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Section 27- Informatique

Une approche multidisciplinaire pour l'inclusion des personnes handicapées dans les systèmes de transport public : management, optimisation et aide à la décision

Présentée et soutenue par : Danijela DORIC

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Ph.D. Thesis

Submitted for the degree of Doctor of Philosophy from

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Section 27 - Computer Science

A multidisciplinary approach to the inclusion of persons with disabilities in a public transport system: Management, Optimization, and Decision Aiding (MODA)

Presented and defended by Danijela DORIC

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Abstract

Without question, alongside human rights, one of the primary motives for investigating the inclusion of persons with disabilities is that they total one billion worldwide, which gives this topic the highest level of urgency in providing their full inclusion in society. According to the World Health Organization report, this number represents 15% of the world population. Consequently, the inclusion of Persons With Disabilities (PWD) in the domain of public transport is exceptionally significant. Public transportation is a crucial matter for PWD as part of their inclusion in society. The provision of a fully accessible service for PWD in public transport systems is a long and complex process, which involves many parties. The diversity of PWD needs, and the interactions between these needs and transport organizations, demonstrate this process's complexity. To the best of our knowledge, this research states for the first time the criteria of the 5As (**A**vailability, **A**ccessibility, **A**cceptability, **A**ffordability, and **A**daptability) that address PWD needs concerning transport optimization models. The research purpose of using these 5As is to empower the independence of PWD mobility in using the transport system by showing the adequacy of existing transportation optimization models for PWD, such as transportation on demand and constrained shortest path problems.

The breakdown of this complex problem began by applying the decision-aiding process (DAP). The first DAP phase identified the problem's participants and defined their stakes within three decision levels: - strategic, tactical, and operational. In this phase, management is recognized as a discipline that could capture several different organization domains and ponderate equal utilization of three different approaches in this thesis. Additionally, knowledge management provided a systematic review of the optimization models concerning the 5As, and the legislative review formed an essential part of defining PWD rights.

In the second DAP phase, the matrix of different decision fields is developed by the needs and obstacles for PWD transport inclusion with the specific actions they could carry out. The DAP led to a comprehensive analysis, enabling the selection of a suitable transportation model for the inclusion of disabled persons. An integrative framework of optimization model correlations was developed, relating to public network information, specifically the accessibility of the public network. This analysis demonstrated optimization models of transport-on-demand, and the shortest path provided partial independence for PWD.

Those optimization models are more oriented to improving company organizational performance than the advancement of the independent mobility of PWD. These two models give different ways of providing the solution to PWD transport with different organizational frames. The integration and coordination of these models along the PWD transportation journey provide the missing link in the same chain, leading to the clustering approach.

The clustering approach operated in two directions by employing both the network and user data. From the real data set of “on-demand” service transport, the clustering provides an analysis of the PWD transport flow, with the geo-location of PWD using existing hub locations on the network. Further research has generated several situations with various clusters, reporting 23% of satisfied PWD users in the case of five clusters. One of the thesis's key findings is the practical implementation of the decision-aiding process, with the problem reframing from the transport on-demand and shortest path optimization models to the clustering approach. The application of cluster analysis of the public transport network in Valenciennes presents a further contribution.

Keywords: *Decision aiding process, transportation, optimization models, management, public transport, persons with disabilities*

Résumé

Sans aucun doute, à côté des droits de l'homme, l'un des principaux motifs d'étudier l'inclusion des personnes handicapées (PH) est qu'ils totalisent un milliard dans le monde, ce qui confère à ce sujet le plus haut niveau d'urgence pour assurer leur pleine intégration dans la société. Selon le rapport de l'Organisation mondiale de la santé, ce nombre représente 15% de la population mondiale. Les transports publics sont une question cruciale pour les PH dans le cadre de leur intégration dans la société. L'offre d'un service entièrement accessible aux PH dans les systèmes de transport public est un processus long et complexe qui implique de nombreuses parties. La diversité des besoins des PH et les interactions entre ces besoins et les organisations de transport démontrent la complexité de ce processus. Cette recherche, à la pointe de nos connaissances, énonce pour la première fois les critères des 5A (Disponibilité, Accessibilité, Acceptabilité, Abordabilité et Adaptabilité) qui répondent aux besoins des PH concernant les modèles d'optimisation des transports. Le but de l'utilisation de ces 5A est de renforcer l'indépendance de la mobilité des PH dans l'utilisation du système de transport en montrant l'adéquation des modèles d'optimisation, tels que le transport à la demande et les problèmes liés aux trajets les plus courts.

