that their system provides an intelligent matching service along with a smart routing engine that can use real time information (for instance, considering weather and traffic conditions). Cheikh and Hammadi (Ben Cheikh & Hammadi, 2014), present a multi-agent system for the management of dynamic carpooling by proposing an original alliance between optimization and a multi agent concept to perform parallel optimized assignment of vehicles to users queries. A decomposition process intended to subdivide the global problem into several sub-problems with a reasonable search space was also presented. Authors propose to break geographic areas (global problem) into distinct zones (sub-problems) where each zone is controlled by an agent with an optimized behavior.

In the context of *travel demand*, cooperation aspects apply to joint activity execution and joint trip execution. Ronald *et al.,* (Ronald, et al., 2012) 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, (Chun & 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 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.

5.4.2 Rescheduling and Matching

A large body of literature (e.g. Nijland, et al., (2009); Guo et al., (2013)) 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.*, (Knapen, et al., 2014) 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 et *al.* (Joh, et al., 2006) 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*, (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 (Gan & Recker, 2008), authors presented a mixed integer linear program model of household activity rescheduling behavior. It comprised complicated human decisions as activity cancellation, insertion, and duration adjustment and is formulated as a Mixed Integer Linear Program called HARP. The model differs from existing rescheduling models in a number of important aspects: (1) rescheduling is driven by similarity maximization, (2) the model output structure is defined in terms of a similarity/difference measurement scheme and (3) the model accommodates rescheduling processes that are not only strictly driven by the similarity-maximization principle but also those based on utility maximization. Gupta and Vovsha, (Gupta & Vovsha, 2013) present a hybrid discrete choice-duration model for work activity scheduling with interactions between workers in a multiple-worker household. The key feature is the introduction of intra-household interactions through worker schedule synchronization mechanisms.

Xia et *al.*, (Xia, et al., 2015) propose a model for carpool matching services, and both optimal and heuristic approaches are tested to find solutions. It is demonstrated that a new formulation and associated solution procedures can permit the determination of optimal carpool teams and routes. Martinez, et al., (2015) present an agent-based simulation model for shared taxis in which a set of rules for space and time matching are identified. It considers that the client is only willing to accept a maximum deviation from his or her direct route. The authors establishes an objective function for selecting the best candidate taxi. Knapen, et al., (2014) 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 in Knapen et al., (2012) study the problem of finding an optimal tree structured route for carpooling in case some participants leave their car at a carpool parking. They propose an algorithm to find the optimal solution for the join tree (i.e. the case where passengers are picked up at carpool parking places). Each individual declares the maximal time and/or distance that is acceptable to move from origin to destination.

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.

5.5 Carpooling Model

This research specifies an agent-based model to simulate carpooling for commuting in the long-term by assigning a detailed route to each trip and by determining likely carpool matches subject to different constraints on drivers and passengers. Mutual coordination for carpooling has been found a challenging task both for the driver and for the passengers. The main focus is on mechanisms to simulate human behavior when decisions for cooperation are to be taken. The interaction mechanism is designed so that the participants who are working at a particular company or organization and living in spatially dispersed home-locations can interact with each other in order to carpool. The accuracy is obtained by the use of individuals' street addresses and by computing the route length directly from the network.

5.5.1 Problem Description

The problem consists of (see Figure 5.1): a set A of identified agents $a_i \in A$ and for each agent a_i the home $h_{a_i} \in H$ and work $w_i \in W$ locations. Furthermore A'_{a_i} is the set of agents who are mutually compatible for negotiation in carpooling. The set $A'_{a_i} \subseteq A$ is called a *carpooling social group (CPGS)*. Such CPSG is a group of agents who belong to the same company (same work-location) w_j. They can interact and negotiate within the *carpooling social group*. The negotiation can be done on the HW and WH trips start times, the driver and vehicle selection and on the *pick-up* and *drop-off* order of the *carpoolers*. An agent a_i having solo-trip duration d_{solo,a_i} specifies a maximum excess time or detour $d_{maxDetour,a_i}$ which is an upper limit for the extension to d_{solo,a_i} acceptable by a_i to travel from h_{a_i} to w_i. Passengers within the detour time can picked-up by the driver.

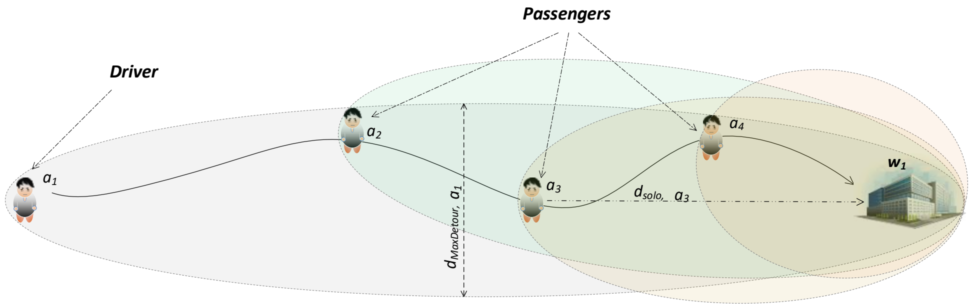


Figure 5.1. Problem description: for the successful carpool group , the constraints of driver selection, trips start times and the maximum excess duration must be fulfilled.

5.5.2 Agent-based Modeling

An agent-based modeling approach is used for assessing the effects of individual's decision-making and for simulating the interactions of autonomous agents. The ABM approach, which is essentially distributed and individual-centric is appropriate for systems that exhibit complex behavior. The "Capacity, Role, Interaction and Organization" (CRIO) meta-model (Cossentino, et al., 2010b) provides organizational concepts for modeling complex systems in terms of role and their relationships. This meta-model provides 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), (Ferber, Gutknecht, & Michel, 2004) 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.

For the implementation, the Janus (Gaud et al., 2009), multi-agent based platform is used which provides an efficient implementation of agent-based and organizational-based concepts. Janus is built upon the CRIO organizational meta-model in which the concepts of role and organization are first-class entities. 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., 2010a; Cossentino, et al., 2010b).

5.5.3 Agents in the Carpooling Model

In this study, an agent (either non-carpooling or carpooling) is defined as someone who lives in the study area and executes his/her daily schedule in order to satisfy requirements. A daily schedule is a timed sequence of trips and activities of different categories (work activities with fixed or flexible timings) with a specified start time and duration of each activity and trip. The modeling structure claims that individuals spend the day taking part in activities and traveling between activity locations. Each agent looks for other individuals to cooperate while executing its periodic trips by exploring the *carpooling social network*.

5.5.4 Carpooling Social Network

The *carpooling social network* is made up of nodes representing individuals and social links defined by one or more specific types of interdependency. It slightly differs from general social networks in two ways: Firstly, the *carpooling social network* considers not only socio-demographic attributes but also spatiotemporal attributes i.e. activity or trip start times and home and work locations and secondly, *carpooling social network* is specifically aimed at carpool partner selection and interaction between participants. In this paper, the strength of relationship is measured by calculating the number of similar attributes for the agents. Two agents are considered to be mutually compatible for carpooling if they share the work location and if their feasible arrival and required departure time intervals intersect in each passenger pick-up and drop-off location.

5.5.5 Actual Travel Times

The route choice focuses on the selection of routes between origins and destinations in transportation networks. In order to co-travel, the actual travel times play an important role to support the negotiation process. To calculate the travel times accurately, the present pattern of the traffic delay must be known. The actual travel times and travel distances of the road network are obtained by computing the route length directly from the OSM database using the *GraphHopper*. The OSM is a digital map database of the world and is freely available for visualization, query, download, and modification under open licenses. *GraphHopper* is a fast and memory efficient open source routing library and server that can be used to calculate the travel times and travel distances of the road network (of the study area). In this simulation model, the GraphHopper API library is used directly to obtain the travel times from the GraphHopper server which is configured to run on the computer system that runs the agent-based model.

5.5.6 Setup of the Framework

This section presents the setup of the agent-based framework for carpooling. Several preliminary steps are taken in a *pre-processing* stage before the start of the actual carpooling model. The actual carpooling model for an individual is iterative and consists of three activities (shown in Figure 3): (1) exploration and interaction, (2) negotiation and (3) trip execution.

5.5.6.1 Pre-processing

In the pre-processing firstly, participants decide to become a candidate for long-term carpooling (i.e. decide to look for an alternative to solo driving). Details about the respective trips and daily schedules are determined. Secondly, formation of the *carpooling social groups* ($CPSG$) is required to limit the interaction requirements among the individuals in the *carpooling social network*.

Mutual *compatibility* for carpooling depends on spatio-temporal constraints of individuals. The compatibility relation defines a large *carpooling social network*. The *carpooling social network* is subdivided into connected components. Each component corresponds to a *carpooling social group(*$CPSG$*)*. The $CPSG$ concept is used to limit agent interactions at runtime.

$CPSGs$ are formed by considering similar characteristics (i.e. similar work-location) of the individuals. Sets of individuals who are working at a particular work-location (same company or institution) and living in spatially dispersed home-locations (homes) of the *carpooling social network* are considered (see Figure 5.2). Within these $CPSGs$, agents can interact and negotiate with each other on trip (*HW* and *WH*) start times, pick-up and drop-off orders and on vehicle and driver selection. Conditions for agents to be compatible are detailed below.

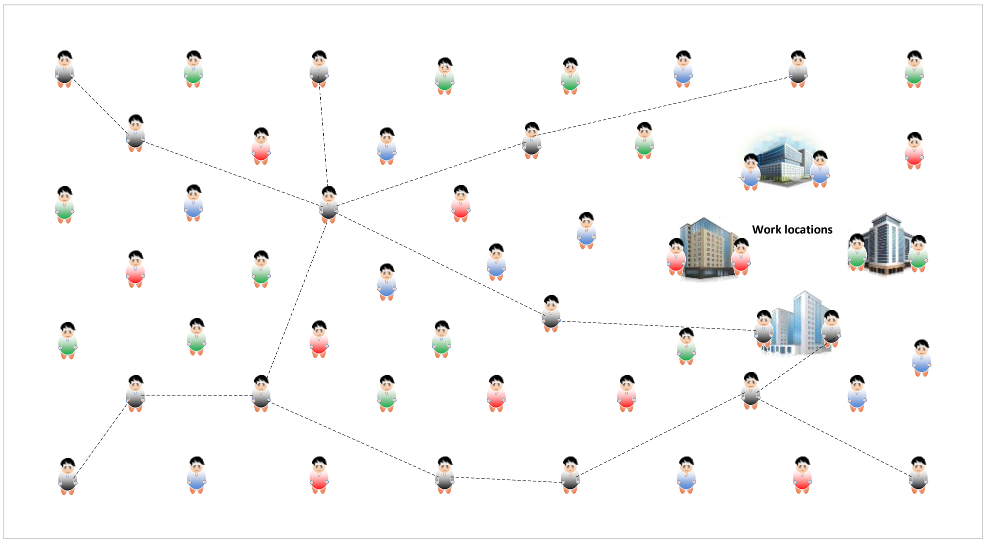


Figure 5.2. CPSG formation according to the same work-location (same company or institution). Identically colored agents belong to the same CPSG.

5.5.6.2 The Carpooling Model

The long-term carpooling model is illustrated in Figure 5.3. It has two situations: solo driving and carpooling. The non-carpooling agent will remain in the solo driving situation while the carpooling agent will be in the carpooling situation throughout the carpooling period. Following activities are performed by the agents (either non-carpooling or carpooling): (i) network exploration and interaction, (ii) negotiation and (iii) carpooling. In this model the day-switching activity is used solely for the day switching purpose. In what follows, each of these activities is described in more detail.

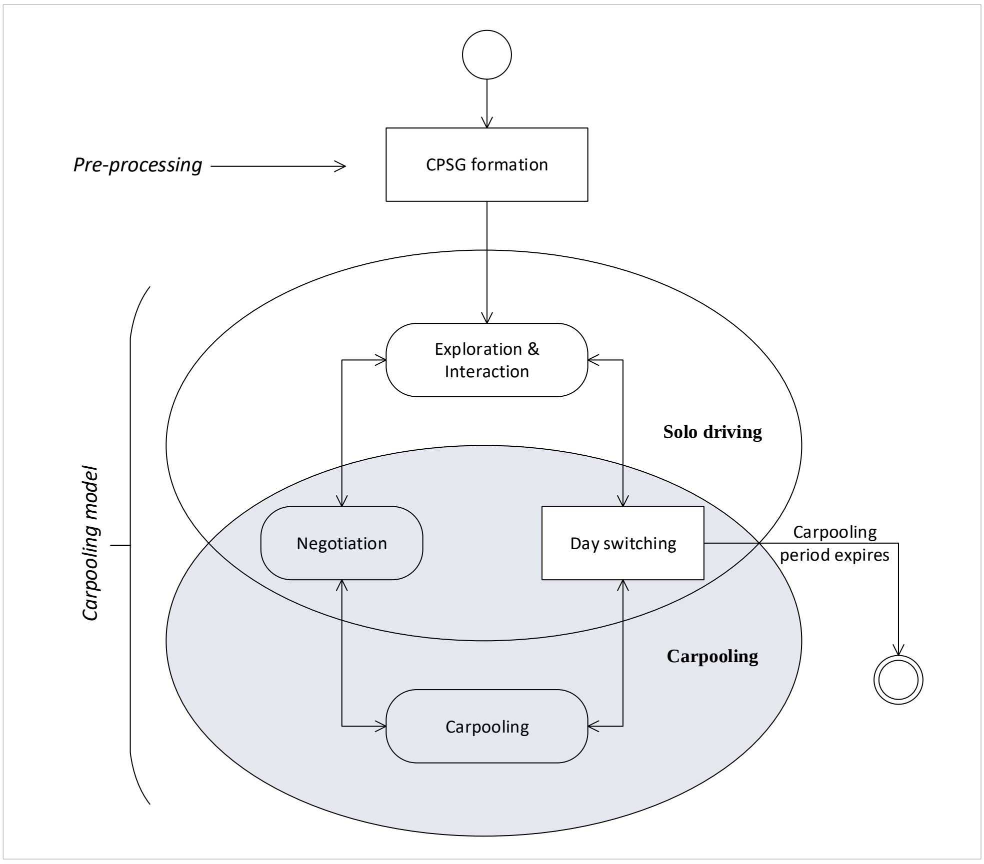


Figure 5.3: Carpooling framework and model.

5.5.6.2.1 Network Exploration and Interaction

In this step, the non-carpooling agent looks for other individuals to cooperate while executing their periodic trips by exploring the CPSG (*carpooling social group*) of the *carpooling social network*. The non-carpooling agent continues driving solo throughout the period (in case (s)he is unable to find a carpool partner).

Each participant (*sender*) may search for a partner (*receiver*) by sending a carpool invitation to individuals in the same *carpooling social group*. An individual can explore the carpooling social network multiple times in a day. The receiver accepts the sender as a carpooling partner when negotiation between *all* members of the newly proposed carpool succeeds: in case of carpool extension, every participant in the existing carpool is involved in the negotiation.

5.5.6.2.2 Negotiation-Carpool Formation

The matching is applied in the negotiation phase where final decisions to carpool are revealed by finding the optimal sequence that meets the conditions stated by the candidate participants. Both commuting trips (HW and WH) for a given day shall use the same carpool. This is assumed to be realistic at behavioral level although it may induce stringent timing constraints. This requirement avoids multi-party negotiations which require a large mental effort. The participants negotiate on trip (HW and WH) departure times, pick-up and drop-off orders, and also on the vehicle and driver selection.

Every individual owning a vehicle and driving-license can act as the driver. Each individual specifies a maximum value for the detour distance or duration relative to the solo-trip. Maximum detour distance or duration leads to the path similarity concept. This *path similarity* relation consisting of ordered pairs of individuals. It is easily seen that the relation in general is not symmetric because the distance driven depends on the driver selection; the driver needs to pick-up passengers.

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. Valid pick-up orders of participants are found by means of the path similarity relation.

Details about carpool formation are described in the following subsections.

i. Time Preference Function

In this paper, every moment (the intervals between earliest and latest moments) in the time windows specified by the candidates is assumed to be equivalent: i.e. the *time preference function* is assumed to be constant and identical for each participant over the time. A time window is defined by: (1) a time interval I specified by the earliest and latest moments (expressed as time-of-day) respectively and (2) a preference function $P()$ that in each point in the time interval is non-negative and finite and has a non-zero integral over I. For each trip (either HW or WH) of an agent, two time windows (departure and arrival) are considered.

ii. Time Intervals Induced by the Constraining Activities

The time intervals are determined by considering all possible constraining activities. In the simplest case, the individual a_i is assumed to accept a symmetric maximum deviation $\pm\Delta T$ with respect to the preferred trip start. In general, this is not necessarily true since preceding or succeeding activities can induce timing constraints. The constraining activities may be scheduled before the morning trip and/or immediately after the work activity.

iii. Individuals' Matching

Since the carpool capacity is limited (usually, 4 or 5 persons), it is feasible to check every permutation of the candidate participants that is compatible with the path similarity relation mentioned before. For the valid cases, the order of participants in the permutation defines the pick-up order in the HW trip and the (reverse of the) drop-off order in the WH trip. The negotiation among individuals succeeds if and only if all the following constraints are satisfied:

a. Driver and Vehicle Selection

Each agent who owns a car and a driving license, may become the driver when carpooling. The driver in the carpool needs to pick up every carpooler from their home-locations. Hence the first participant in the permutation (agents' pick-up and drop-off order list) shall be the driver. The permutations, where the first participant cannot act as the driver are infeasible and they can be dropped immediately.

b. Departure Time Choices

Let A be the set of all individuals or agents. For an agent a_i, the earliest and latest departure times for the trip are $T^b_{a_i}$, $T^e_{a_i}$ and the preferred trip start time of a_i is T_{a_i}. The arrival time window of carpooling participants at the destination or work location h_N is $T_{carpool,\,h_N}$. It is the intersection of the arrival time windows for the respective participants. The earliest $T^b_{carpool,h_N}$ and latest $T^e_{carpool,h_N}$ time of the intersection of the arrival time windows can be calculated as specified in equation (1); the indices used for the *max()* and *min()* functions range over the set of candidate participants. The available arrival time intervals of trips (HW or WH) for the carpool are given by the equation (1) where the index j identifies the carpool participant candidate.

$$\left.\begin{aligned} T^b_{carpool,h_N} &= \max_{j=1\ldots N}(T^b_{a_j}) \\ T^e_{carpool,h_N} &= \min_{j=1\ldots N}(T^e_{a_j}) \end{aligned}\right. \quad = \bigcap_{j=1}^{N} T_{a_j h_N} \qquad (1)$$

For the trip departure time in *HW* trip, the time window $T_{carpool,h}$ for home-location h_i is calculated in reverse individual's location visit order. The $T_{carpool,h}$ for h_i

follows from the one for h_{i+1} by subtracting the expected travel time d_{h_i+1} and calculating the intersection with the time window specified by the participants to be picked up at h (Eq. (2)). The circled minus applied to a time window and a scalar, denotes a time window shift.

$$T_{carpool,h_i} = (T_{carpool,h_i+1} \ominus d_{h_i+1}) \cap T_{a_i,h_i} \tag{2}$$

The backward shifted arrival time window specifies the required departure time window at the location. This is to be intersected with the departure time window of the person to be picked up at that location. The resulting time window is shifted further to the predecessor location.