La décomposition de ce problème complexe a commencé par l'application du processus d'aide à la décision (PAD). La première phase du PAD a identifié les acteurs du problème et défini leurs enjeux au sein de trois niveaux de décision: - stratégique, tactique et opérationnel. Dans cette phase, la gestion est reconnue comme une discipline qui pourrait appréhender plusieurs domaines d'organisation différents et peser l'utilisation égale de trois approches différentes dans cette thèse. De plus, la gestion des connaissances a fourni une revue systématique des modèles d'optimisation concernant les 5A et la revue législative a constitué un élément essentiel de la définition des droits des PH.

Dans la deuxième phase du PAD, la matrice des différents champs de décision est développée en fonction des besoins et des obstacles pour l'inclusion du transport des PH avec les actions spécifiques qu'elles pourraient mener. Le PAD a conduit à une analyse complète, permettant de sélectionner un modèle de transport adapté à l'inclusion des personnes handicapées. Un cadre intégratif de corrélations de modèles d'optimisation a été développé, relatif aux informations du réseau public, en particulier son accessibilité. Cette analyse a démontré l'aptitude des modèles d'optimisation du transport à la demande et de plus court chemin à fournir une indépendance partielle aux PH. Ces deux modèles offrent différentes manières de fournir la solution au transport des PH avec des cadres organisationnels différents. L'intégration et la coordination de ces modèles tout au long du parcours de transport des PH fournissent le chaînon manquant dans la même chaîne, conduisant à l'approche de regroupement.

L'approche de clustering fonctionne dans deux directions en utilisant à la fois le réseau et les données utilisateur. À partir de l'ensemble de données réelles de services de transport « à la demande », le clustering fournit une analyse du flux de transport des PH, avec la géolocalisation, en utilisant les emplacements de hub existants sur le réseau. Des recherches plus poussées ont généré plusieurs situations avec différents clusters, faisant état de 23% d'utilisateurs de PH satisfaits dans un cas de cinq clusters. L'une des principales conclusions de la thèse est la mise en œuvre pratique du processus d'aide à la décision, avec le recadrage du problème à partir des modèles d'optimisation du transport à la demande, et de plus court chemin vers l'approche de clustering. L'application de l'analyse par clustering du réseau de transport public à Valenciennes présente une contribution complémentaire.

Mots clés: *Processus d'aide à la décision, transport, modèles d'optimisation, gestion, transports en commun, personnes handicapées*

Apstrakt

Bez sumnje, pored ljudska prava, jedan od primarnih motiva za istraživanje inkluzije osoba sa invaliditetom je taj da oni ukupno čine milijardu širom sveta, što ovoj temi daje najviši nivo hitnosti u obezbeđivanju njihovog potpunog uključivanja u društvo. Prema izveštaju Svetske zdravstvene organizacije, ovaj broj predstavlja 15% svetske populacije. Shodno tome, uključivanje osoba sa invaliditetom (OSI) u domen javnog prevoza je izuzetno značajno. Javni prevoz predstavlja ključno sredstvo za OSI kao deo njihovog uključivanja u društvo. Pružanje potpuno dostupne usluge za OSI u sistemima javnog prevoza je dug i složen proces sa velikim brojem učesnika. Raznolikost potreba za OSI i interakcija između ovih potreba i transportnih organizacija pokazuje složenost ovog procesa. Ovo istraživanje, prema našim saznanjima, prvi put uvodi kriterijume 5A (dostupnost, pristupačnost, prihvatljivost, pristupačnost i prilagodljivost) koji se bave potrebama OSI u odnosu na modele za optimizaciju transporta. Svrha istraživanja korišćenja 5A je osnaživanje nezavisne mobilnosti OSI u korišćenju transportnog sistema pokazujući adekvatnost postojećih modela optimizacije prevoza za OSI, kao što su prevoz na zahtev i problem najkraćeg puta.

Raščlanjivanje ovog složenog problema započeto je primenom procesa pomoći u odlučivanju (PPO). Prva PPO faza identifikovala je učesnike u problemu i definisala njihov uloge na tri nivoa odlučivanja: - strateškom, taktičkom i operativnom. U ovoj fazi menadžment je prepoznat kao disciplina koja može obuhvatiti nekoliko različitih organizacionih domena i uravnotežiti procenat korišćenja različitih pristupa u tezi. Pored toga, upravljanje znanjem pružilo je sistematski pregled modela optimizacije koji se odnose na 5As, a zakonodavna revizija činila je važan deo definisanja prava OSI.

U drugoj PPO fazi, matrica različitih polja odlučivanja sačinjena je prema potrebama i preprekama za uključivanje u transport OSI sa specifičnim akcijama koje bi mogle da se preduzmu. PPO je doveo do sveobuhvatne analize koja je omogućila izbor odgovarajućeg modela prevoza za uključivanje osoba sa invaliditetom. Razvijen je integrativni okvir korelacije modela optimizacije koji se odnosi na informacije o javnoj mreži, posebno na pristup javnoj mreži. Ova analiza je pokazala da optimizacioni modeli transport na zahtev i najkraći put pružaju delimičnu nezavisnost OSI.

Ovi modeli optimizacije su više orijentisani ka poboljšanju organizacionih performansi preduzeća nego na unapređenje nezavisne mobilnosti OSI. Ova dva modela daju različite načine pružanja rešenja za transport OSI sa različitim organizacionim okvirima. Integracija i koordinacija ovih modela tokom transportnog putovanja OSI pružaju kariku koja nedostaje u istom lancu, što dovodi do pristupa klasterovanja.

Pristup klasterovanja funkcionisao je u dva pravca, koristeći mrežne i korisničke podatke. Na osnovu realnog skupa podataka o transportnim uslugama „na zahtev“, klaster pruža analizu transportnog toka OSI, sa geolokacijom OSI koristeći postojeća čvorišta na mreži. Dalja istraživanja generasala su nekoliko situacija sa različitim brojem klastera, postižući 23% zadovoljnih korisnika OSI u slučaju od pet klastera. Jedno od ključnih nalaza teze je praktična primena procesa donošenja odluka, sa redefinisanjem problema modela optimizacije transport na zahtev i najkraći putem ka klasterovanju. Primena klaster analize na javnu mrežu prevoza u Valensijenu predstavlja još jedan doprinos.

Ključne reči: *Proces pomoći u odlučivanju, transport, modeli optimizacije, upravljanje, javni prevoz, osobe sa invaliditetom*

Preface

This thesis is a part of the project: “*ACCROCHE ACTIVE! Pour une jeunesse mobilisée et actrice de son avenir”* (Accroche Active, For a mobilized youth and role of its future), identified as the ValMobile action. The Valenciennes Métropole Agglomeration Community supports the project within the framework of the “*Programme d’Investissement d’Avenir Jeunesse*” (Future Investment Program for Youth), by the “*Agence nationale pour la Rénovation Urbaine - ANRU*” (National Urban Renewal Agency). The ValMobile is led by the “*Pôle De Recherche Et D’innovation En Mobilite Et Handicap de la région Hauts-de-France – PRIMoH*” (Mobility and Disability Research and Innovation Center of the Hauts-de-France region).

The present research work has also been carried out in the context of the LIA (International Associate Laboratory) ROI-TML (Operational Research and Computer Science in Transportation, Mobility and Logistics) between the LAMIH UMR 8201 (France) and the CIRRELT (Canada).

I gratefully acknowledge the support of the ValMobile project and these laboratories and relating institutions.

Acknowledgments

My academic development did not take the standard path of a Ph.D. student. Namely, before my Ph.D. studies, I had ten years of working experience. During one of my last stops at the European Agency for Railways, I met the remarkable lady who sowed the seeds of my Ph.D. studies. Without you, dear late Carolina Fischer, I would probably not have taken this road. Thank you wherever you are. You will always be in my prayers and thoughts.

At the beginning of my academic years, I was given the great opportunity to work with Professor Nenad Mladenović to whom I am very grateful for all his advice on how to become a good researcher. I am especially grateful to Professor Abdelhakim Artiba, who saw potential in me and thus enabled me to become a Ph.D. student.