The negotiation outcome needs to be within the intersection of the time intervals of the individuals. When for some h_i, if the time window $T_{carpool,h_i}$ of the negotiators is empty (time windows do not intersect) then the case is infeasible and the negotiation on the trip start time fails.

$$\forall_i : feasible_i \iff (T_{carpool,h_i} \neq \emptyset) \tag{3}$$

A *permutation* can be dropped immediately when induces infeasible time windows.

c. Detour Duration Relative to Solo-driving

The user can specify upper boundary values for both absolute and relative detour values. Those are determined for both the *HW* and the *WH* trips. Both absolute and relative values are checked and the most strict condition applies.

The maximum value of the detour (duration or distance) relative to the solo-driving case is given by the function specified by equations (4) and (5). It is used to introduce the path and time similarity concepts. An individual having a solo trip duration $d_{a_i,solo}$ has an upper limit $d_{a_i,maxDetour}$ for the detour delay in the trip from home to work. The maximum relative excess is defined as follows:

1. It is assumed that for short trips a larger relative detour will be considered to be acceptable than for long trips
2. Trips with size (distance, duration) less than minimum d_{min} accept a relative excess of 1 (i.e. the trip size can be doubled). Trips with size larger or equal to maximum d_{max} accept a relative excess r_{min}. In the interval $[d_{min}; d_{max}]$ an exponential decay is used. The maximal relative detour then is given by:

$$r(d) = \begin{cases} 1 & if\ d \leq d_{min} \\ e^{(d_{a_i,solo} - d_{min}).\alpha} & if\ d_{min} < d < d_{max} \\ r_{\min} & if\ d \geq d_{max} \end{cases} \tag{4}$$

with

$$\alpha = \frac{\ln(r_{min})}{d_{max} - d_{min}} \tag{5}$$

For each individual a_i, the carpool duration must be less than or equal to the individual's maximum detour value

$$d_{a_i,carpool} \leq d_{a_i,maxDetour} = d_{a_i,solo} \cdot \left(1 + r\left(d_{a_i,solo}\right)\right) \tag{6}$$

iv. Evaluation of the Candidate Solutions

Due to the permutation process, there can be more than one candidate solution for the same carpooling group of participants. The difference between these solutions can be the driver selection and/or the pick-up and drop-off orders of the participants. To get the optimal solution from the candidate solutions, following scoring functions are used: (1) degree of flexibility and (2) the time loss. The range of the scoring function values is in [0, 1] and a higher value is better.

a. Degree of Flexibility

The value for the degree of flexibility (DoF) for each candidate j is determined at their home location by taking the time window length ΔT_j for their valid trip start time: this is a measure for the DoF for the departure time at each location and hence for the ability to meet the schedule (because travel times may be uncertain). The candidates delivering the highest score is kept. The DoF score for carpool is given by:

$$DoF = \prod_{j=0}^{n} \left(1 - e^{-\alpha \,.\, \Delta T_j}\right) \tag{7}$$

where j ranges over the set of home locations. The α in Eq. (7) is determined by specifying the DoF score value for a given minimum interval length. For $\Delta T = 5[min]$ we required a value 0.9. The value for α is be determined by Eq. (8).

$$\alpha = \frac{-\ln(0.1)}{\Delta T} \tag{8}$$

b. Time Loss

The time loss due to the detour duration relative to solo-driving duration is scored as follows. Let L_j^C denote the time loss for participant j by carpooling and let L_j^A denote the maximum acceptable detour duration specified by the participant j. The time loss score for carpool is given by:

$$S_{timeLoss} = \prod_{j=0}^{n} \left(1 - \frac{L_j^C}{L_j^A}\right) \tag{9}$$

c. Overall Score

The overall scoring probabilities can be estimated by taking the product of each score as shown in Eq. (10).

$$S_{overall} = DoF()\ .\ timeLoss() \qquad (10)$$

The permutation of candidates exhibiting the maximum overall score is kept and this solution is chosen as the optimal solution.

As soon as it becomes clear that candidates will carpool, the trip start time needs to be determined at each agent's location. 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 feasible trips start time for an agent is the middle value of the feasible time window at specific location.

5.5.6.2.3 Carpooling

The carpooling activity corresponds to the execution of the trips (HW and WH) over multiple 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 locations are computed from the OSM dataset using the GraphHopper API. The associated actual travel times between home and work locations for each individual are used. The individuals' daily schedule of a working day remains the same for all working days.

During carpooling, carpoolers (either driver or 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 of candidates. Handling incoming invitations during the carpool lifetime, requires additional negotiation between the carpoolers and the new candidates to join the carpool.

5.6 Simulation Experiments and Discussion

5.6.1 Dataset

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.*, 2010b). 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 FEATHERS model for Flanders region is characterized by: about six million inhabitants and the area is subdivided into *2386* TAZs. On average, a TAZ covers approximately $5[km^2]$.

The actual travel times and travel distances on the road network are obtained and used by computing the route length directly from the OSM dataset using the GraphHopper API and server. Those actual travel times estimate the durations of the trips. The street-addresses (latitude and longitude based) of the individuals are used to calculate the travel times. The success of negotiation may result in reconsideration of departure and arrival times for planned trips.

The individuals' commuting trips (*HW* and *WH*) in their daily schedules are detailed and discussed in relation to long term carpooling. The set of other (constraining) activities including pick-drop, shopping etc. is also considered because they can induce timing constraints to trips commuting trips. The 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. People living in the range of *1Km* of their working location are not considered to be carpooling candidates.

5.6.2 Experiments and Results

A set of experiments was designed to evaluate the overall behavior of the model. This evaluation is executed: in order to estimate the effect on the global model results of the chosen values for parameters for which no evidence is available from surveys yet and in order to evaluate computational resources requirements.

5.6.2.1 Data

Experiments were conducted at the scale of the Flanders region (Belgium). Particular TAZs from the Brussels region where people daily come to perform their work activities are considered as work area. Individuals whose transportation mode is *car* and having at least one *work activity* (daily) at one of the selected work TAZ are considered as candidate carpoolers. Note that individuals having a common destination or work TAZ can carpool with each other only. Each TAZ Is considered as a company. For the experiments, the *carpooling social network* characterized by number of:

Individuals whose travel mode is *car* only: (all trips in the schedule are car trips)	*18,218*
Destination locations:	*22*

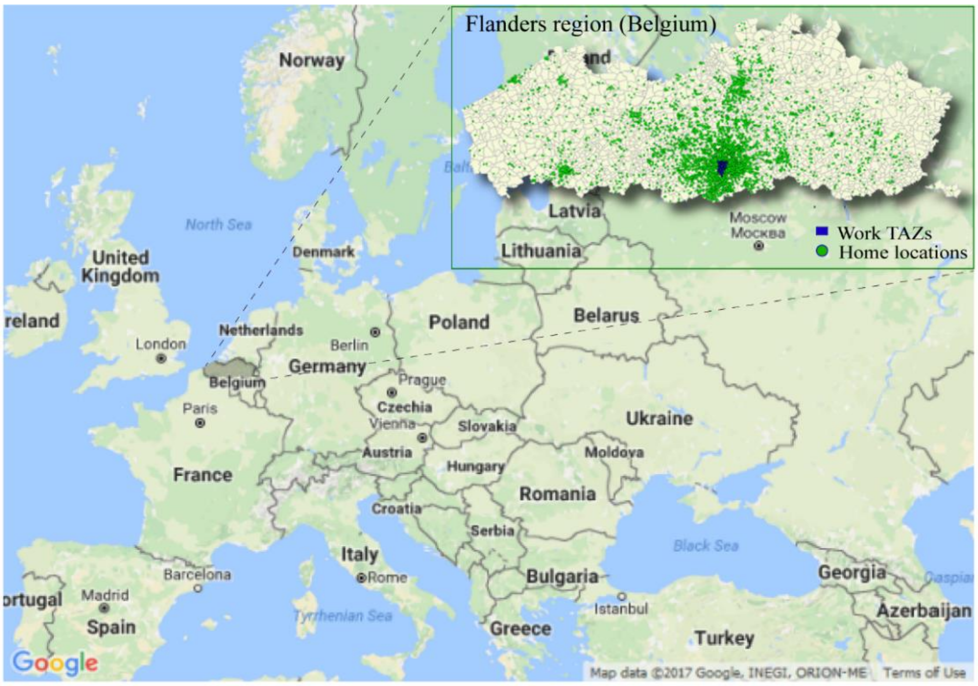


Figure 5.4. Distribution of the agent population over the Flanders region of Belgium.

The distribution of the individuals (with green dots) over the Flanders region is shown by Figure 5.4. The highlighted area (with *blue* color) represents the work TAZs.

The distribution of the trip durations of the individuals for home-to-work trip is shown in Figure 5.5. The x-axis represents duration (in min.) while the y-axis shows the number of individuals.

In order to analyze the computational properties of the proposed model, the presented framework is simulated for three years (*660 working days)* and following constraints apply (see table 5.1):

Table 5.1. Constraints and their values for the experiment.

An exploring agent can contact at most	*10 people / simulated day*
Time window length	ΔT *= 30[min]*
Maximum detour ratio for short trips	*for duration ≤ 5 [min.] is 1*
Maximum detour ratio for long trips	*for duration ≥ 90[min.] is 0.15*
Car capacity (driver included)	*5* people at most can share a car
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.	

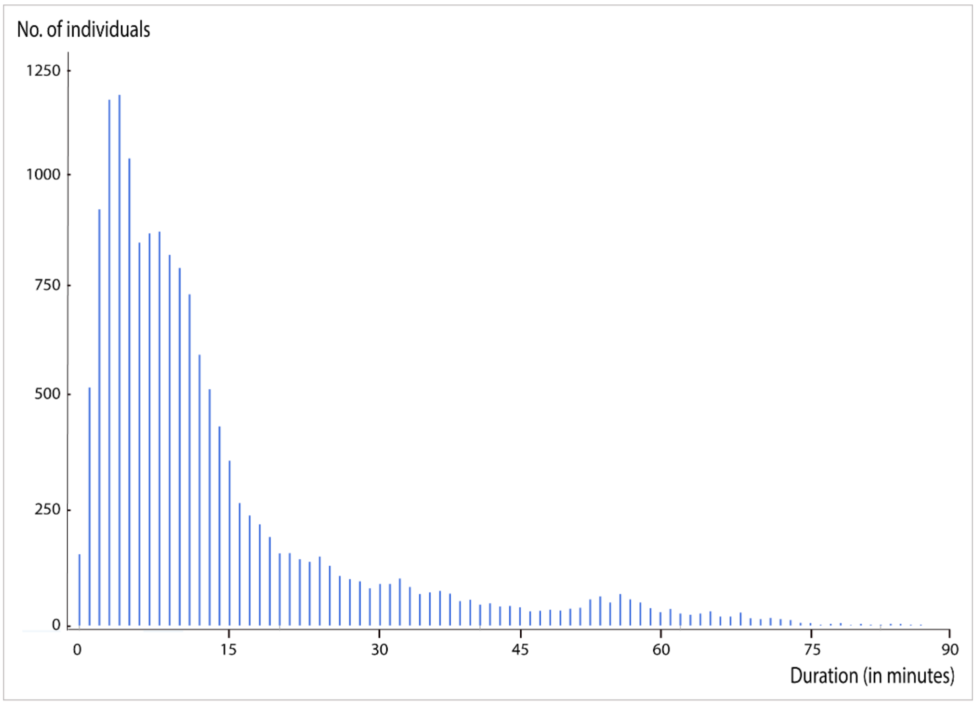


Figure 5.5. Frequency distribution of the travel duration [in mins.] between home locations and work locations of the individuals.

5.6.2.2 Results

In the experiments described here, an individual who starts carpooling continues forever (i.e. never leaves the carpool group).

Figure 5.6 shows the number of active carpoolers throughout the simulation period. There are 22-*CPSGs* within which the candidates can communicate, negotiate and coordinated for carpooling. The x-axis shows each simulated day while the y-axis represents the number of active carpoolers.

The diagram shows how the number of carpoolers evolves over time when simulating a population of *18,218* agents. It gives an idea of the duration of the transient phenomenon in a specific situation. The properties of the transient mainly depend on the exploration intensity (the maximum number of invitations sent by an individual during a single simulated day) and on the car capacity. This is because exploration only occurs among people who are mutually compatible w.r.t. *path and time similarity*. The curve shows that most of the individuals become a carpooler in a short period after the start of the simulation. The growth rate decreases with the passage of time because it becomes more difficult to find suitable partners. It is worth noting that the growth is still quite large after 3 months (100 days) even when using a very high exploration rate of 10 explorations/day.

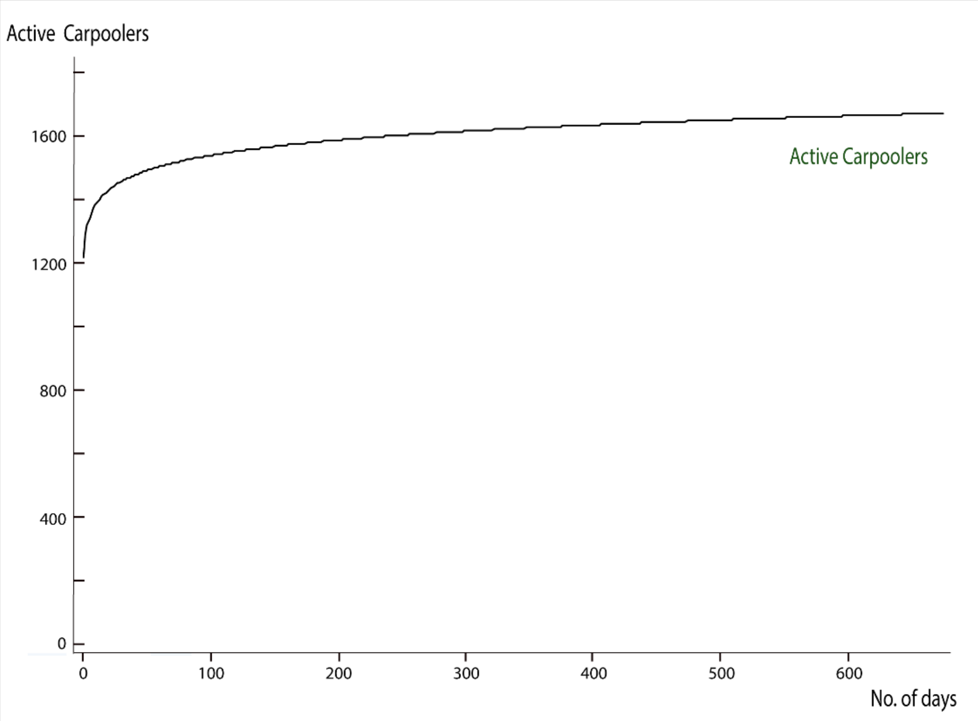


Figure 5.6. The number of carpoolers evolves over time throughout the simulation period.

One of the major goals of our experimentation is to compute and possibly optimize the computation time. The experiment is conducted on an Intel ® Xeon ® CPU E5-2643 v2 @3.50GHz 3.50 GHz (2 processors), with 128GB RAM and Windows server 2012 R2 Standard (64 bits) machine. Figure 5.7 shows the execution time of the carpooling simulation for different numbers of individuals and for different simulation period lengths (100 up to 500 days) (see Table 5.2). The time required for pre-processing is shown separately. Each curve shows the execution time as a function of the population size for a specific simulation period length (number of days). The x-axis represents the number of individuals while the y-axis shows the execution time in minutes. The framework was run multiple times by taking different agent population sizes (1000, 2000, 3000, 4000, 5000, 6000). The agents are taken from the data mentioned above (from *18,218* individuals) by taking the first ones from a random set of agents. Each simulation created 22-CPSGs within which the agents can interact to find carpool groups. It can be assumed that the size of each *CPSG* grows by the increase of number of agents because the agents were selected from a random set of agents of the population. The graph shows that: (1) the carpooling simulation took more execution time for the higher number of agents because of their involvement in the interaction and negotiation process, (2) the execution time does not grow more than quadratic with the number of agents. This is expected because the effort required for exploration grows with the second power of the CPSG size (because invitations are sent by individuals to individuals). The size of the CPSG grows less than linear with the population because of the limited size of the companies and institutions the individuals belong to.

The preselection phase took only a small portion of the execution time.

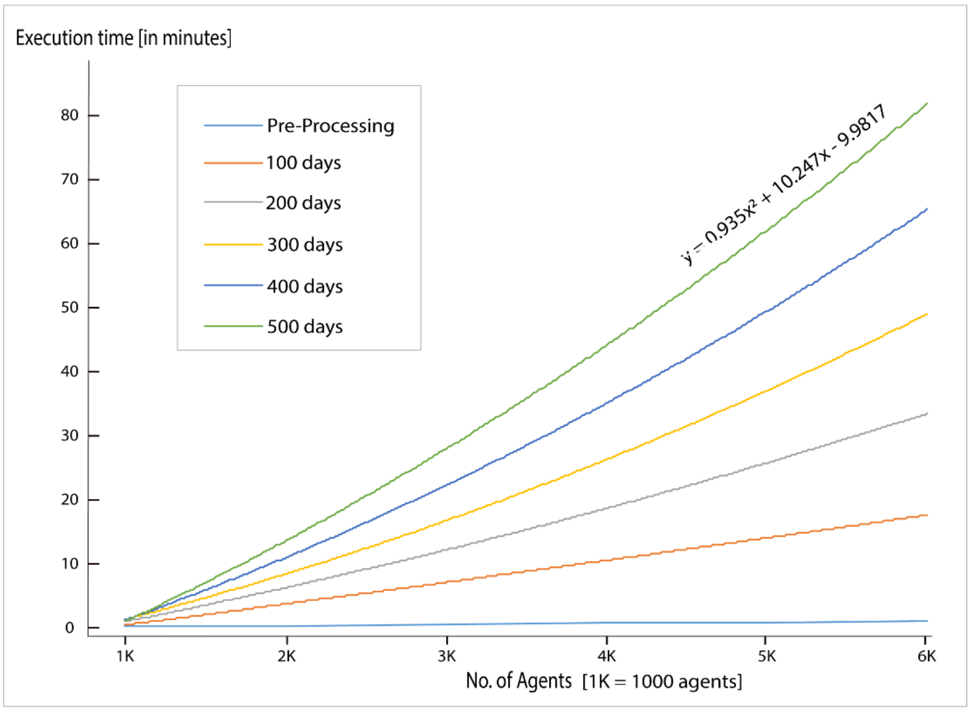


Figure 5.7. Execution time of the simulation of different companies.

Table 5.2. The execution time of multiple companies of carpooling simulation for different numbers of individuals and for different simulation period lengths.

	1000 [agents]	**2000 [agents]**	**3000 [agents]**	**4000 [agents]**	**5000 [agents]**	**6000 [agents]**
Pre-processing	0.34	0.53	0.70	0.92	1.10	1.27
100 days	1.19	4.05	5.02	13.19	15.48	17.68
200 days	2.07	6.43	9.18	23.10	27.25	34.01
300 days	2.73	8.24	13.28	32.08	38.74	50.06
400 days	3.53	9.96	17.26	43.17	52.20	66.22
500 days	4.31	11.60	21.33	54.29	66.55	82.29

The experiment to compute the execution time is also conducted for a separate company. The number of agents is again taken from the data mentioned above. The simulation framework was run multiple times by taking different agent population sizes 1000, 2000, 3000, 4000, 5000 and 6000 respectively. Figure 5.8 shows the execution time of the carpooling simulation for different numbers of agents of the same company and for different simulation period lengths from 100 up to 500 days (see Table 5.3). The time required for pre-processing is shown separately. Each curve shows the execution time as a function of the population size for a specific simulation period length (number of days). The x-axis represents the number of individuals while the y-axis shows the execution time in minutes. The graph shows that: (1) the carpooling simulation took more execution time for the higher number of agents because of their involvement in the interaction and negotiation process, (2) the execution time increases in a polynomial way with the number of agents. This is because the combinatorial operations are limited (1) to finding cliques of a given small size (the maximum car capacity) and (2) to generating permutations of these small sets.

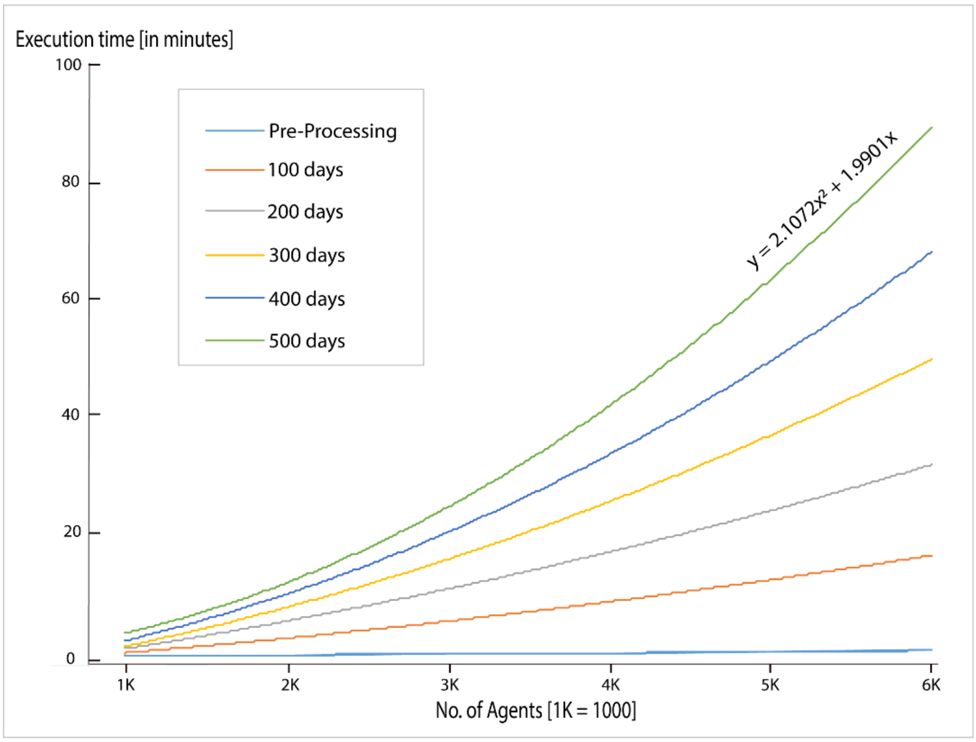


Figure 5.8. Execution time of the simulation of a single company.

Table 5.3. The execution time of a single company of carpooling simulation for different numbers of agents and for different simulation period lengths.

	1000 [agents]	2000 [agents]	3000 [agents]	4000 [agents]	5000 [agents]	6000 [agents]
Pre-processing	0.36	0.47	0.64	0.80	1.00	1.19
100 days	1.13	3.05	5.56	8.93	14.37	16.21
200 days	1.90	5.57	11.19	17.22	25.55	31.31
300 days	2.51	7.77	15.89	24.59	39.87	47.95
400 days	3.05	10.56	20.38	33.07	50.47	66.50
500 days	3.67	12.72	24.27	43.41	61.01	88.31

5.7 Conclusion and Future Work

The design of carpooling model has been mapped to an agent-based simulation. The model covers agents' interaction, negotiation and the actual carpooling on long-term basis. We considered a set of individuals working at a particular company or institution. The goal of the research is to evaluate the computational effort to execute the framework that was set up to simulate the network of the carpooling candidates.

The potential carpooler's behavior and network information has been covered so that the complete carpooling problem can be examined. The accuracy has been obtained by the use of individuals' street addresses and by computing the route length directly from the OSM dataset using GraphHopper. An set of scoring functions is to be evaluated for the simulation of each negotiation trial. Different experiments have been conducted to measure the computation time of the simulation framework. The results showed that the carpooling simulation execution time does not grow more than quadratic with the number of agents. Computing travel durations using GraphHopper adds negligible computational effort and is essential to increase the accuracy of the results.

The simulation model requires a large amount of accurate input data. Indeed, it is necessary to consider a sufficiently large region to evaluate the carpooling process. The future research will mainly focus on the effect of more elaborated schedule adaptation.

5.8 References

ARENTZE, T., PELIZARO, C., & TIMMERMANS, H. J. P. (2005). Implementation of a model of dynamic activity-travel rescheduling decisions: an agent-based microsimulation framework. In *Proceedings of CUPUM 05* (p. paper no. 48). London. http://128.40.111.250/cupum/searchpapers/papers/paper48.pdf

Armendáriz, M., Burguillo, J. C., Peleteiro-Ramallo, A., Arnould, G., & Khadraoui, D. (2011). Carpooling: A Multi-Agent Simulation In Netlogo. (pp. 61–67). Presented at the ECMS.

Bellemans, T., Bothe, S., Cho, S., Giannotti, F., Janssens, D., Knapen, L., … Wets, G. (2012). An Agent-Based Model to Evaluate Carpooling at Large Manufacturing Plants. *ANT 2012 and MobiWIS 2012*, *10*, 1221–1227. https://doi.org/10.1016/j.procs.2012.08.001

Bellemans, T., Kochan, B., Janssens, D., Wets, G., Arentze, T., & Timmermans, H. (2010a). Implementation framework and development trajectory of FEATHERS activity-based simulation platform. *Transportation Research Record: Journal of the Transportation Research Board*, (2175), 111–119.

Bellemans, T., Kochan, B., Janssens, D., Wets, G., Arentze, T., & Timmermans, H. (2010b). Implementation Framework and Development Trajectory of FEATHERS Activity-Based Simulation Platform. *Transportation Research Record: Journal of the Transportation Research Board*, *2175*, 111–119. https://doi.org/10.3141/2175-13

Ben Cheikh, S., & Hammadi, S. (2014). The Alliance between Optimization and Multi-Agent System for the Management of the Dynamic Carpooling. In G. Jezic, M. Kusek, I. Lovrek, R. J. Howlett, & L. C. Jain (Eds.), *Agent and Multi-Agent Systems: Technologies and Applications: Proceedings of the 8th International Conference KES-AMSTA 2014 Chania, Greece, June 2014* (pp. 193–202). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-07650-8_20

Cho, S., Yasar, A.-U.-H., Knapen, L., Bellemans, T., Janssens, D., & Wets, G. (2012). A Conceptual Design of an Agent-based Interaction Model for the Carpooling Application. *ANT 2012 and MobiWIS 2012*, *10*, 801–807. https://doi.org/10.1016/j.procs.2012.06.103

Chun, H. W., & Wong, R. Y. M. (2003). N∗—an agent-based negotiation algorithm for dynamic scheduling and rescheduling. *Advanced Engineering Informatics*, *17*(1), 1–22. https://doi.org/10.1016/S1474-0346(03)00019-3

Cossentino, M., Galland, S., Gaud, N., Hilaire, V., & Koukam, A. (2010a). An Organisational Approach to Engineer Emergence Within Holarchies. *Int. J. Agent-Oriented Softw. Eng.*, *4*(3), 304–329. https://doi.org/10.1504/IJAOSE.2010.036986

Cossentino, M., Gaud, N., Hilaire, V., Galland, S., & Koukam, A. (2010b). ASPECS: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent Systems*, *20*(2), 260–304. https://doi.org/10.1007/s10458-009-9099-4

Ferber, J., Gutknecht, O., & Michel, F. (2004). From Agents to Organizations: An Organizational View of Multi-agent Systems. In P. Giorgini, J. P. Müller, & J. Odell (Eds.), *Agent-Oriented Software Engineering IV: 4th InternationalWorkshop, AOSE 2003, Melbourne, Australia, July 15, 2003. Revised Papers* (pp. 214–230). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-24620-6_15

Galland, S., Knapen, L., Yasar, A.-U.-H., Gaud, N., Janssens, D., Lamotte, O., … Wets, G. (2014). Multi-agent simulation of individual mobility behavior in carpooling. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, *45*, 83–98. https://doi.org/10.1016/j.trc.2013.12.012

Gan, L. P., & Recker, W. (2008). A mathematical programming formulation of the household activity rescheduling problem. *Transportation Research Part B: Methodological*, *42*(6), 571–606. https://doi.org/10.1016/j.trb.2007.11.004

Gaud, N., Galland, S., Hilaire, V., & Koukam, A. (2009). An Organisational Platform for Holonic and Multiagent Systems. In K. V. Hindriks, A. Pokahr, & S. Sardina (Eds.), *Programming Multi-Agent Systems: 6th International Workshop, ProMAS 2008, Estoril, Portugal, May 13, 2008. Revised Invited and Selected Papers* (pp. 104–119). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-03278-3_7

Guo, Y., Goncalves, G., & Hsu, T. (2013). RETRACTED ARTICLE: A Multi-agent Based Self-adaptive Genetic Algorithm for the Long-term Car Pooling Problem. *Journal of Mathematical Modelling and Algorithms in Operations Research*, *12*(1), 45–66. https://doi.org/10.1007/s10852-012-9175-7

Gupta, S., & Vovsha, P. (2013). A model for work activity schedules with synchronization for multiple-worker households. *Transportation*, *40*(4), 827–845. https://doi.org/10.1007/s11116-013-9469-2

Hendrickson, C., & Plank, E. (1984). The flexibility of departure times for work trips. *Transportation Research Part A: General*, *18*(1), 25–36. https://doi.org/10.1016/0191-2607(84)90091-8

Horvitz, E., Apacible, J., Sarin, R., & Liao, L. (2005). Prediction, Expectation, and

Surprise: Methods, Designs, and Study of a Deployed Traffic Forecasting Service. In *Proceedings of the Twenty-First Conference on Uncertainty in Artificial Intelligence* (pp. 275–283). Arlington, Virginia, United States: AUAI Press.
Retrieved from http://dl.acm.org/citation.cfm?id=3020336.3020371

Hussain, I., Knapen, L., Galland, S., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016). Organizational-based model and agent-based simulation for long-term carpooling. *Future Generation Computer Systems*, *64*, 125–139.
https://doi.org/10.1016/j.future.2016.02.019

Hussain, I., Knapen, L., Yasar, A.-U.-H., Bellemans, T., Janssens, D., & Wets, G. (2016). Negotiation and Coordination in Carpooling. *Transportation Research Record: Journal of the Transportation Research Board*, *2542*, 92–101.
https://doi.org/10.3141/2542-11

Jennings, N. R. (2000). On agent-based software engineering. *Artificial Intelligence*, *117*(2), 277–296. https://doi.org/10.1016/S0004-3702(99)00107-1

Joh, C.-H., Timmermans, H. J. P., & Arentze, T. A. (2006). MEASURING AND PREDICTING ADAPTATION BEHAVIOR IN MULTIDIMENSIONAL ACTIVITY-TRAVEL PATTERNS. *Transportmetrica*, *2*(2), 153–173.
https://doi.org/10.1080/18128600608685659

Karich, P.: GraphHopper (2014).
https://graphhopper.com/

Knapen, L., Bellemans, T., Usman, M., Janssens, D., & Wets, G. (2014). Within day rescheduling microsimulation combined with macrosimulated traffic. *Advances in Computing and Communications and Their Impact on Transportation Science and Technologies*, *45*, 99–118. https://doi.org/10.1016/j.trc.2014.04.012

Knapen, L., Keren, D., Yasar, A.-U.-H., Cho, S., Bellemans, T., Janssens, D., & Wets, G. (2012). Analysis of the Co-routing Problem in Agent-based Carpooling Simulation. *ANT 2012 and MobiWIS 2012*, *10*, 821–826. https://doi.org/10.1016/j.procs.2012.06.106

Knapen, L., Yasar, A., Cho, S., Keren, D., Dbai, A. A., Bellemans, T., … Bhaduri, K. (2014). Exploiting graph-theoretic tools for matching in carpooling applications. *Journal of Ambient Intelligence and Humanized Computing*, *5*(3), 393–407.
https://doi.org/10.1007/s12652-013-0197-4

Martinez, L. M., Correia, G. H. A., & Viegas, J. M. (2015). An agent-based simulation model to assess the impacts of introducing a shared-taxi system: an application to Lisbon (Portugal). *Journal of Advanced Transportation*, *49*(3), 475–495. https://doi.org/10.1002/atr.1283

Nijland, E. W. L., Arentze, T. A., Borgers, A. W. J., & Timmermans, H. J. P. (2009). Individuals' Activity–Travel Rescheduling Behaviour: Experiment and Model-Based Analysis. *Environment and Planning A*, *41*(6), 1511–1522. https://doi.org/10.1068/a4134

Ronald, N., Arentze, T., & Timmermans, H. (2012). Modeling social interactions between individuals for joint activity scheduling. *Emerging and Innovative Directions in Choice Modeling*, *46*(2), 276–290. https://doi.org/10.1016/j.trb.2011.10.003

Urquhart, N. (2015). Optimising the Scheduling and Planning of Urban Milk Deliveries. In A. M. Mora & G. Squillero (Eds.), *Applications of Evolutionary Computation: 18th European Conference, EvoApplications 2015, Copenhagen, Denmark, April 8-10, 2015, Proceedings* (pp. 604–615). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-16549-3_49

Xia, J., Curtin, K. M., Li, W., & Zhao, Y. (2015). A New Model for a Carpool Matching Service. *PLOS ONE*, *10*(6), e0129257. https://doi.org/10.1371/journal.pone.0129257

Part-I

Conclusions and Future Work

Motivated by the limitations of coordination and negotiation mechanisms, an agent-based simulation for long-term carpooling has been developed and presented to simulate human behavior when decisions for cooperation are to be taken. The research aimed at the setup of the framework and of a network of the carpooling candidates. One of the major contributions of this research is to model and simulate the agents' behavior in the carpooling simulation to investigate the effect of *cooperation* among individuals with regard to trip execution. Another major contribution is the development of a mechanism to simulate the outcome of *multiple trips based negotiation.* It was used to find and evaluate feasible carpool sequences for the participants and to select the optimal one. The carpooling social network of candidates was established starting from results predicted by FEATHERS.

This section presents the summary of the Part-I of dissertation and also discuss the major contributions as well as the recommendations for the future research.

Summary

As described in the introduction (chapter 1), the study of human behavior has been considered important for the outcome of cooperation in carpooling. Mutual coordination for carpooling has been found a challenging task both for the driver and for all the passengers. The negotiation is essential to cooperation both on activity and on trip execution. The need for agent-based simulation raised because on one hand individuals have their own goals and plans, and on the other hand they need to communicate, negotiate, coordinate and adapt their daily schedule to enable cooperation to achieve their goals.

The presented agent-based simulation model has analyzed various effects of individuals' interaction and behavior adaptation of a set of candidate carpoolers. The concept of communication, negotiation, and coordination has been investigated in a multiple-trip context and for long-term carpooling. The implementation also applies constraining activities by considering the personal daily schedule of each individual. The direct interaction between agents was restricted to communication within carpooling social groups (CPSGs) of the carpooling social network (CPSN). A multiple-trips negotiation outcome model based on a preference function for the trip departure times, route optimization, driver and vehicle selection and pick-up and drop-off orders of the carpoolers has been presented. The driver and vehicle selection, pick-up and drop-off order, and the preferred trip departure time intervals of the optimal carpool group are evaluated by using scoring functions.

The agent-based simulation model for carpooling has been implemented by some increments: each increment was discussed in a different chapter. The first two increments presented in chapter 2 and chapter 3 respectively, are just developed chronologically and have limited features as compared to the increments presented in chapter 4 and chapter 5. Chapter 2 presented the base model that has been developed to measure the carpool potential on similar trips and without taking into account the pick-up and drop-off orders of the passengers. The individuals board and alight at same home and work TAZs. The second increment (chapter 3) has been presented and described using the CRIO organizational meta-model. This model is used to measure the evolution of carpooling potential over time by taking into account the pick-up and drop-off order of the passengers. In this increment the carpoolers board from their home TAZs (spatially dispersed) but alight at the same work TAZ.

In chapter 4, a negotiation model has been presented that highly depends on the factors that influence the departure time decision, on the individuals' profile, route optimization and on the effect of constraining activities. The selection of the most preferred trip departure time partly derived from existing departure time studies, (Hendrickson & Plank, 1984; Hussain et *al.*, 2015) has also presented. The driver and vehicle selection, pick-up and drop-off order, and the preferred trip start time intervals of the optimal carpool group are evaluated by using scoring functions i.e. time of day, degree of flexibility and the time loss. The model presented in the Chapter 5 improves the accuracy by using street addresses of the individuals and by computing the route lengths directly from a detailed road network using the GraphHopper API. It enables communication within CPSGs that coincide with the sets of agents working at a particular company or institution. One of the purposes of the reported research is to investigate the computational performance of the model that contains features described in the chapter.

On the basis of features covered in the agent-based simulation, the model presented in chapter 4 is recommended when (i) the aggregate (TAZ based) behavior of the carpooling social network and (ii) the personal preferences for the trips departure time are taken into account. The model presented in chapter 5 is recommended for employees of a specific company or institution when the disaggregate behavior (carpoolers behavior and network information) of the carpooling social network is taken into account.