I would not have this title today without my supervisors. Many thanks to Professor Saïd Hanafi for accepting me as his student and letting me be myself; it is a great honor. Many thanks to HDR Igor Crévits, who introduced me to the process of Decision-aiding, who taught me that "no reaction is also action," and who dealt daily with my "scientific doubts." Many thanks to Professor Yan Cimon, who has always found time to support me and help me through all my difficulties despite his busy schedule. He has shown me that another world exists by always offering another – more positive – point of view, thus helping me keep my smile. Many thanks to Raca Todosijević Ph.D. for everything; there are no words to express my gratitude and happiness that you are my supervisor, my colleague, and above all, my friend. Once more: "Merci mes directeurs".

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I have to go back to my home university and express my gratitude to my professors at the Faculty of Transport and Traffic Engineering, University of Belgrade, for their support and cooperation before and during my Ph.D. studies.

Valenciennes has presented me with the gift of one incredible experience so I even have a French family now: Ingrid Serman, thank you for existing and for opening the door of your home to me! Many thanks to all my friends here, especially for two extraordinary ladies Valérie and Pascale. Since I first arrived in Valenciennes in 2013 and after more than six years at the university, it is almost impossible to name all the people whose roads I have crossed. Still, all of them are deep in my heart and mind. I would like to thank them by their institutions: many thanks to my labmates and the whole LAMIH team – administrative staff, colleagues, professors; to my colleagues and friends from ERA and "Alliance française." It is a pleasure and honor for me to be called your friend and colleague.

During my studies, I went twice to Laval University, CIRRELT, City of Quebec, Canada, where I had an amazing nine-month experience: hospitable, polite, friendly, ever so helpful are the words that could best describe my Canadian colleagues and friends. Thank you for sharing your time and friendship with me, dear Charles Fahridine, Pierre Marchand, Louise Doyon, Mireille Leclerc, Marion Voisin, Maryam Darvish, Imadeddine Aziez, Roberto Cantu-Funes, Carise Schmidt. I hope I did not forget anyone. And one special thanks to Lucie Fortin for all her scheduled meetings.

I would like to thank my colleagues and friends from Montenegro; we worked for three years together only, but we became friends. To one terrific woman, Željka, my special gratitude for being a part of my life.

They say you are worth as much as you have friends. So I could say that I am a wealthy woman. But also they say, the real value of friendships is how long they last. This is the achievement I am most proud of. I still have my kindergarten friend Slađa and elementary school friends Cicojka, Dželena, Peđa, Pera, Joca, and Verka whose maid of honor I was lucky to be; my college friends Mićoni, Lale, Stole; my university friends Žaba, Madža, Ana, Ruža, Kolja, Gogi, Žarko, Slavica, Elena. Thank you for all these years, for love and support even when I lost faith in myself. Special thanks to Lepotica for all our online parties and our nights spent crying together. You made my life easier and funnier.

Although our story isn't as long as my other friendships, your unreserved support and firsthand tips on running the last mile of my thesis are unforgettable: Thanks Zoki for being a part of this journey and making it all the sweeter.

In Serbia, we are very close to our family and relatives. I have a lot of uncles, aunts, sisters, brothers, and I will name them by their last names. Thank you, my Kneževići, Vulovići, Rankovići, Kovačevići, Dražanjci, Šepšinci, Jovanovići, Živkovici, Krzmani, Bojati, Đorići, Đorđevići, Vujići. I am grateful to have you in my life. Special thanks to my Caca, Deda, Ješa, and Cojka for making your homes mine.

They come last in my list but first in my heart: my highest gratitude to my parents, Dobrica and Dragica, for everything they taught me. I am proud to be your daughter. Many thanks to my sister Jelena and brother-in-law Ivan for being around me whenever was necessary, to my nephews, Stefan and Jana, the enormous loves of my life. Their hugs and kisses drove me back home whenever possible.