Experiments were conducted on the data produced by the FEATHERS, operational activity-based model for Flanders, Belgium. Sensitivity analysis of the simulation model was conducted throughout the PhD research. The results showed that when the probabilities of the preferences of individuals with a lower threshold value were compared and when the time window was larger, the chances for a successful negotiation were greater. It means carpooling requires time flexibility. The results produced by the simulation are also compared with the OVG data. The computation time of the simulation was calculated and the results showed that the carpooling simulation execution time does not grow more than quadratic with number of agents. Computing travel durations using GraphHopper adds negligible computational effort and is essential to increase the accuracy of the results.

Model and Simulate the Agents' Behavior

Human behavior is not always rational, decisions can be based on large number of indicators. Modeling and simulation of agents' behavior in the carpooling model to investigate the effect of cooperation among individuals is required but is not simple. Individuals may act based on their knowledge. As described in the introduction, the agent-based approach has been used for modeling the human behavior for accessing the effects of individual's decision-making and for simulating the interactions of autonomous agents. It allows us to focus on individuals or groups of individuals and give them diverse knowledge and abilities (Crooks and Heppenstall, 2012). This approach is appropriate because the carpooling individuals are dynamically changing their role in the carpooling social network. Adopting an organizational approach enables the agents to dynamically change their behaviors without changing their internal architecture. It provides the ability to determine where the relationships between agents exist and how these relationships influence the results (Cossentino et al., 2010). The Janus, multi-agent based platform has used for simulating the interactions of autonomous individuals: it provides an efficient implementation of agent-based and organizational-based concepts.

Within a simulation, agents are autonomous individuals with heterogeneous properties and they can use active independent influence. The individuals' behavior can be influenced by CPSN. By using organizational concepts of the agent-based approach, the CPSN is segmented into CPSGs because it is difficult and unrealistic to find an ideal carpool partner from a large network space. We assume that the individuals who have close associations to each other have a strong relationship for carpooling. In the carpooling simulation, the CPSGs are segmented on the basis of work destinations. Within the CPSG, individuals are able to process and exchange information with other agents in order to make carpooling decisions. In this carpooling model, the individuals interact with each other by sending and receiving messages. By using Janus framework the CPSGs formation and the interaction mechanisms modeled sufficient well.

Each agent initially has a basic set of communication characteristics, such as common interests and requirements. To interact, the interests and requirements for the respective agents need to match sufficiently well. Each agent looks (by exploring the CPSN) for other individuals to cooperate with while executing its periodic trips. Interests and requirements are conveyed by means of a *Carpool Invitation*. But the problem is how and to whom an agent will emit the carpool invitation message. In the presented carpooling simulation an agent selects someone to invite for carpooling randomly. But this mechanism still to be improved. Similarly, when full population of the CPSN is simulated then the problem arises to determine how many people have intention or interest to carpool. In the presented simulation a parameter *probabilityToInvite* is used. If we set this parameter (i.e. *probabilityToInvite* = 0.3), 30% population of the CPSN have intention to carpool and will emit carpool invitations. This component still needs more research. The complete and accurate dataset of the study area may be required to simulate and validate.

To model decision making within an agent-based simulation is an important consideration. In the presented simulation, the negotiation *outcome* is determined by a deterministic function based on the candidates' profiles and time windows. The actual negotiation *process* is not simulated in detail. The actual *negotiation process* can be modeled by setting values (0,1) in advance for each preference which later on can be used in the negotiation process. To model actual *negotiation process*, the Negotiation Organization is also required for the additional interaction and coordination.

Multiple Trips Based Negotiation Model

In this research a multiple trips based negotiation model is presented to find and evaluate feasible carpool sequences for the group of participants and to select the optimal one. The feasible carpool groups are identified on the basis of a time preference function, the maximum detour time loss duration, the driver and vehicle selection, and the pick-up and drop order of the participants.

In the carpooling simulation presented in this dissertation, the constant preference time function as well as the preference time function based on an existing study partly derived from Hendrickson & Plank, (1984) has been implemented. The existing study was originally designed on the basis of a survey conducted in an American State. Although, there might be some concerns regarding the validity of the model coefficients of the proposed preference function for European region. However, the selected approach towards the construction of a close-to-reality individualized preference function for each agent in the population can eventually turn out to be helpful for future studies. Only a few adjustments to the coefficients of the multinomial logit model will lead to a model that will be accurately representative of the actual negotiation mechanism specifically for Flanders, Belgium.

However, the construction of behaviorally accurate agent based models require an extensive and detailed dataset in order to simulate the actual mechanism. Many authors have attempted to formulate individual utility functions but due to lack of tangible data, none of them can be said to fully represent the real-life behavioral mechanism, as (Wooldridge, 2009) also suggests that utility functions are difficult to develop and tend to oversimplify the real-world processes.

The feasible carpool trips are found by considering the maximum detour (time loss) acceptable to each participant. It has incorporated for the path or route selection for the carpooling trips. Currently it is based on common sense estimations which need to be validated for the study area. Thereto data need to be collected from individuals by means of surveys.

The driver and vehicle selection is modeled by inspecting the personal profiles of the individuals. The pick-up and drop-off order sequences of the participants is modeled by using the permutation concept. It can further be improved by reducing the computation time when the actual negotiation will be modeled.

The negotiated group of participants may have more than one feasible carpooling sequence and to select the optimal one the scoring mechanism is proposed and implemented. The scoring mechanism is based on the degree of flexibility, time loss and time of day scoring functions. Currently the parameters for the scoring functions are based on common sense estimations not on observations and their validity is still to be verified.

During this research project, various elements were identified that will require a deeper investigation. Future research will mainly focus on:

1. To model and simulate the actual negotiation behavior by enhancing the presented negotiation mechanism. An *Organization* needs to be introduced and added to the model that will handle the further interaction and cooperation process between participants. In the presented negotiation mechanism, the *outcome* is determined by a deterministic function based on the candidates' profiles and time windows.
2. The schedule adaptation mechanism will be formally defined to model the adaptations in the participants' schedules to cooperate for carpooling during the negotiation process.
3. The individuals' behavior for carpooling experience (either good or bad) and their daily feedback is important and requires a comprehensive behavioral model that can also be considered in the future studies.

4. The interaction between the driver and the passenger and to measure the impact and influence of their behaviors in the carpooling groups can be taken into account.
5. The simulation model may be extended by providing a feature which enables carpooling between employees who belong to different destinations / companies (or may alight at different car parks). The driver will first drop-off all the passengers at their car park locations and then will park car at his/her nearest car park.
6. The presented carpooling model can be extended to support other type of trips i.e. work-to-shopping, work-to-restaurant (other than work activities) of the individuals' schedules. Other trips may studied to see the effect of the time pressure caused by those trips on the work trips.
7. 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.
8. The integration of the *day switching mechanism* can be improved to better reflect its role as a *supporting* component in the model.
9. The development of a visual representation of the scenarios to allow for easy manipulation of parameters and to analyze the outcomes of the simulation.

References

Cossentino, M., Gaud, N., Hilaire, V., Galland, S., & Koukam, A. (2010). ASPECS: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent Systems*, 20(2), 260–304. https://doi.org/10.1007/s10458-009-9099-4

Crooks, A.T. and Heppenstall, A.J. (2012), Introduction to agent-based modeling. In: A.J. Heppenstall, A.T. Crooks, L.M. See & M. Batty (Eds.), *Agent-based models of geographical systems*, (pp. 50 - 150). Dordrekht: Springer.

Hendrickson, C., & Plank, E. (1984). The flexibility of departure times for work trips. *Transportation Research Part A: General*, 18(1), 25–36. https://doi.org/10.1016/0191-2607(84)90091-8

Hussain, I., Knapen, L., Khan, M. A., Bellemans, T., Janssens, D., & Wets, G. (2015). Agent-based negotiation model for long-term carpooling: A flexible mechanism for trip departure times. *Urban Transport XXI*, 146, 461.

Wooldridge, M. J. (2009). An introduction to multiagent systems. 2nd Edition, *John Wiley & Sons, Chichester, England*.

Part II

Matching Support Framework and Service for Carpooling

Chapter 6

Framework to Support Matching for Carpooling

This chapter consists of following paper

Hussain, I., et *al.*, (2017). Matching Framework for Employees to Support Carpooling in Context of Large Companies, *IEEE ITS Magazine (ITSM)*.

Which is based on following conference papers

Hussain, I., Knapen, L., Bellemans, T., Janssens, D., & Wets, G. (2017). Employees' Matching to Support Carpooling in Context of Large Companies, In: *BIVEC/GIBET Transport Research Days 2017*.

6.1 Overview

This chapter presents a matching support framework for employees who are candidates for carpooling, it is based on the agent-based carpooling simulation model presented in chapter 5 of this dissertation. It aims to support large companies and institutions located in congested areas where parking space is expensive or scarce. The presented matching framework accounts for dynamic evolution of the extracted personnel database in order to minimize burden on the users and notifies interested carpoolers about new opportunities to find partners belonging to a closed managed group. The framework matches candidates based on source (home) and target (specific car parks) locations as well as on the time windows specified by the interested candidates. The matching is also based on path similarity, personal profile of employees. The proposed framework finds suitable groups of people to carpool. A large number of groups can be found for a particular individual and not all of those can be presented to the user. Therefore, scoring functions are used to qualify the solutions. A small set of groups having the highest scores is presented to the candidates. For each group, the timely feasible pick-up and drop-off orders are evaluated. Those are scored at the carpool level. The best groups are evaluated by the group members who in turn evaluate them using their own individual scoring criteria and start a negotiation to take the final decision. As a proof-of-concept of the proposed framework, experiments were conducted at the scale of the Doppahuis database.

6.2 Abstract

Large companies or institutions can be mainly effective in changing their employees travel behavior. Intensifying carpooling within the context of a large company is expected to be feasible and effective. Carpooling contributes to the solution of congestion and lack of parking space. Matching potential carpool partners in large companies are one of the essential needs in setting up carpooling. This paper presents an advisory framework for matching employees who are candidates for carpooling to support large companies located in congested areas where parking space is expensive or scarce. The core objective is to show the feasibility of matching for recurrent travel demand. The goal is to notify people about new opportunities to find partners belonging to a closed managed group and interested in carpooling. The framework accounts for the dynamic evolution of the extracted personnel database in order to minimize the burden on the users. It matches candidates based on source and target locations as well as on the time windows specified by the interested candidates. The proposed framework finds suitable groups of people to carpool. For a given group, the timely feasible pick-up and drop-off orders are evaluated. Those are scored at the carpool level. The best groups are kept and presented to the group members who in turn evaluate them using their own individual scoring criteria. Supporting carpooling by personnel contributes to the mobility plan to be established by the company. The framework is intended to be rolled out to companies as a pilot project after integrating a feedback mechanism.

Keywords: Commuting, travel behavior, carpooling, individual matching, advisory framework.

6.3 Introduction

Large companies or institutions can be mainly effective in changing their employees travel behavior. They are more influential than community institutions or less significant enterprises. Large companies, especially those located in the important region, frequently have limitations on parking. These limitations are due to the unaffordable cost of the facility or the limited number of available space due to local and/or state regulations. This usually means that large companies are more actively encouraging employees to travel in alternate ways (Amey, 2010). Increasing carpooling within the context of a company is expected to be feasible and effective. Carpooling contributes of making savings in parking, it reduces costs associated with company cars and crucially contributes to the solution of traffic congestion. It improves relationships and strengthens social cohesion between personnel to create a sociable working environment. Since carpooling aids both employers and employees, many companies may be interested in increasing it. The main advantage for the employer is the requirement of less number of parking spaces. For the employees, it can reduce the employees' stress and also improve their productivity. Large companies or institutions can encourage employees by providing a variety of means, including discounted or free carpool parking, incentive programs, and provide an employee matching service to identify matching colleagues (solutions) directly (Eastern Research Group, 2005; Knapen et *al.*, 2013). From a matching point of view, the presence of large companies ensures that a large number of people will travel to the destination. According to (Amey, 2010), the match of individuals in a large company is more likely than among persons who are not associated with the same company. Large employers (companies or institutions) can positively impact private household travel choices without causing an excessive burden on individuals (Amey, 2010).

The carpooling problem has been advanced from various views e.g. "*how to find compatible carpool participants to share a car?*", and how to agree "*who will be the driver to pick-up and drop-off the passengers?*" Mutual coordination may be a challenging task both for the driver and for all the passengers (Tyagi & Niladhuri, 2016). Matching and coordination for carpooling are challenging tasks especially if every driver is able to pick up at least one and up to four passengers. Matching passengers for the carpooling is a combinatorial problem (Furuhata et al. 2013; Agatz et al., 2012). Normally, employees choose carpool participants without any contribution from the large employers. However, suggesting employees carpool matching solutions directly is an effective way for employers to encourage employees. This research aims to support large companies and institutions located in congested areas where parking space is expensive or scarce (which is assumed to be equivalent). The purpose is to propose carpool groups to the employees who are potential carpoolers; after that the individuals shall negotiate about cooperation. Supporting carpooling by personnel contributes to the mobility plan to be established by the company.

This paper presents a framework derived from a comprehensive tool described in (Knapen et *al.*, 2016) for matching employees who are candidates for carpooling to support large companies. It accounts for the dynamic evolution of the extracted personnel database in order to minimize the burden on the users. It notifies people about new opportunities to find partners belonging to a closed managed group. The framework matches candidates based on source (home) and target (specific car parks) locations as well as on the time windows specified by the interested candidates. The matching is also based on path, personal profile of employees. Other criteria can be used in a post-processing step by sorting the presented options according to a specific criterion (that can be reputation based). Such system allows to qualify people as safe and timely drivers and maintains reputation attributes that can be used to control the advisory process. The proposed framework finds suitable groups of people to carpool. A large number of groups can be found for a particular individual and not all of those can be presented to the user. Therefore, scoring functions are used to qualify the solutions. A small set of groups having the highest scores is presented to the candidates. For each group, the timely feasible pick-up and drop-off orders are evaluated. Those are scored at the carpool level. The best groups are evaluated by the group members who in turn evaluate them using their own individual scoring criteria and start a negotiation to take the final decision. As a proof-of-concept of the proposed framework, experiments were conducted at the scale of the *Doppahuis* database.

This paper is organized as follows: Section 6.4 presents the related work on carpool matching services and factors involved in carpooling activities and its incentives. Section 6.5 describes the carpooling model for employees matching. Some definitions and requirements are also offered to explain the carpool matching framework. The matching framework (to *propose* carpool groups) and the evaluation criteria (to *evaluate* carpool groups) are explained in detail. Section 6.6 explains the experimental setup and discusses some of the effects. Finally, the conclusions and suggestions for future work, are presented in section 6.7.

6.4 Related Work

The first subsection covers literature related to the factors involved in carpooling activities and its incentives; the second one focuses on carpooling matching frameworks and services.

6.4.1 Incentives Factors

In the procedure of planning a carpooling matching framework and service, it is serious to recognize the factors involved in the carpooling actions. The involved factors may be the awareness of the benefits and traveling cost for the carpooling candidate as well as concerns concerning safety. In Levin (1982), the author determined that the time cost and the accessibility are two crucial reasons in the carpooling decision. The carpool participant conveyed anxieties about their personal ease and also about the gender mix among them. Li, et *al*. (2007) concluded that accessibility to the HOV traffic lane and also decrease in the stress of driving are the most important motives for carpooling. The reasons for the participants who do not want to share a ride are: (1) the struggle in finding a compatible candidate with the similar destination and agenda (2) the flexibility of driving or traveling alone and (3) a vehicle is needed in emergency circumstances. Correia and Viegas (2011), reported that the inflexible in the daily schedules of the carpool participants and the lack of faith or trust between the strangers are the major obstacles for co-traveling. Destination location and agenda requirements are factors which extremely bounded the suitability and flexibility for co-traveling. Although a significant portion of travelers possibly share a similar route and also a similar schedule but might be hard to coordinate with each other for their travel. Thus, a well-organized carpool matching framework which allows travelers to form a possible carpool group can be a serious component in encouraging carpooling.

Tischer et *al*. (1979) recognized that the safety, cost, and relieving congestion are key factors in the incentives for carpooling. Some of the studies have acknowledged the eco-friendly consciousness and unfortunate transfer facility by way of key reasons for successive carpooling (Collura, 1994). With regard to individual properties, the literature arguments that gender, income, and educational accomplishment are important for carpooling choice (Ferguson, 1995).

Companies have the privileged association with their workers, therefore, are used as mediators between administration and travelers regularly (Ferguson, 2007). Concerning carpool establishment, the volume of the carpool potential of matches associates with carpool formation (Kaufman, 2002). Hwang and Giuliano (1990) indicate a higher attention of employees as a first element due to the possible matches between them. Authors illustrate that a regular work schedule makes it convenient to identify carpooling partners with the similar working periods (hours). The involvement of private sector may reduce the load of transportation strategies on the community budget (Cairns et *al*., 2008; Roby, 2010). Vanoutrive et *al*., (2009) takes the employer as main research element since the work side of home-to-work commute receives less attention in commuting research. Regular work schedules and employees at a destination site are definitely associated with an upper share of carpooling employees. Additionally, employers are also further professionally organized to establish transportation management actions i.e. parking restrictions, allowances and bicycle facilities (Vanoutrive et al., 2012).

6.4.2 Matching Frameworks and Services

The carpool matching service in the literature is modeled as a combinatorial problem (Furuhata et al. 2013; Agatz et al., 2012) and its main target is to reduce the general travel distances and the travel times. There can be other objectives like the expansion of the number of matches for carpooling and also the reduction of the computation time. The technical challenge to model carpooling matching is the complication of accurately demonstrating the carpoolers behavior and the actual matching method itself. The practical challenge can be the critical mass issue; it contains difficulty in attaining the users mass in order to find a suitable carpool partner in response to the user's requests.

Agatz et al. (2011) consider the matching problem for a complex ridesharing situation. Authors presented a simulation based study established on the travel demand data and for the city of Atlanta. The ride-matching problem is pronounced by the authors as, the minimization of the traveled vehicle miles experienced by the users and also by their specific traveling costs. The authors claim that using classy optimization approaches considerably increases the efficiency of the ridesharing schemes over the greedy matching algorithm. The effort in Herbawi et al. (2012) reports the dynamic ride-matching problem by the use of the time windows and optimizes a multi-standards objective function. The authors prolong the exertion presented by Agatz, by proposing an algorithm (genetic and insertion-based heuristic) for solving the combinatorial problem. The authors also considered the multi-ride problem. In Di Febbraro et al. (2013), the authors propose a matching system for carpooling by considering the interactions between potential candidates and the system manager. The authors used a model to maximize the performance of dynamic carpooling systems based on mixed continuous-integer linear programming. The efficiency of the presented model is examined by a simulation, established on the modeling structure for Discrete Event Systems (DES).

Xia et al., 2015 presented a model for carpooling-matching services. In the presented research both the optimal and heuristic approaches are tested to find the matching solutions. It is confirmed that a new formulation and related solution measures permit for resolving the ideal carpool groups and also routes. Martinez et al., (2015) presented an agent-based simulation for mutual taxis where a set of rules for space and matching time are recognized. It is considered that the consumer is the only one who is willing to receive a deviation from the direct route, up to the agreed maximum. The authors found an objective function for choosing the ideal candidates for the taxi-sharing. Knapen et al., 2014(b) offered an automated advisory service to match commuting trips for carpooling. The possibility for successful cooperation is designed by means of a learning mechanism. The matcher module desires to deal with dynamically changing graph with regard to the topology and the edge weights.

Numerous carpooling matching services have been developed with specific approaches and functions. These are organized in different ways containing numerous functions and properties. Nowadays potential candidates organized their daily trips through the Internet and Geographic Information System (GIS) supplied by the available matching services. Steger-Vonmetz (2005) presented a GIS-based traveler info scheme that achieves the carpool matching based on the network places. It offers the following carpool services: (1) the driver and passenger searching, (2) carpool group matching, and (3) commute cost sharing. Buliung et al. (2010) helped travelers in the area of Toronto and Hamilton, Canada. The authors offered the following services: (1) smart route matching, (2) cooperative mapping, (3) pin-point geocoding, (4) security and privacy and (5) managerial functions for the communicating and matching procedures. Agatz et al. (2011) matching policies are intended to enhance the over-all system-wide traveled miles and the rate of the carpool matching. The benefits of a single user might not be certain from an individual viewpoint because discrete preferences are not considered. Abrahamse and Keall (2012) and Buliung et al. (2010) helped travelers to find other travelers who share a related route with particular requirements i.e. agenda, gender, language. Through network analysis, the presented scheme provides the part of resemblance between two routes. Huang et al. (2014) presented a carpooling service by a moveable user and cloud-based carpool-matching component. The method accepted a genetic algorithm in order to offer network-based matching service.

There are over 70 different carpooling-matching services and platforms are operational in Europe (Kesternich, 2015). They differ in terms of organizational form, their inner construction, offered services on their websites and the catchment zones or areas. The carpooling marketplace has been grown since one service provider offered a fee-based carpooling facility.

None of the reported research describes a solution by providing carpool matching solutions directly by the employers. In this paper, our focus is to present a framework which may help employers to find matching carpool solutions and propose those solutions to the candidate carpoolers in large companies and institutions.

6.5 Matching Framework for Carpooling

This research presents a framework for matching employees who are candidates for carpooling. It proposes carpool solutions based on the optimal matching of candidates to the employees who are potential carpoolers and shall negotiate about cooperation. It aims to support large companies located in congested areas where parking space is expensive or scarce. It is based on (Knapen et *al.*, 2013) although that research is not restricted to single companies and the research goal was different. The core objective is to show the feasibility of matching for recurrent travel demand. The goal is to notify people about new opportunities to find partners belonging to a closed managed group (e.g. colleagues working for a specific company) and who are interested in carpooling. Motivators to participate are listed to evaluate their effect on the product design: (1) financial savings due to sharing travel cost in case a private car is used, (2) financial savings for the passenger in case the driver has a company car available which can be viewed as an incentive provided by the employer; (3) organizational and time pressure problems in the exploration stage are solved by efficient matching and (4) individual preferences are taken into account.

The method proposed in this paper produces an advice for individuals. Each person is considered to be a utility optimizer. Hence, a large set of optimization problems is to be solved. This paper shows that the individual optimization problems are of moderate complexity. This allows to enumerate the possible solutions for each driver, to evaluate those using scoring functions and to present the best ones to the users, sorted by decreasing score. Mutual effects between people occur by feedback via the personnel database where individuals register their availability as a passenger or driver during a particular period of time. Every successful negotiation leads to an agreement to carpool and hence to an update of the database. The problem does not suffer from the combinatorial explosion because the method does not aim to find a system optimum.

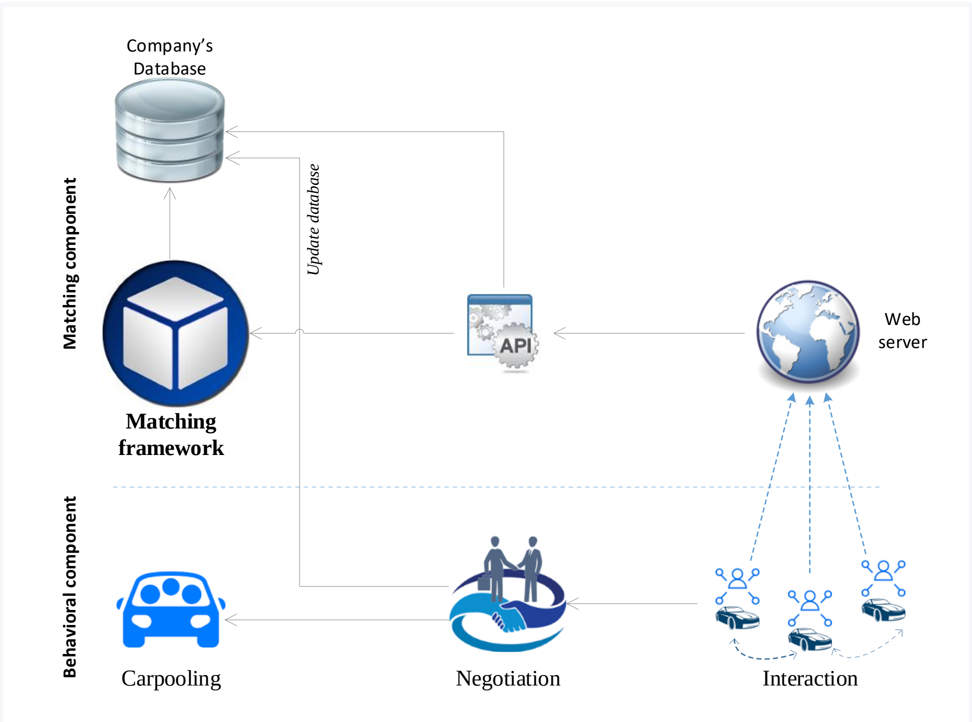


Figure 6.1. The architectural diagram of employees' matching carpooling model to support large companies.

The design of the *employees matching carpooling model* for the large company is presented in Figure 6.1. It has two components: (1) the matching component and (2) the behavioral (negotiation) component. The matching component comprises a *matching framework* which consumes a *personnel database* maintained by the HR-department in a company or organization. It proposes sets of people who are mutually compatible for negotiation on carpooling and decides which carpools to present and in which order. The application program interface (API) is used to manage the matching framework and to access restricted data in the company's database directly from the web server. The *web server* provides an interactive mechanism to the employees of the company. Each employee who is the candidate for carpooling needs to specify a *periodic scheme* specifying on which days the individual is available either as a passenger or as a driver as well as the time windows for each departure and arrival. A more elaborated definition is given in the next section. The periodic scheme and the time windows need to be supplied interactively (via a web application). The behavioral component is accomplished by the employees themselves, considering their own preferences and choices. It depends on the matching model which proposes the best scoring feasible advice first. When the matching model proposes the carpool solutions to the candidate carpooler, (s)he) may interact and negotiate with the participants of the proposed solution in order to select the optimal one. In this research, our main focus is on the matching framework of the carpooling model.

The matching framework uses the periodic scheme and time windows information provided by the candidates. This is essential: if some candidates refrain from specifying time windows, advice can be wrong for many others. Candidates are also required to specify the maximal excess trip duration (this is used for both drivers and passengers). Candidates whose trips can be combined with respect to the detour time can picked-up by the driver. If the set of candidates for a carpool contains a non-empty subset of company car users, only the people in that subset are allowed to act as a driver. The matching applies to both the home-work (HW) and work-home (WH) trips and covers trip start times, the driver and vehicle selection and the *pick-up* and *drop-off* order of the *carpoolers*.

6.5.1 Basic Concepts: *Definitions*

This section presents some definitions and user requirements that are the prerequisite to explain the framework aimed at advising employees with respect to carpooling based on the optimal matching of candidates.

Definition 1 (*Company - Organization*) A *company* (institution, organization) can have multiple addresses (sites of employment). The requirements list assumes that each company (i.e. the collection of people whose data are maintained in a particular personnel database) is handled as an independent case. Different sites from a particular company can be handled by means of *destination car parks*.

Definition 2 (*Destination Car Park*) The *destination car park* is the location where the car mode part of the trip ends and for which the generalized cost (i.e. distance, travel time, parking cost) of the complete trip from the source location (mostly home) to the workplace desk is perceived to be (nearly) minimal.

- The generalized cost to travel between the car park and the work desk is individual specific.
- In many cases, the workplace desk is reachable in at most *10[min]* walking time or at a distance of at most *1[km]* from the parking place.
- A public transferium near the city border can be used to park the car and to continue the trip by another mode. Note that this excludes carpool parks: the car trip ends at the transferium.
- A car park is usable by an employee as a driver if and only if it is both feasible and accessible to the employee. Car park usability for a passenger is inherited from the driver.
- When a carpool is formed, the car park used is not recorded and hence not checked. Carpoolers possibly can make use of carpool parking spaces but their management is a different problem and the proposed framework does not provide any optimization support.

Definition 3 (*Base Period*) Life is assumed to be periodic w.r.t. trips driven, trip timing, car and seats availability. Therefore, we state the existence of a base period although we do not fix its duration in advance. Combining people having different base periods into carpools so that individuals can be a member of several carpools for different days in the base period and is expected to be very complex (both to develop the solution and to use the framework).

- For most employees, a week is a suitable base period but for some part-time workers a period of two or more weeks is required (e.g. for people working in shifts: early (06:00h-14:00h), late (14:00h-22:00h) or night (22:00h-06:00h)).
- The first day of the base period is fixed to the calendar in the same way for all employees known by the application (and hence it can differ between companies).
- The same base period is used for all employees in the company deploying the framework. The base period may differ between companies (independent installations of the framework).
- The base period cannot be repeated in the first case, for each day or date the periodic scheme has to be entered by the employee.

Definition 4 (*A Day*) The definition of *a day* is not straightforward. A day is a 24[h] period but the start of such period needs to be fixed in time (using time-of-day). Observe that work shifts occur together with the requirement to use at most one carpool in a day (the same carpool for both commuting trips). The current implementation assumes a day to start at 00:00h.

Definition 5 (*Time Windows*) A *time window* is defined by: (1) a time interval I specified by the earliest and latest moments (expressed as time-of-day) respectively and (2) a preference function $P()$ that in each point in the time interval is non-negative and finite and has a non-zero integral over I.

- For particular types of time windows more specific constraints can apply (e.g. the requirement that the preference function is continuous and differentiable at each point in I).
- The software is designed and implemented so that generic preference functions are supported. However, the first implementation of the matching phase only supports time windows equipped with a constant preference function i.e. $\forall t \in I: P(t) = 1$. In the evaluation phase, a triangular based preference function is used (see *subsection 6.5.2.2.2(iii)*).

Definition 6 (*Periodic Scheme*) The *periodic scheme* for an employee defines the commuting trip requirements for the employee to every day in the base period.

- Examples for a 2-week base period:
    - (a) everyday same trip and same timing for both home-work (HW) and work-home (WH)
    - (b) every Monday, Tuesday, Thursday and Friday: same trip and trip timing for HW and WH. Furthermore, on the first Wednesday no commuting, on the second Wednesday HW trip in the morning, WH trip at 13:00h.
- Note that the definition of the periodic scheme depends on the date used to fix the scheme to the calendar. Note also that more data have to be supplied for each day in the periodic scheme than suggested by the example.
- Each employee defines and maintains the own periodic scheme since it contains data that are not managed by the personnel service.

A $periodicScheme$ is defined by the set of attributes shown in Table 1 for every day in the base period:

Table 6.1. Set of attributes for the base period of the periodic scheme.

Symbol	Definition or meanings
$\boldsymbol{T_{dep,hw}}$	Time window for the home-work trip departure time
$\boldsymbol{T_{arr,hw}}$	Time window for the home-work trip arrival time
$\boldsymbol{T_{dep,wh}}$	Time window for the work-home trip departure time
$\boldsymbol{T_{arr,wh}}$	Time window for the work-home trip arrival time

$\boldsymbol{d_{solo,hw}}$	The travel duration in minutes for the solo trip based on the home and work addresses for the participant
$\boldsymbol{d_{maxExcess}}$	Maximum excess trip duration in minutes (maximal travel duration increase that is acceptable for each individual trip). The $d_{maxExcess}$ accounts for the both the trips separately of the same carpool.
$\boldsymbol{carCapacity}$	A maximum number of people in the car, driver included; $carCapacity = 1$ means that the person can drive but cannot take any passengers. $carCapacity = 0$ means that the person cannot drive (due to lack of the car (on a particular day) or driver license).

Definition 7 (*Member of Carpool*) For every day in the periodic scheme, everyone who looks for a carpool (initial or replacement) is to be considered as a candidate. For a given day an employee can be the member of at most one carpool. As a consequence both the home-work and work-home trips are driven by means of the same carpool. Hence, people can only be advised to carpool in case they are sufficiently compatible w.r.t. both commuting trips.

6.5.2 Matching Framework Setup

The framework makes use of extracts of the personnel database maintained by the HR-department in a company or organization in order to minimize the burden on the users. It accounts for dynamic evolution because the underlying personnel database evolves (new employees, leaving employees, residence address changes, emerging or dissolving interest in carpooling due to family changes). Data are delivered via (a) periodic imports from the personnel database (b) user interaction via a Graphical User Interface (GUI) to maintain trip and carpooling preferences, to keep track of actual carpooling and exploration for partners and to keep track of temporary unavailability due to holidays and other reasons for absence. Every change in the data acts as a trigger to calculate new advice for employees exploring to find partners. Advice shall be sent to employees in a sufficient but sparse way (i.e. relevant advice only, no spamming).

The proposed matching framework is divided into two stages (Figure 6.2): (1) pre-selection and (2) advisory. A directed graph is used which contains the pairs of potential candidates in the pre-selection stage where nodes represent the compatible candidates for carpooling and are connected by edges. The edge constitutes a feasible and directed when the predecessor node acts as a driver while the successor node is the passenger in the specific pair of the graph. All the cliques (sub-graphs) are extracted and further check every *permutation* (for each clique) of the candidate participants from the directed graph in the advisory stage.

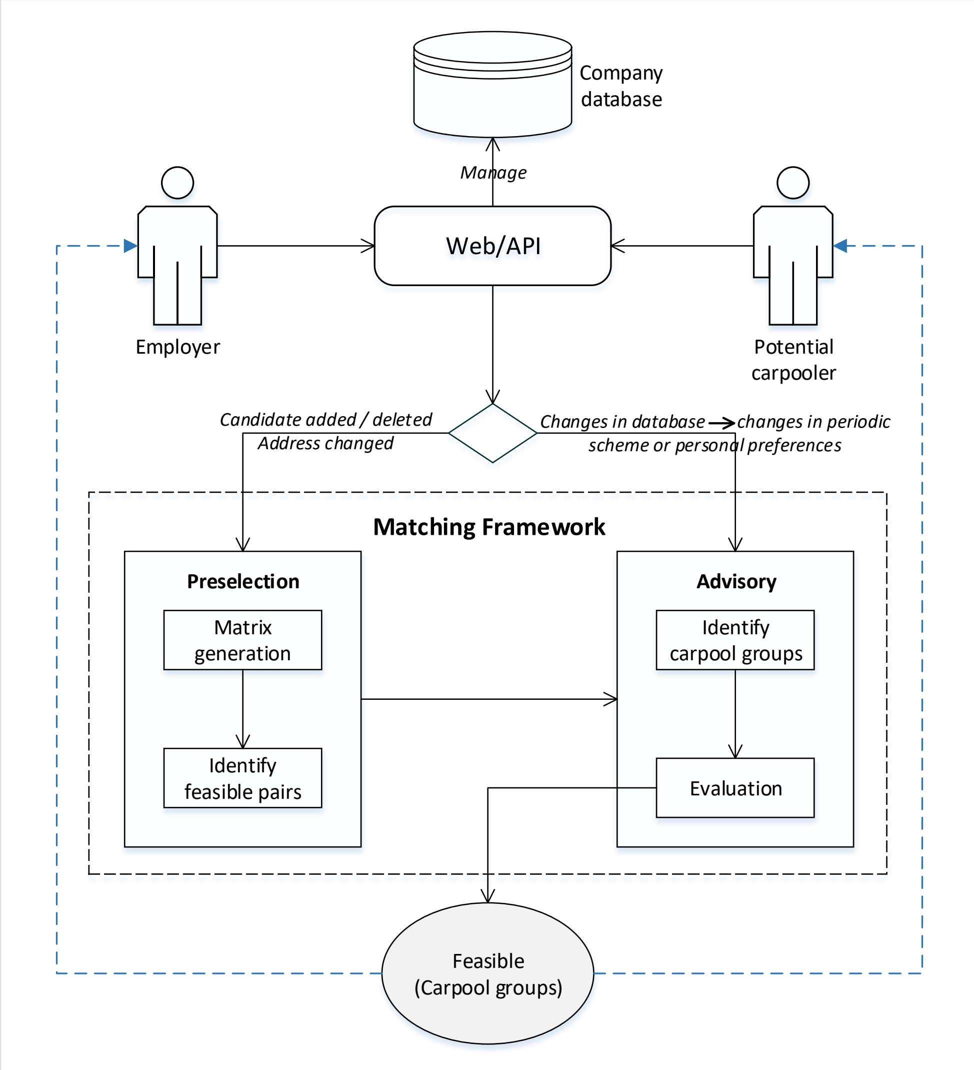


Figure 6.2. Structure of the matching framework for a large company.

6.5.2.1 Preselection Stage

Preselection is required to save computation cost. It makes use of a travel time and travel distance matrices computed in advance and aim to filter infeasible cases in an early stage. It is assumed to sufficiently reduce the computational effort associated with database updates. Updates in the database are assumed to be quite rare so that the preselection is not to be executed frequently. They occur due to the addition of employees and to changes in the *street address* of an employee (moving). Two activities are performed in this stage: (1) travel duration matrices generation and (2) feasible pairs formation.