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List of Abbreviations

Shortened term	Full title
ANRU	*Agence nationale pour la Rénovation Urbain - ANRU"* (National Urban Renewal Agency)
ATPDR	Accessible Transportation for Persons with Disabilities Regulations, Canada
DAP	Decision – aiding process
DARP	Dial-a-Ride Problem
DAS	Demand Adaptive System
DRBRP	Demand Responsive Bus Routing Problem
EN	European Standard
EU	European Union
FTS	Semi-Flexible Transport System
IDARP	Integrated Dial-a-Ride Problem
ICF	International Classification of Functioning, Disability, and Health
GTFS	General Transit Feed Specification
MAST	Mobility Allowance Shuttle Transit
MOSPP	Multi-Objective Shortest Path Problem
MSPP	Multimodal Shortest Path Problem
MSSC	Minimum Sum-of-Squares Clustering
PRIMoH	*Pôle De Recherche Et D'innovation En Mobilite Et Handicap de la région Hauts-de-France* (Mobility and Handicap Research and Innovation Center of the Hauts-de-France region)
PWD	Persons with disabilities
RCSPP	Resource-Constrained Shortest Path Problem
SDA	*Schéma Directeur d'Accessibilité des services de transports*

SIMOUV	*Syndicat Intercommunal de Mobilité et d'Organisation Urbaine du Valenciennois* (Inter-municipal Syndicate of Urban Transport of the Valenciennes Region)
SNCF	*Société nationale des chemins de fer français* (French National Railway Company)
SPP	Shortest path problem
SPTS	Scheduled Paratransit Transport System
TDSPP	Time-Dependent Shortest Path Problem
TER	*Transport express regional* (Regional express transport)
TSI	Technical specifications for interoperability
TSI-PRM	Technical specifications for interoperability relating to the accessibility of the Union's rail system for persons with disabilities and persons with reduced mobility
TAP-TSI	Technical specification for interoperability relating to the subsystem "telematics applications for passengers' services" of the trans-European rail system
WB	World Bank Group
WHO	World Health Organization
WRD	World Report on Disability
UN	United Nations
UNCRPD	United Nations Convention on the Rights of People with Disabilities

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Biography

Danijela Doric was born in Belgrade, Serbia, in 1979. She obtained her M.Sc. from the University of Belgrade, Faculty of Transport and Traffic Engineering, in 2007. She then gained around ten years of work experience, progressing from assistant to decision-maker through a private international transport company, the Ministry of Transportation, the European Agency for Railways, Research Center for Railways, and the University. Throughout her career, her primary motivation has been to optimize the accessibility of public transport systems using different organizational, practical, and policy approaches.

In 2015 she attended the University Polytechnique Hauts-de-France Department of Computer Science in the Laboratory of Industrial and Human Automation Control, Mechanical Engineering, and Computer Science (LAMIH). She joined as a research engineer, and in 2017 she became a Ph.D. candidate.

In 2019, she received an international scholarship from the Quebec Research Fund, Nature and Technology, one of Canada's main research funds. This enabled her to spend six months at the Interuniversity Research Centre of Enterprise Networks, Logistics and Transportation (CIRRELT), a global leader in transport research.

The Centre also offered her a scholarship in 2018. Her research was also supported by the French Organisation for Operational Research (GDRRO), a funding program for international Ph.D. exchange students.

Danijela currently works as a teaching and research temporary agent (ATER) at the University Polytechnique Hauts-de-France, the National Institute of Applied Sciences (INSA) (for teaching), and LAMIH (for research).

Introduction

The integration of persons with disabilities attracts a lot of attention, particularly now, when it is estimated that one billion people live with disabilities worldwide. The World Health Organization reports that this represents 15% of the world population, which adds urgency to the inclusion of persons with disabilities (PWD) in public transport (World Health Organization, 2011). PWD consider that public transport is a fundamental system for their inclusion in society. Inclusion in public transport systems is a human right and has positive economic consequences for both PWD and society. The autonomy of mobility in the use of public transport supports PWD as workers, customers and suppliers, and their contribution to all aspects of society (Kett, Cole, & Turner, 2020). The utility of the transport system highlights PWD as a recovered group of transport users, and the associated increase of transport customers increases revenue when PWD user groups are included. Economically and socially, the goal is to provide equal opportunities for PWD to use the transport system freely. PWD have reported that obstructions to access public transport profoundly impact their daily lives (Jette & Field, 2007). Comprehensive advances in the flexibility of transport systems facilitate the autonomous mobility of PWD.

The term for persons with disabilities will be explained at the outset since several terms are currently used for "*Persons With Disabilities*." This term was adopted as the most appropriate for the needs of this study. The term aligns with the definition of disability: - "Disability is the umbrella term for impairments, activity limitations, and participation restrictions, referring to the negative aspects of the interaction between an individual (with a health condition) and that individual's contextual factors (environmental and personal factors) (World Health Organization, 2011, p. 4)" (Leonardi, Bickenbach, Ustun, Kostanjsek, & Chatterji, 2006; World Health Organization, 2011)."

The United Nations also uses this term in the Convention on the Rights of persons with disabilities (United Nations, 2006). This research is supported by many studies, where different terms are used, such as people with reduced mobility, people with limited mobility, seniors, etc. It was necessary to state that seniors have also been included in the category "persons with disabilities." Persons with disabilities (PWD) include sub-groups with particular needs, and types of disability (physical, intellectual, and motor, visual) generate diverse specific requirements to enable the use of public transport. This thesis is limited to the consideration of PWD wheelchair users.

The research conducted for this thesis has focused on the inclusion of disabled persons in public transport systems, supporting their full autonomy without the intervention of the network. Existing studies have not addressed all issues simultaneously or considered all elements in their model development. Several operational research models have investigated transport on-demand themes with all their variants and the shortest path problem. Moreover, these optimization models are proposed as a possible solution to the problem in one of the ValMobile project axes that supported this research.

Additionally, the stated optimization models play a more significant part in improving company organizational performance beyond service quality for PWD. PWD needs are addressed by the quality of the public transport service, particularly transport-on-demand, but only a small percentage of research has explored this question (Paquette, Cordeau, & Laporte, 2009). Even when it is the case, the quality of service is presented through objective functions such as user time preference, maximum user ride time, and service duration, etc. (Cordeau & Laporte, 2003a, 2007; Ho et al., 2018; Molenbruch, Braekers, & Caris, 2017).

For the first time, this research incorporates the 5As criteria that summarise PWD needs: Availability, Accessibility, Acceptability, Affordability, and Adaptability, as defined by U.S. Government Accountability Office (Shrestha, Millonig, Hounsell, & McDonald, 2017; U.S. Government Accountability Office (GAO), 2004). The research purpose of using the 5As is to empower independent PWD mobility in using the transport system by showing the adequacy of existing transportation optimization models for PWD. A complete analysis is achieved through various regulatory levels, studies of PWDs needs, technical requirements (accessibility), and transport models.

Enabling full access of PWDs to public transport systems is complex, involving many participants. The diversity of PWD needs and the interactions between these needs increases this complexity. An interdisciplinary approach was used to investigate this issue through discipline management, decision-aiding, and optimization. A multidisciplinary approach was used, as the problem includes several aspects that a single discipline could not fully capture. Optimization and decision-aiding were identified initially, and the regulations enforced in institutions at different decision levels required the discipline of management. These three disciplines constitute the foundations of the thesis.

The identification of PWD needs and opportunities for inclusion was carried out with management and decision aiding. The management discipline is used as a framework for the organization's representation of optimization models through a systematic review supported by the analysis of optimization models for the transport of PWDs. This included the optimization domain, along with the analysis of the transport on-demand and shortest path models and the implementation of the clustering approach. This multi-disciplinary approach was based on integrating ideas from different fields that responded to the stated problem. The structure of this multidisciplinary integration process is similar to the structure applied to decision-making, where the leading role is on decision-aiding performance. The decision-aiding process, one of the decision-aiding tools, was used as an overall approach to structure this thesis (Crévits, 2013).

The processes of this thesis are diverse. The breakdown of this complex problem started by using the approach of the decision-aiding process (DAP). The first DAP phase identified the actors (participants) involved in the problem and defined objectives (stakes) within three decision levels: - strategic, tactical, and operational. In this phase, management was recognized as a discipline that could consider several different organization domains ponderate equal utilization of three different approaches in this thesis. Additionally, knowledge management systematically reviewed the optimizations models concerning the 5As, and the legislative review forms an essential part of addressing PWD rights.

The second DAP phase - the matrix of different decision fields - is developed from the needs of and obstacles to transport inclusion of PWDs, with the specific actions that can be carried out. The needs are presented through the 5As, with detailed incorporated plans for all tasks. For example, accessibility is separated into five major groups:- i) information and travel training; ii) pedestrian footways and street crossings; iii) public transport stops and station infrastructure; iv) public vehicles, and v) private modes of transportation. In addition, the matrix generates the institutions that are in charge of specific areas and could be engaged for possible actions.