6.5.2.1.1 Travel Duration: Matrix Generation

Individuals' home-addresses (street addresses) based travel time and travel distance matrices are generated in advance using *GraphHopper (*Karich, 2014*). "GraphHopper is an open source routing library and server, provides a web interface called GraphHopper Maps. It also provides a routing API over HTTP. By default GraphHopper uses OpenStreetMap data for the road network and elevation data from the Shuttle Radar Topography Mission is used" (*Urquhart, 2015*).* The travel times estimate the duration of the trips while the travel distances assess the cost of the trips.

6.5.2.1.2 Feasible Pairs

In the preselection phase, the feasible pairs of potential carpooling candidates are identified and established for the advisory stage. In order to identify the feasible pairs, each employee is compared with every other employee and compatibility indicators are computed. The compatibility indicators are applied on both the commuting trips (*HW* and the *WH*) in the periodic scheme of each candidate.

i. Driver Selection

For each pair, a driver is required. The driver candidate must have a vehicle available and own a driving-license.

ii. Time Intervals

Time intervals similarity is based on departure time window limits and arrival time window limits of the pairing candidates. The arrival time window of both individuals (a_1 *and* a_2 in this case) at the work location l_{work} is $T_{(a_1,a_2),\, l_{work}}$. It is the intersection of the arrival time windows for the respective participants as shown by Eq. (1).

$$T_{a_1,\, l_{work}} \bigcap T_{a_2,\, l_{work}} \tag{1}$$

The departure time windows of individuals a_1 and a_2 are $T_{a_1,l_{a_1}}$ and $T_{a_2,l_{a_2}}$. The home locations for a_1 and a_2 are l_{a_1} and l_{a_2} respectively. When a_1 precedes a_2 in the carpool pick-up sequence then the departure time window at l_{a_2} of the respective pair at l_{a_2} is $T_{(a_1,a_2),\; l_{a_2}} = T_{a_1,l_{a_1}} \oplus d_{l_{a_1},l_{a_2}}$ and the intersection of the departure time windows is given by Eq. (2).

$$(T_{a_1,l_{a_1}} \oplus \, d_{l_{a_1},l_{a_2}}) \bigcap T_{a_2,l_{a_2}} \qquad (2)$$

In case a_2 precedes a_1 in the carpool pick-up sequence then the departure time window at l_{a_1} is $T_{(a_2,a_1),l_{a_1}} = T_{a_2,l_{a_2}} \oplus \, d_{l_{a_2},l_{a_1}}$ and the intersection of the departure time windows for this sequence is given by Eq. (3).

$$(T_{a_2,l_{a_2}} \oplus \, d_{l_{a_2},l_{a_1}}) \bigcap T_{a_1,l_{a_1}} \qquad (3)$$

Each pair for which no non-empty time windows do exist for both the HW and WH trips can be dropped immediately.

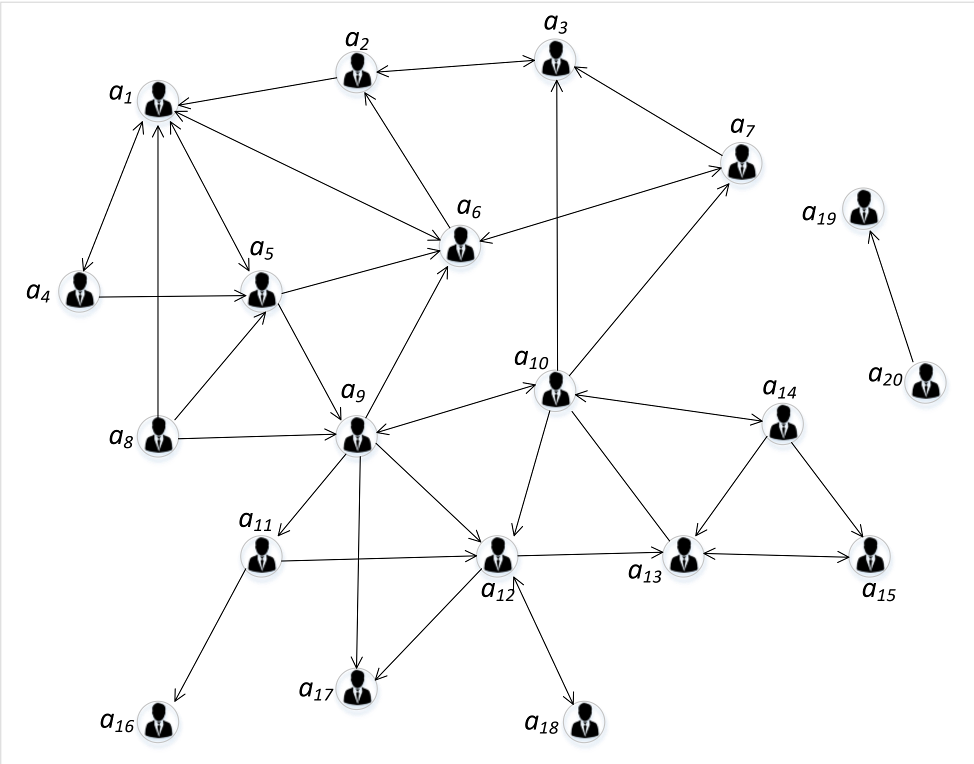


Figure 6.3. A directed graph generated by the preselection phase of the proposed framework. The nodes are the candidates while the edges correspond to pairs suitable for carpooling.

iii. Maximal Detour Duration

The maximal detour duration (maximum excess duration) uses the solo driving car trip as a reference. A value for this quantity is to be determined from surveys. In this research the maximum feasible detour is specified by a function discussed in *subsection 6.5.2.2.1-iii*. The excess travel duration for a carpooling pair must be less than or equal to the maximal detour duration otherwise the pair is considered as infeasible and can be dropped.

When the compatibility requirements are achieved and the pairs are identified, a directed graph is used to contain the pairs of potential candidates. Each node in the *compatibility graph* represents a candidate for carpooling. Two nodes are connected by an edge if and only if the individuals constitute a feasible pair for carpooling. The predecessor individual or node may act as a driver while the successor individual is the passenger in the specific pair of the graph. If the first member in the pair is unable to drive, the pair is still usable for inclusion in a larger sequence. The flow can be bidirectional, when both the pairs i.e. $a_1 \rightarrow a_2$ and $a_2 \rightarrow a_1$ are feasible.

6.5.2.2 Advisory Stage

The matching framework proposes sets of people who are mutually compatible for negotiation on carpooling; so, at this stage, we need to decide which possible carpools to present to the user and in which order. Every change to the database triggers an execution of the advisory unit including the calculation of new advice for the employees. Hence, the advisory execution is triggered both by employee and employer (personnel service) interactions. An employee will receive tens of notifications every day and will decide to ignore them. The filtering is required e.g. a user can specify that (s)he wants at most one notification in 3 days. The system will emit only the last notifications generated before midnight.

The advisory stage is based on two activities (1) finding feasible solutions and (2) evaluate feasible solutions and propose some of them to the carpooling candidates.

6.5.2.2.1 Finding Feasible Solutions

This unit first finds all the feasible solutions (up to the size of appropriate car capacity) of mutually compatible candidate participants. This can be achieved by (1) finding in the smallest *general* graph that contains the *compatibility graph* all the possible cliques having a size that does not exceed the maximum car capacity and (2) extracting the feasible solutions from the cliques of each level. Cliques having the same size belong to the same *level*. Levels are processed completely one after another. The cliques are extracted from the graph created in the preselection stage by considering the nodes and the directed edges between them. For each clique, all possible orders of participant pick-up (for HW trip) and drop-off (for WH trip) are evaluated. In general, not every pick-up order for a clique leads to a feasible solution.

A clique is considered to be feasible if and only if negotiation among the members may lead to carpooling. We define negotiation as the cooperative selection of a value for a tuple of quantities. The selected value for each quantity shall be acceptable for each participant in the negotiation. In all cases a predefined set of negotiation variables is specified for which compatibility is required. Each candidate participant is assumed to specify a set of acceptable values for each negotiation variable. During the negotiation, the participants will collectively and unanimously select values for the variables. To identify the feasible solution for each level, the compatibility condition is verified by checking whether a tuple of assignments does exist that is acceptable for every candidate involved in the future negotiation. The compatibility is achieved by finding the feasible solution that meets the conditions stated by the candidate participants. Several compatibility indicators can be used i.e. *path* compatibility, *time* compatibility etc. Note that *path compatibility* needs to be evaluated (again) because the cliques were found in a general graph containing the compatibility graph. The participants need to be compatible on trip (*HW* and *WH*) departure times, pick-up and drop-off orders, and also on the vehicle and driver selection.

The framework comprises the symmetrical commuting trips (HW and WH): this is assumed to be realistic from a behavioral point of view (less mental effort) although it induces more stringent timing constraints. Hence, a carpool is feasible only if it is for both the HW and WH trips.

i. Driver and Vehicle Selection

Every individual owning a vehicle and driving-license can act as the driver. The distance driven depends on driver selection; the driver needs to pick-up passengers from their home locations and is the first one to board. Hence, driver selection and timing constraints are interrelated. Participants can join the carpool for a given trip in several sequence orders. Such sequence (*permutation*) is valid if and only if the first participant shall be the driver. Hence *permutations*, where the first participant cannot act as the driver are infeasible and they can be dropped immediately. Since the carpool size is limited (usually, 4 or 5 persons), it is feasible to check every *permutation* (for each clique) of the candidate participants.

ii. Departure and Arrival Time Choices

Departure time choice is an important component of the travel decision-making process. This is treated as a simultaneous interactive decision based upon maximization of individual travelers satisfaction with each departure time. The trip start times shall be at the intersection of the respective *HW* and *WH* time intervals of the individuals. For the timing compatibility checking, the constant preference function is used which means that travelers do not prefer any particular moment within the time window.

The arrival time window of carpooling participants at work location is $T_{carpool,\, l_N}$. It is the intersection of the arrival time windows for the respective participants. The lower and upper bounds of the intersection of the arrival time windows can be calculated as specified in equation (4); the indices used for the *max()* and *min()* functions range over the set of candidate participants. The $T^b_{a_i}$ and $T^e_{a_i}$ are the earliest and latest departure time intervals for the trip of an agent.

$$\begin{aligned} T^b_{carpool,l_N} &= \max_{j=1\ldots N}(T^b_{a_j}) \\ T^e_{carpool,l_N} &= \min_{j=1\ldots N}(T^e_{a_j}) \end{aligned} \quad = \bigcap_{j=1}^{N} T_{a_j l_N} \tag{4}$$

The time window $T_{carpool,l}$ for home location *l* in the *HW* trip is calculated in reverse home-location visit order. The $T_{carpool,l}$ for *l* follows from the one for *l+1* by subtracting the expected travel time d_{l_i+1} 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.

$$T_{carpool,l_i} = (T_{carpool,l_i+1} \ominus d_{l_i+1}) \cap T_{\mathrm{d},l_i} \tag{5}$$

The backward shifted arrival time window specifies the required departure window at the specific location. This is to be intersected with the departure window of the person to be picked up at that location. The resulting time window is shifted further to the predecessor location.

If for some l_i, the time window $T_{carpool,l_i}$ of the participants is empty (time windows do not intersect) then the case is infeasible.

$$\forall_i : feasible_i \iff T_{carpool,l_i} \neq \emptyset \tag{6}$$

A permutation can be dropped immediately when there exists an infeasible time window.

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. An employee can be the member of multiple carpools simultaneously (each such carpool applies to a given day in a scheme). Note that the home-work and work-home trips for a given day always use the same carpool.

iii. Detour Duration Relative to Solo-driving Duration

The user can specify upper boundary values for both absolute and relative detour values. Those are determined for both the *HW* and the *WH* trips. Both absolute and relative values are checked and the most strict condition applies.

The maximum value of the detour (duration or distance) relative to the solo-driving case is given by the function specified by equations (7) and (8). It is used to introduce the path and time similarity concepts. An individual having a solo trip duration $d_{a_i,solo}$ has an upper limit $d_{a_i,maxDetour}$ for the detour delay in the trip from home to work. The maximum relative excess is defined as follows:

3. It is assumed that for short trips a larger relative detour will be considered to be acceptable than for long trips
4. Trips with size (distance, duration) less than minimum d_{min} accept a relative excess of 1 (i.e. the trip size can be doubled). Trips with size larger or equal to maximum d_{max} accept a relative excess r_{min}. In the interval $[d_{min}; d_{max}]$ an exponential decay is used. The maximal relative detour then is given by:

$$r(d) = \begin{cases} 1 & if\ d \leq d_{min} \\ e^{\left(d_{a_i,solo}-d_{min}\right).\alpha} & if\ d_{min} < d < d_{max} \\ r_{\min} & if\ d \geq d_{max} \end{cases} \tag{7}$$

with

$$\alpha = \frac{\ln(r_{min})}{d_{max} - d_{min}} \tag{8}$$

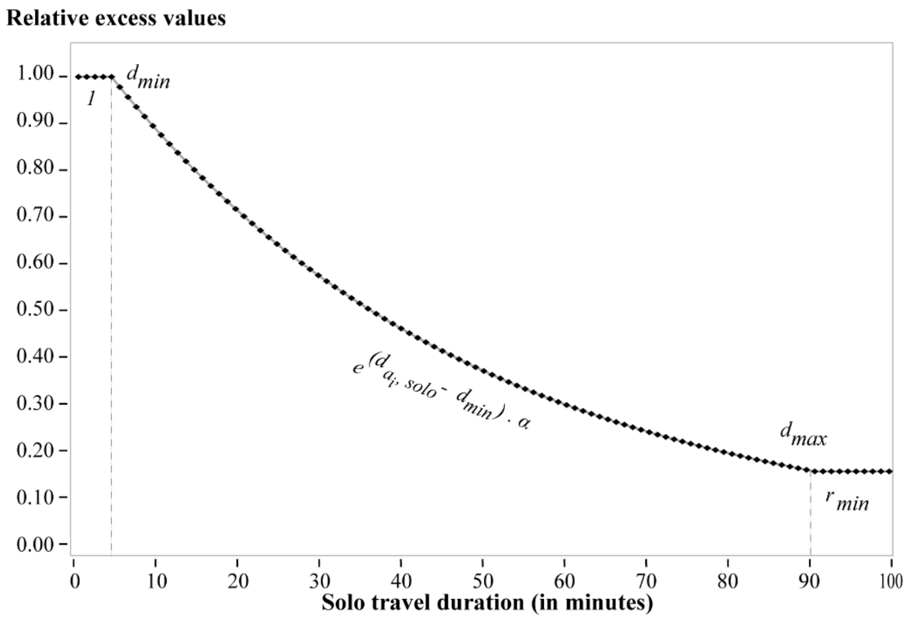


Figure 6.4: Distribution of the maximum excess overhead relative to the solo trip durations.

As an example Figure 6.4 shows the distribution of the maximum excess overhead relative to the solo trips durations. The values used for different parameters are: $d_{min} = 5mins.$, $d_{max} = 90mins$ and $r_{\min} = 0.15$ respectively.

For each individual a_i, the carpool duration must be less than or equal to the individual's maximum detour value

$$d_{a_i,carpool} \leq d_{a_i,maxDetour} = d_{a_i,solo} \cdot \left(1 + r\left(d_{a_i,solo}\right)\right) \tag{9}$$

6.5.2.2.2 Carpool Group Scoring

When all the feasible carpool groups are identified some of the solutions need to be presented to the carpooling candidates. Hence, a mechanism is required for evaluation (scoring). Scoring of proposed alternatives is a complex task. It heavily influences the outcome of the advisory procedure and hence needs to be plausible from the point of view of candidate carpoolers (and not only technically feasible). By means of the advisory stage the individual chooses between carpool proposals in order to optimize the private situation. The individuals evaluate and compare carpool proposals based on following scoring functions: (i) monetary cost $S(cost)$, (ii) excess time loss relative to the solo car trip $S(timeLoss)$, (iii) the time of day preference $S_{todp}(t)$ and (iv) degree of flexibility $S(DoF)$. The scores are used to compare different alternatives from the point of view of a single individual. The range of the scoring function values are in [0, 1] and a higher value is better.

The personal carpool estimate can be extracted by taking the product of all the scoring functions (see Eq. 10).

$$S_{ICS} = S(cost) \ . \ S(timeLoss) \ . \ S_{todp}(t) . \ S(DoF) \tag{10}$$

The *group carpool score* is attained by taking the product of the *personal carpool scores* for all the members of the carpool group (see Eq. 11). Here i is the member of the carpool group.

$$S_{GCS} = \prod_{i=0}^{n} (S_{ICS,i}) \tag{11}$$

It is assumed to be a measure for the probability that the carpool proposal will be accepted after negotiation. The scoring functions are described in more detail below:

i. Cost

In this study only one cost distribution model is implemented (although the software design allows for easy integration of additional functions).

1. In case the driver has a company car available to the driver, the cost for the trips C is determined by the employer (most of the time the cost for the employees will equal zero).
2. Otherwise, everyone pays for the distance (s)he traveled in the car and the cost is given by

$$C = d_D . C_D^{u,d} \tag{12}$$

where C denotes the trip cost, d_D is the trip length (i.e. the distance driven by the driver D) and $C_D^{u,d}$ denotes the cost per distance unit when using the car owned by D. Everyone pays for the distance in the car. Let d_j denote the distance for which participant j is in the car. Let C_j^C denote the cost for participation by individual j in carpool C is (see equation (13)). Then the cost for carpooling to be paid by j is given by:

$$C_j^C = \frac{d_j}{\sum_i d_i} . C \tag{13}$$

The cost for solo driving is

$$C_j^S = d_j^S . C_j^{u,d} \tag{14}$$

The best case occurs when a car is used for which the unit distance cost per participant is minimal: i.e. for which $\frac{C^{u,d}}{cap}$ is minimal. This is denoted by $C_{min}^{-u,d}$. The minimum personal cost is achieved only when everyone participates in the complete trip (i.e. everyone boards and alights at the driver's location) and the car is full. In such case the cost for every participant is:

$$d_j^S . C_{min}^{-u,d} \tag{15}$$

The score is defined as the ratio of the actual cost saving to the maximal cost saving:

$$S(cost) = \frac{C_j^S - C_j^C}{C_j^S - d_j^S . C_{min}^{-u,d}} \tag{16}$$

Note that $C_{min}^{u,d}$ is to be computed over all cars involved. As a consequence, the value is not constant in the time since (i) car engines become more efficient and (ii) the set of cars used by the employees changes in time. In actual practice, the value for $C_{min}^{u,d}$ can be calculated at system startup and later every year. Underestimation of $C_{min}^{u,d}$ is not harmful, overestimation is harmful (because overestimation can cause the score S_{cost} > 1 which is not allowed.

ii. Time Loss

Let L_j^C denote the time loss for participant j by carpooling and let L_j^A denote the maximum acceptable detour duration specified by participant j. The time loss score is given by:

$$S(timeLoss) = 1 - \frac{L_j^C}{L_j^A} \tag{17}$$

iii. Time-of-Day Preference

As soon as the time window for departure at the first location is determined, the optimal starting time can be found. Each participant can specify a preference function $f(t)$. Such function $f(t)$ is defined in the feasible time interval for the participant, is non-negative and its integral equals one. In practice, $f(t)$ either is a constant or has a triangular shape. Here we used the triangular shaped preference function for the evaluation. The function value equals zero at the time window borders and is positive at the preferred time. Note that in order to find feasible carpools, we used the constant preference function.

Then we consider a *probability interval* δ (e.g. 2[min]) in order to specify the interval $[t-\delta, t+\delta]$ for the expected departure/arrival time. The preferred departure time for the carpool is the value t that maximizes the sum of the $f_j(t)$ over all participants. The score then is given by:

$$S_{todp}(t) = \frac{\int_{\max(t_0(I_f),t-\delta)}^{\min(t_1(I_f),t+\delta)} f(\tau)d\tau}{\max\limits_{t\in[t_0(I_f),t_1(I_f)]} \int_{\max(t_0(I_f),t-\delta)}^{\min(t_1(I_f),t+\delta)} f(\tau)d\tau} \tag{18}$$

It gives the expected value of the actual preference realized.

iv. Degree of Flexibility

The score for the *degree of flexibility* (DoF) specified by Eq. (19) is 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 flexibility for the departure time at each location and hence for the ability to meet the schedule (because travel times may be uncertain). The candidate delivering the highest score is kept.

$$S(DoF) = 1 - e^{-\alpha \cdot \Delta T} \tag{19}$$

Eq. (19) is used to determine *DoF* where ΔT is the minimum interval length to set a value; e.g. for $\Delta T = 5[min]$ if we required a value 0.9 then the α can be determined by Eq. (20).

$$\alpha = \frac{-\ln(0.1)}{\Delta T} \tag{20}$$

6.6 Experiments and Results

As a proof-of-concept of the proposed framework, experiments were conducted at the scale of the *Doppahuis* database. *Doppahuis* is a non-profit organization that provides courses in practical skills and language courses for adults. About 1500 people registered as a *student*. Courses are taught (by volunteers) in the morning, the afternoon and the evening time slots. The offices are located in the center of the city of Hasselt (Flanders region of Belgium) near the railway and bus station. This location is situated in a zone where free street-side parking is not available. Course attendants not arriving by bike, bus, train or walking have free parking available at a distance of about *1[km].*

The *Doppahuis* kindly provided us with the courses attendants list. This was used to contact candidates to ask for participation in the carpooling matching project: 1088 people agreed. Their street address and list of courses (date, time) they are enrolled in were made available in a database to feed the matching tool. A matrix for travel times and distances is pre-calculated using *GraphHopper* and used to evaluate *path similarity* among participants during the *advisory stage* of the framework. The distribution of the trip durations and distances of the *students* for *home-to-work* trip is shown in Fig. 6.5. The x-axis represents the distance (in *Km*) and duration (in *min*.) while the y-axis shows the number of students.

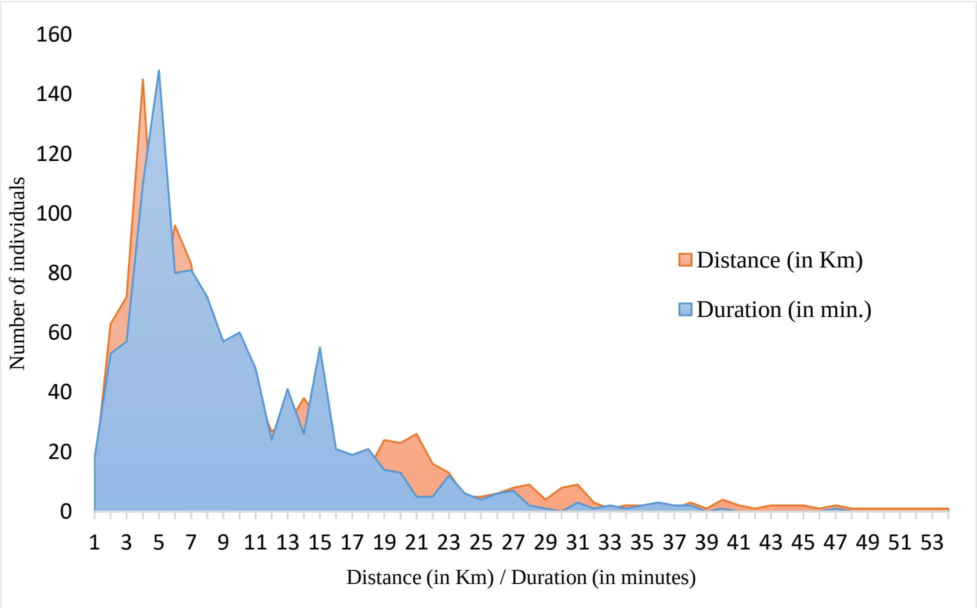


Figure 6.5. Frequency distribution of the travel duration and travel distance between home locations and Doppahuis.

Figure 6.6 shows some of proposed feasible solutions for some of the candidates. Each column represents the feasible solutions for a particular participant. All the advices provided by the matching framework look decent. Such set of proposals is sent to the candidate(s) for whom they are the best options in order to trigger negotiation. The destination of such notification is not necessarily the driver of the carpool.

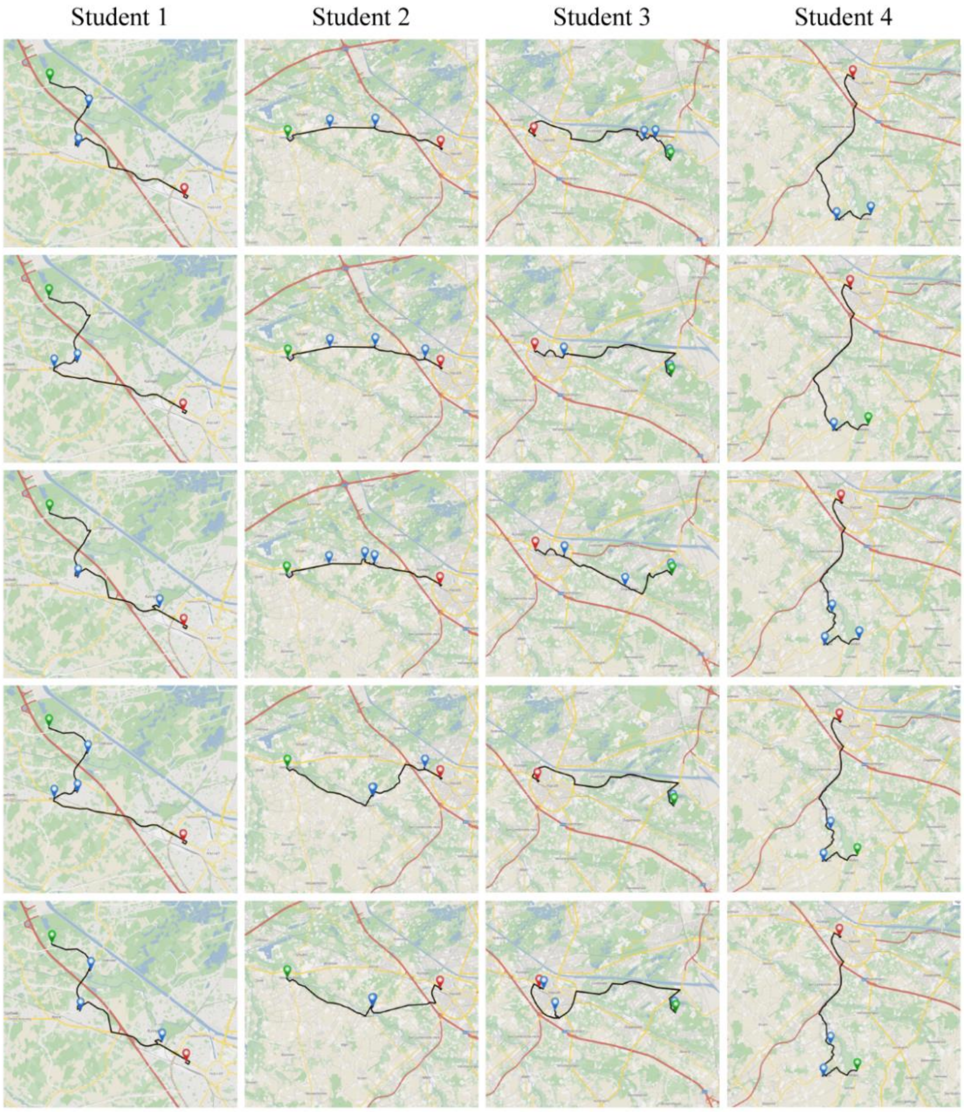


Figure 6.6. Some of feasible solutions proposed by the matching framework for the candidates. A column shows the groups and corresponding routes proposed to a particular user. The green marker represents the driver's home, the red marker represents the Doppahuis location. Blue markers indicate passenger pick up locations.

One of the major goals of our experimentation is to compute and possibly optimize the solution (execution time of the matching framework). One reason for doing this is to be able to accurately predict the time required to potential realistic carpools in the database of a large company or organization. The experiment is conducted on an Intel ® Core ™ i5-3230M CPU@2.60GHz 2.20GHz, with 4GB RAM and Windows 10 (64 bits) machine. Figure 6.7 shows the execution time of different levels of the matching framework. The x-axis represents the levels of the framework while the y-axis shows the execution time in minutes. The framework was run by extracting the *Doppahuis* database and by considering potential candidate for carpooling only. The framework is run multiple times by taking different maximum excess durations i.e. 5[min]., 10[min], 15[min], 20[min], 25[min], 30[min] and 35[min]. The relative excess values for the maximum excess durations are shown by a small graph in the same Figure 6.7. The graph shows that: (1) the matching framework took more execution time for the higher *maximum excess travel duration* values than for the smaller ones, (2) for each matching level (clique size) the framework spends more execution time to the evaluation (scoring) than to the actual cliques determination and (3) the execution time grows in a polynomial way with the increase of each level. The preselection phase took only a small portion of the execution time and it is nearly independent of the maximum excess travel duration value.

An ordered set of participants defines the passenger pick-up order. Such set is a permutation of a clique of individuals showing pairwise *time and path similarity*. Not every ordered set derived from a clique leads to a valid carpool solution (as explained above). For each carpool level, both the number of ordered sets and the number of feasible carpools are shown in Figure 6.8.

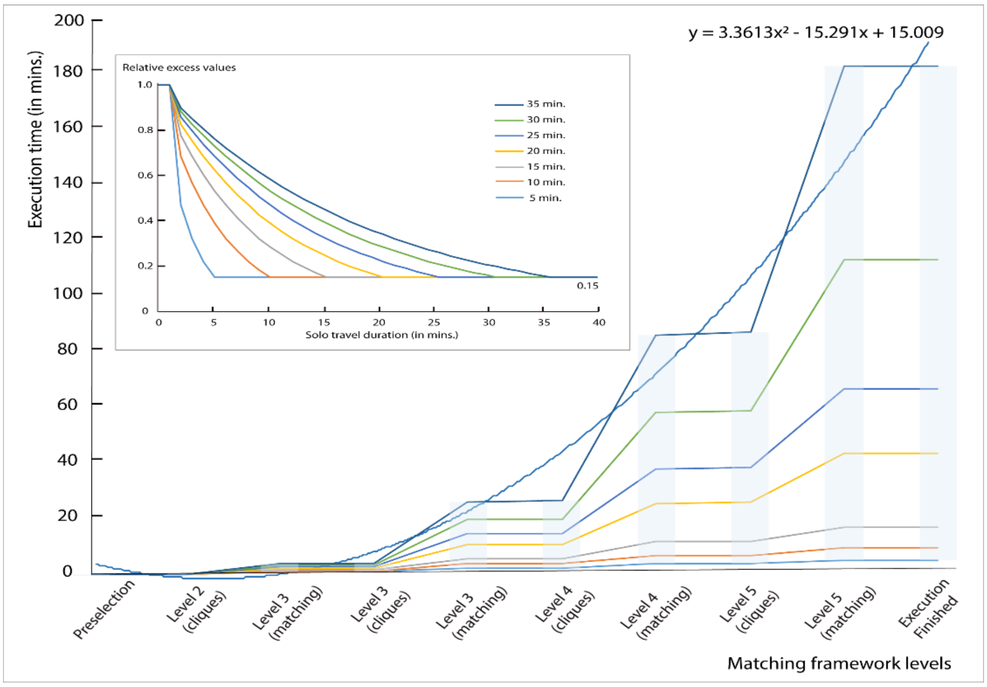


Figure 6.7. Execution time for different levels of the matching framework. Each color corresponds to one particular value for the maximum detour excess travel time.

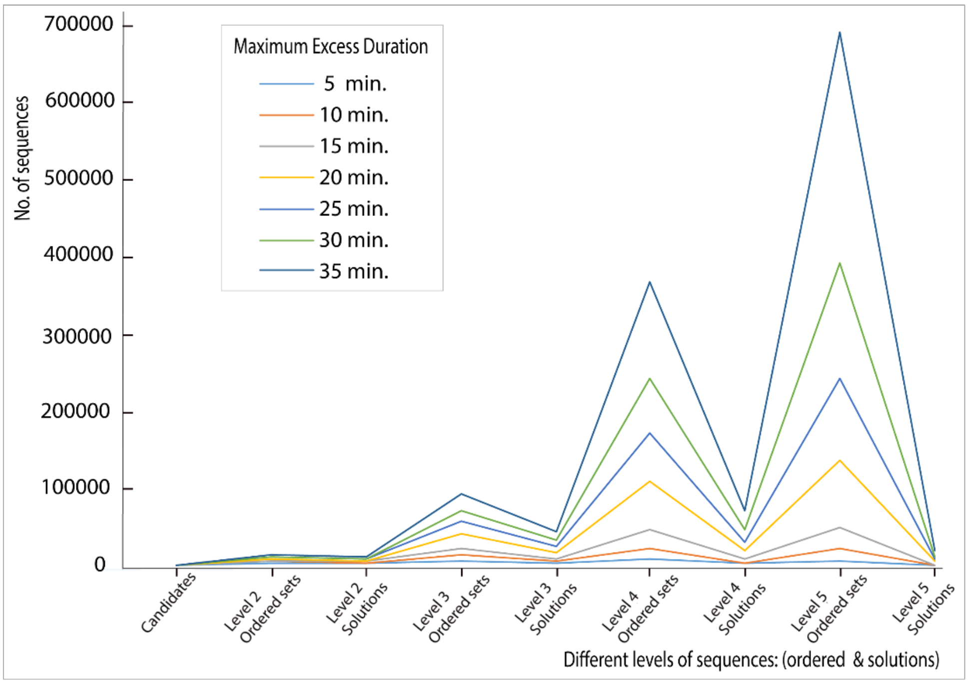


Figure 6.8. The ordered sets and the feasible solutions for different levels.

Table 6.2 represents the outcomes of different trials by passing different values of the maximum excess travel duration i.e. 5[min], 10[min], 15[min], 20[min], 25[min], 30[min] and 35[min], the same used to calculate the execution time as in Figure 6.7. The Table 6.2 shows the number of potential candidates for the carpooling (the solo drivers appearing in at least one feasible pair), and the number of ordered sets (cliques) and the feasible carpools (the solutions) for each level up to the maximum car capacity (5 in this case).

Table 6.2. Results of the experiment.

Max. Excess Dur.	**Candidates member of at least one feasible pair**	**Ordered sets (level-2)**	**Solutions (level-2)**	**Ordered sets (level-3)**	**Solutions (level-3)**	**Ordered sets (level-4)**	**Solutions (level-4)**	**Cliques (level-5)**	**Solutions (level-5)**
5[min]	981	4285	3246	7644	3651	8896	2602	7486	645
10[min]	1020	5615	4304	14420	6135	22965	5237	22372	1414
15[min]	1038	7184	5589	23751	9971	46514	9425	50258	2316
20[min]	1066	9599	7540	42736	17839	110276	19464	138157	5718
25[min]	1071	11220	8760	57701	25643	172440	31272	244627	8424
30[min]	1072	12449	9713	71733	33231	242167	46236	394023	12143
35[min]	1078	13884	10831	93423	44705	369104	71794	693727	21257

6.7 Conclusion and Future Work

This research shows the feasibility of candidates matching for recurrent travel demand. It aims to support large companies and institutions located in congested areas where parking space is expensive or scarce (which is assumed to be equivalent). Supporting carpooling by personnel contributes to the mobility plan to be established by the company. The presented framework accounts for dynamic evolution of the extracted personnel database and notifies interested candidates for carpooling about new opportunities to find partners belonging to a closed managed group. The feasible solutions shown by the experiments of the framework are optimal for the candidates (user optimal) and look decent according to our expectations. The processing speed is small enough to regenerate a new advice every night (which is required due to potential changes in the personnel database, the availability status of candidates and the timing constraints that can be modified in an ad hoc way). The proposed solution is computationally feasible because it solves a large number of small optimization problems and hence does not suffer from combinatorial explosion. This research shows the feasibility of a matching service to be set up as a pilot project in a typical organization. A feedback mechanism for registration of carpooling agreements is an essential component to be integrated before the proposed framework can be rolled out to companies and organizations. It marks individuals as no longer being exploring for partners in order to minimize the number of notifications sent to candidates.

6.8 References

Abrahamse, W., & Keall, M. (2012). Effectiveness of a web-based intervention to encourage carpooling to work: A case study of Wellington, New Zealand. *Transport Policy*, *21*(Supplement C), 45–51. https://doi.org/10.1016/j.tranpol.2012.01.005

Agatz, N. A. H., Erera, A. L., Savelsbergh, M. W. P., & Wang, X. (2011). Dynamic ride-sharing: A simulation study in metro Atlanta. *Select Papers from the 19th ISTTT*, *45*(9), 1450–1464. https://doi.org/10.1016/j.trb.2011.05.017

Agatz, N., Erera, A., Savelsbergh, M., & Wang, X. (2012). Optimization for dynamic ride-sharing: A review. *European Journal of Operational Research*, *223*(2), 295–303. https://doi.org/10.1016/j.ejor.2012.05.028

Andrew M., A. (2010, June). *Real-Time Ridesharing: Exploring the Opportunities and Challenges of Designing a Technology-based Rideshare Trial for the*

MIT Community. MASSACHUSETTS INSTITUTE OF TECHNOLOGY, Calgary, Canada. Retrieved from https://ridesharechoices.scripts.mit.edu/home/wp-content/papers/AMEY_Thesis_Final.pdf

Buliung, R. N., Soltys, K., Bui, R., Habel, C., & Lanyon, R. (2010). Catching a ride on the information super-highway: toward an understanding of internet-based carpool formation and use. *Transportation*, *37*(6), 849–873. https://doi.org/10.1007/s11116-010-9266-0

Cairns, S., Sloman, L., Newson, C., Anable, J., Kirkbride, A., & Goodwin, P. (2008). Smarter Choices: Assessing the Potential to Achieve Traffic Reduction Using "Soft Measures." *Transport Reviews*, *28*(5), 593–618. https://doi.org/10.1080/01441640801892504

Collura John. (1994). Evaluating Ride-Sharing Programs: Massachusetts' Experience. *Journal of Urban Planning and Development*, *120*(1), 28–47. https://doi.org/10.1061/(ASCE)0733-9488(1994)120:1(28)

Correia, G., & Viegas, J. M. (2011). Carpooling and carpool clubs: Clarifying concepts and assessing value enhancement possibilities through a Stated Preference web survey in Lisbon, Portugal. *Transportation Research Part A: Policy and Practice*, *45*(2), 81–90. https://doi.org/10.1016/j.tra.2010.11.001

Di Febbraro, A., Gattorna, E., & Sacco, N. (2013). Optimization of Dynamic Ridesharing Systems. *Transportation Research Record: Journal of the Transportation Research Board*, *2359*, 44–50. https://doi.org/10.3141/2359-06

Eastern Research Group. (2005). Carpool Incentive Programs: Implementing Commuter Benefits as One of the Nation's Best Workplaces for CommutersSM. National Transportation Demand Management (TDM) and Telework Clearinghouse, National Center for Transit Research, University of South Florida.

Ferguson, E. (1995). The Demographics of Carpooling. *Transportation Research Record*, *1496*, 142–150.

Ferguson, E. (2007). Transportation Management Associations: A Reappraisal. *Journal of Public Transportation*, *10*, 1–26.

Furuhata, M., Dessouky, M., Ordóñez, F., Brunet, M.-E., Wang, X., & Koenig, S. (2013). Ridesharing: The state-of-the-art and future directions. *Transportation Research Part B: Methodological*, *57*(Supplement C), 28–46. https://doi.org/10.1016/j.trb.2013.08.012

Herbawi, W. M., & Weber, M. (2012). A Genetic and Insertion Heuristic Algorithm for Solving the Dynamic Ridematching Problem with Time Windows. In *Proceedings of the 14th Annual Conference on Genetic and Evolutionary Computation* (pp. 385–392). New York, NY, USA: ACM. https://doi.org/10.1145/2330163.2330219

Huang, S.-C., Jiau, M.-K., & Lin, C.-H. (2015). Optimization of the Carpool Service Problem via a Fuzzy Controlled Genetic Algorithm. *IEEE Transactions on Fuzzy Systems*, *23*(5).

Hwang, K., & Giuliano, G. (1990). The Determinants of Ridesharing: Literature Review. University of California Transportation Center. Retrieved from http://escholarship.org/uc/item/3r91r3r4., http://uctc.berkeley.edu/research/papers/038.pdf

Karich, P. (2014). GraphHopper. Retrieved from https://graphhopper.com/

Kaufman, S. (2002). Why people (don't) carpool and change for the better: A social capital framework for investigating environmental behaviour. Presented at the 2nd National Conference of Sustainable Campuses, RMIT, Melbourne.

Kesternich, E. (2015). *What factors explain carpoolers' decision to use carpooling matching platforms?: A survey-based observation of carpooling matching platforms in Europe*. Retrieved from http://essay.utwente.nl/66952/1/Kesternich_MA_BMS.pdf

Knapen, L., & Janssens, D. (2016). *Matching to Support Carpooling in Company Context, Internal IMOB, Software requirements and design*. Transportation Research Institute (IMOB), Hasselt University, Belgium.

Knapen, L., Yasar, A., Cho, S., Keren, D., Dbai, A. A., Bellemans, T., … Bhaduri, K. (2014). Exploiting graph-theoretic tools for matching in carpooling applications. *Journal of Ambient Intelligence and Humanized Computing*, *5*(3), 393–407. https://doi.org/10.1007/s12652-013-0197-4

Levin, I. P. (1982). Measuring tradeoffs in carpool driving arrangement preferences. *Transportation*, *11*(1), 71–85. https://doi.org/10.1007/BF00165595

Li, J., Embry, P., Mattingly, S., Sadabadi, K., Rasmidatta, I., & Burris, M. (2007). Who Chooses to Carpool and Why?: Examination of Texas Carpoolers. *Transportation Research Record: Journal of the Transportation Research Board*, *2021*, 110–117. https://doi.org/10.3141/2021-13

Martinez, L. M., Correia, G. H. A., & Viegas, J. M. (2015). An agent-based simulation model to assess the impacts of introducing a shared-taxi system: an application to Lisbon (Portugal). *Journal of Advanced Transportation*, *49*(3), 475–495. https://doi.org/10.1002/atr.1283

Roby, H. (2010). Workplace travel plans: past, present and future. *Journal of Transport Geography*, *18*(1), 23–30. https://doi.org/10.1016/j.jtrangeo.2008.11.010

Steger-Vonmetz, D. C. (2005). Improving modal choice and transport efficiency with the virtual ridesharing agency (pp. 994–999). Presented at the Proceedings. 2005 IEEE Intelligent Transportation Systems, 2005. https://doi.org/10.1109/ITSC.2005.1520186

Tischer, M. L., & Dobson, R. (1979). An empirical analysis of behavioral intentions of single-occupant auto drivers to shift to high occupancy vehicles. *Transportation Research Part A: General*, *13*(3), 143–158. https://doi.org/10.1016/0191-2607(79)90066-9

Tyagi, A. K., & Niladhuri, S. (2016). Vehicular Ad Hoc Networks: New Challenges in Carpooling and Parking Services. *International Journal of Computer Science and Information Security*, *14*.

Urquhart, N. (2015). Optimising the Scheduling and Planning of Urban Milk Deliveries. In A. M. Mora & G. Squillero (Eds.), *Applications of Evolutionary Computation: 18th European Conference, EvoApplications 2015, Copenhagen, Denmark, April 8-10, 2015, Proceedings* (pp. 604–615). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-16549-3_49

Vanoutrive, T., Van Malderen, L., Jourquin, B., Thomas, I., Verhetsel, A., & Witlox, F. (2009). Carpooling and employers: a multilevel modelling approach (pp. 335–349). Presented at the In 3rd Transport Research Day, VUB Press.

Xia, J., Curtin, K. M., Li, W., & Zhao, Y. (2015). A New Model for a Carpool Matching Service. *PLOS ONE*, *10*(6). https://doi.org/10.1371/journal.pone.0129257

Part-II

Conclusions and Future Work

Motivated by the expected benefits of using the personnel databases of large employers to provide carpooling advice, a matching support framework and service for employees who are candidates for carpooling has been presented. It has aimed to support closed-group carpooling. The major contribution of this research is to present a mechanism *to find all the feasible carpool groups* for each employee using mutually compatibility indicators. A *scoring mechanism* has also been anticipated for evaluation of solutions in order to propose a limited set of the feasible carpools to each employee for further negotiation. The purpose is to propose carpool groups to individuals who shall negotiate about cooperation. As a proof-of-concept of the proposed framework, experiments were conducted at the scale of the Doppahuis database.

This section will conclude the matching support framework, as well as assemble ideas for future directions.

Summary

An innovative carpool matching advisory service has been proposed to be rolled out by large companies to expand the range of ways that employees can carpool. It has been designed to be operated by employers in order to find optimal carpool matching solutions which are to be proposed to the candidate carpoolers. It has the capability to account for dynamic evolution of the extracted personnel database in order to minimize burden on the users and notifies interested carpoolers about new opportunities to find partners belonging to a closed managed group. The framework is capable to match candidates based on home and target locations as well as on the time windows and maximum excess durations specified by the interested candidates. The innovative advisory framework proposes suitable groups of people (carpools) to the registered users. For each carpool group, the timely feasible pick-up and drop-off orders are evaluated using scoring functions. Groups are scored at the carpool level. A small set of groups having the highest scores is presented to the candidates. These are evaluated by the group members who in turn evaluate them using their own individual scoring criteria and start a negotiation to take the final decision.

This research shows the feasibility of candidates matching for recurrent travel demand. The feasible solutions shown by the experiments conducted at the scale of the *Doppahuis database* are optimal for the candidates (user optimal) and look decent according to our expectations (Figure 6.6). The required runtime is small enough to regenerate a new advice every night. This is required due to potential changes in the personnel database, in the availability status of candidates and in the timing constraints that can be modified in an ad hoc way. The proposed solution is computationally feasible because it solves a large number of small optimization problems and hence does not suffer from combinatorial explosion. This research shows the feasibility of a matching service to be set up as a pilot project in a typical organization.

Finding and Evaluating the Feasible Carpool Groups

A mechanism to find all the feasible carpool groups for each employee using mutual compatibility indicators is presented along with a *scoring mechanism*.

The matching component described in this thesis looks for groups of people who can drive together while fulfilling all constraints related to time windows, detour time loss and detour distance. Through the feedback mechanism for registration of carpooling agreements, candidates specify their day-specific constraints in a periodic scheme of fixed length (i.e. couple of weeks, group specific). The main constraints are time windows and the maximum excess durations or distances. Individuals register their availability as a driver as well as the car capacity for each day in the periodic scheme. The carpool requirements for an individual apply for a personal specified period of time. The tool determines the sets of drivers and passengers along with the particular individual constraints for every day in the periodic scheme.

The framework is designed and implemented so that generic preference functions are supported. However, the first implementation in the matching phase only supports time windows equipped with a constant preference function. For particular types of time windows more specific constraints can apply (e.g. the requirement that the preference function is continuous and differentiable in each point).

The detour or maximum excess duration is also specified by the individuals. However, the values for the parameters used in the function are based on common sense estimations which need to be validated for the study area.

The scoring mechanism provided in this research is based on the cost, time loss, degree of flexibility and the time of day scoring functions. Some of the scoring functions are extracted from the existing research but others still need further verification using the real data.

There are a variety of challenges that inhibit greater carpool participation. The accurate measurement of successful carpool trips is also one of the challenges that can likely be overcome using new technology. Additional research may try to estimate from such recordings the values for particular parameters used in the simulation models (e.g. time loss for pick-up and drop-off, variability of departure, travel and arrival times).

During this research project, various elements were identified that will require a deeper investigation. Future research shall mainly focus on a feedback mechanism for registration of carpooling agreements: this is an essential component to be integrated before the proposed framework can be rolled out to companies and organizations. It marks individuals as no longer being exploring for partners. This is required in order to minimize the number of unwanted notifications sent to candidates. The expected travel duration may take into account the traffic congestions.

Appendix A

Curriculum Vitae

Iftikhar Hussain

Researcher & Doctoral Student
Transportation Research Institute (IMOB)
Hasselt University, Campus Diepenbeek
Wetenschapspark 5 bus 6,
BE-3590 Diepenbeek Belgium

Contact Details

Tel.: +32 (0) 11 26 91 69
Fax.: +32 (0) 11 26 91 99
Email: iftikhar.hussain@uhasselt.be
Skype: iftikhar.iftikhar786

Personal Details

Place of birth	Kotli, Azad Kashmir, Pakistan
Date of birth	1981-Apr-17
Marital status	Married
Nationality	Pakistani

Educational Backgrounds

2008 – 2010 M.Sc in Computer Science, Specialization in Software Engineering
Institute: Iqra University, Islamabad Campus, Pakistan
Credits/points: 33, Grade: B+, 3.73/4.0 (83%)
Thesis title: New Approaches for Exact Pattern Matching
Supervisor: Prof. Dr. Jamil Ahmad

2003 – 2007	B.Sc in Information Technology University of Azad Jammu & Kashmir, Muzaffarabad, Pakistan Credits/points: 134,Grade: B, 3.4/4.0 Final year project: Online library management system
2012 – 2013	B.A, Diploma in Education University of Azad Jammu & Kashmir, Muzaffarabad, Pakistan Grade: B, First Division

Work Experience

2013-Sep – 2017-Oct	IMOB, Hasselt University, Belgium Job title: Researcher & PhD Student Supervisor: Prof. Dr. Davy Janssens
2014-Jan - 2014-Feb	Universite de technologie de Belfort-Montbeliard, France Research visit: Janus – Agent-based carpool simulation model
2010-Nov - 2013-Sep	Faculty of Administrative Sciences, Kotli, UAJK, Muzaffarabad, Pakistan Job title: Lecturer CS & IT
2010-Aug - 2010-Nov	Save the Children, ERRP Office Islamabad IT Assistant
2010-Jan - 2010-Aug	Ibne-Sina Model College, Kotli, AJK Lecturer, HSSC
2009-Jan - 2010-Aug (Part time)	EezeeSoftSol (Software company) Software Developer
2008-Mar - 2009-Jan (Full time)	EezeeSoftSol (Software company) Software Developer

Conferences Presentations

2-5 June 2015, Valencia, Spain	Paper title: Agent-based Negotiation Model for Long-term Carpooling: A Flexible Mechanism for Trip Departure Times, Conference title*: 21st International Conference on Urban Transport and the Environment*.
28-29 May 2015, Eindhoven, Netherlands	Paper title: An Agent-based Model for Carpooling Conference title*: Proceedings of the BIVEC/GIBET Transport Research Days 2015*.
18-19 May 2017, Liege, Belgium	Paper title: Employees' Matching to Support Carpooling in Context of Large Companies, Conference title*:* Proceedings of the BIVEC/GIBET Transport Research Days 2017.

Appendix B

List of Publications

ISI-Indexed Journals

(Published)

1. Iftikhar Hussain, Luk Knapen, Stéphane Galland, Ansar-Ul-Haque Yasar, Tom Bellemans, Davy Janssens & Geert Wets, Organizational-based model and agent-based simulation for long-term carpooling, *Future Generation Computer Systems*, Volume 64, 2016, Pages 125-139, ISSN 0167-739X.
2. Iftikhar Hussain, Luk Knapen, Ansar-Ul-Haque Yasar, Tom Bellemans, Davy Janssens & Geert Wets, Negotiation and Coordination in Carpooling: Agent-Based Simulation Model, *Transportation Research Record: Journal of the Transportation Research Board*, 2016, Volume 2542:, pages 92-101, DOI: 10.3141/2542-11.

(Submitted for Review)

1. Iftikhar Hussain et *al.*, Agent-based simulation of individual matching and mobility behavior in carpooling, *Transportation Research Part C: Emerging Technologies*, 2017.
2. Iftikhar Hussain et *al.*, Agent-based carpooling model for individuals matching using disaggregated street addresses, *IEEE Transactions on Intelligent Transportation Systems*, 2017.
3. Iftikhar Hussain et *al.*, Matching Framework for Employees to Support Carpooling in Context of Large Companies, *IEEE Intelligent Transportation Systems Magazine (ITSM)*, 2017.
4. Iftikhar Hussain et *al.*, Organizational-based model and agent-based simulation for co-traveling at aggregate level, *Applied Sciences (Special Issue: Multi-agent Systems)*, 2017.

Other Journals

(Published)

1. Iftikhar Hussain, Luk Knapen, Stephane Galland, Ansar-Ul-Haque Yasar, Tom Bellemans, Davy Janssens, Geert Wets, Agent-based Simulation Model for Long-term Carpooling: Effect of Activity Planning Constraints, *Procedia Computer Science*, Volume 52, 2015, Pages 412-419, ISSN 1877-0509.
2. Iftikhar Hussain, Luk Knapen, Stephane Galland, Davy Janssens, Tom Bellemans, Ansar-Ul-Haque Yasar, Geert Wets, Organizational and Agent-based Automated Negotiation Model for Carpooling, *Procedia Computer Science*, Volume 37, 2014, Pages 396-403, ISSN 1877-0509.
3. Iftikhar Hussain, Syed Zaki Hassan Kazmi, Israr Ali Khan and Rashid Mehmood, Improved-Bidirectional Exact Pattern Matching, *International Journal of Scientific & Engineering Research,* Volume 4, Issue 5, May-2013, pages 659-663, ISSN 2229-5518.
4. Iftikhar Hussain, Samina Kausar, Liaqat Hussain & Muhammad Asif Khan, Improved Approach for Exact Pattern Matching: Bidirectional Exact Pattern Matching, *IJCSI International Journal of Computer Science Issues*, Vol. 10, Issue 3, No 1, May 2013, ISSN (Print): 1694-0814 | ISSN (Online): 1694-0784.

Conferences / Proceedings

(Published)

1. Iftikhar Hussain, Luk Knapen, Tom Bellemans, Davy Janssens & Geert Wets, *Employees' Matching to Support Carpooling in Context of Large Companies,* In: *BIVEC/GIBET Transport Research Days 2017*, 2017.
2. Iftikhar Hussain, Luk Knapen, Muhammad Arsalan Khan, Tom Bellemans, Davy Janssens & Geert Wets, Agent-based Negotiation Model For Long-term Carpooling: A Flexible Mechanism For Trip Departure Times, *In the proceedings of the 21st International Conference on Urban Transport and the Environment*, Volume 146, 2015, Pages 461-473.
3. Iftikhar Hussain, Luk Knapen, Tom Bellemans, Davy Janssens & Geert Wets, An Agent-based Negotiation Model for Carpooling: A Case Study for Flanders

(Belgium). *In: The Transportation Research Board (TRB)*, 94th TRB Annual Meeting, 2015.

4. Iftikhar Hussain, Luk Knapen, Bruno Kochan, Tom Bellemans, Davy Janssens & Geert Wets, *An Agent-based Model for Carpooling: Effect of Strict Timing Constraints on Carpooling Trips,* In: *BIVEC/GIBET Transport Research Days 2015*, 2015.

5. Iftikhar Hussain, Imran Ali, Muhammad Zubair and Nazarat Bibi, Fastest approach to exact pattern matching, *2010 International Conference on Information and Emerging Technologies*, Karachi, 2010, pp. 1-5. doi: 10.1109/ICIET.2010.5625685.

6. Iftikhar Hussain, Muhammad Zubair, Jamil Ahmed and Junaid Zaffar, Bidirectional exact pattern matching algorithm, *2010 International Conference on Modern Problems of Radio Engineering, Telecommunications and Computer Science (TCSET)*, Lviv-Slavske, 2010, pp. 293-293.

7. Muhammad Zubair, Fazal Wahab, Iftikhar Hussain and Junaid Zaffar, Improved text scanning approach for exact String matching, *2010 International Conference on Information and Emerging Technologies*, Karachi, 2010, pp. 1-5, doi: 10.1109/ICIET.2010.5625719.

8. Muhammad Zubair, Fazal Wahab, Iftikhar Hussain and Muhammad Ikram, Text scanning approach for exact string matching, *2010 International Conference on Networking and Information Technology*, Manila, 2010, pp. 118-122, doi: 10.1109/ICNIT.2010.5508548.