Furthermore, the decision-aiding process led to a comprehensive analysis, enabling the selection of a suitable transportation model for PWD inclusion. The research is supported by an integrated framework of optimization model correlations relating to public network information, specifically on the accessibility of the public network. The research results are that investigated models, transport-on-demand, and the shortest path are solutions to one part of the problem. Typically, their objective functions focus on maximizing the use of organizational capacities or minimizing cost.

In addition, they do not have the same organizational parameters. The transport-on-demand aims to mobilize internal resources to meet demand and schedule the activities on a daily basis. In contrast, the shortest path enables response to a request without extra activities inside the organization and relies on a network configuration. The first relates to centralized management transport network models, while the second relates to decentralized transport organizations. Two different organizational structures that generate two different ways of responding to requests are brought together using a clustering approach. Using the available data set of the transport-on-demand service, we developed a clustering approach to analyze the transport flow of PWD. The findings are supported by a graphical analysis of departures and arrivals relative to existing hub locations on the network.

One of the main methodological contributions of the thesis is the practical deployment of the decision-aiding process (Tsoukiàs, 2007, 2008). As mentioned before, we used the management discipline to balance three different approaches in the thesis. There was no room to explain the theoretical contribution as part of the decision-aiding process to respect the different disciplines' uniform representation in the thesis. However, the main point of the constructive approach, one of the decision-aiding approaches used in this thesis, confirms the importance of how the problem is formulated, which is valued as highly as the solution. (Dias & Tsoukiàs, 2003; Meinard & Tsoukiàs, 2019; H. A. Simon, 1983; Tsoukiàs, 2008).

In addition to the DAP methodological contribution to the thesis structure and the chapter constructions, DAP provides several other research benefits. The first is recognizing and gathering all participants in the PWD transport chain, with the potential stakes they bring to the process. These participants are divided into three decision levels, depending on their status. This contribution helped position the French project client Metropole Valenciennes, a public institution (agglomeration/municipality).

The second contribution is the matrix of different decision fields. Matrix 20x5 provided a clear picture of all possible actions that institutions can perform to meet PWD needs. It also showed the relationship between the institutions and the 5As as PWD needs, generating a feasible solution to the thesis research problem. Also, the matrix defined a further problem formulation: - **How to frame current optimization models that fit the characteristics of a public network to enable full autonomy for PWD without interrupting the transport journey.** The evaluation model, which presents the thesis contribution, gives the answer to this problem formulation: - the integrative framework of optimization models' correlations to public network information.

Now we arrive at the crucial contribution: - the reframing of the problem. This is an action that is usually avoided in traditional operational research (Rosenhead, 2006; Rosenhead & Mingers, 2001; Tsoukiàs, 2007). The evaluation model has shown that the initial optimization transportation models, transport on-demand, and the shortest path respond to the problem partially. Instead of introducing a new constraint or developing a new methodology for solving familiar transportation models, we decided to introduce a new optimization technique as an analytic tool and a model to integrate the two models defined earlier.

Another important consideration in selecting the clustering method was the availability of data. The clustering contribution can be considered in two respects. Firstly, the coordination of existing optimization models (transport-on-demand and shortest path) provides a new way of integrating operational research models in the transport journey. Secondly, the clustering approach uses both the network and user data. By using the real data set of “on-demand” service transport, clustering provides an analysis of PWD transport flow, including geo-location of PWD, using existing hub locations on the network. One of the clustering solutions reported 23% of satisfied users in a case of five clusters with all users. The optimum number of clusters converge to the numbers of five, seven, and nine, which formed the basis of the analysis.

At this point in the problem evaluation, we recognized the need for a range of expertise. An optimization expert facilitated the assembly of all the models, and understood their functioning. Without a management expert, we could not have understood and presented the organization models and their influence on institutions. The input of a decision-aiding expert enabled the problem structuring and re-definition.

The thesis is composed of five chapters, including a separate introduction and conclusion, with seven parts in total. Figure 1 provides the thesis structure flowchart, and the relationship between parts. Chapters II, III, and IV can be read independently as they form stand-alone articles. In addition to the thesis flowchart, section 1.4.2 shows the relationship between DAP stages and chapters - the thesis structure.

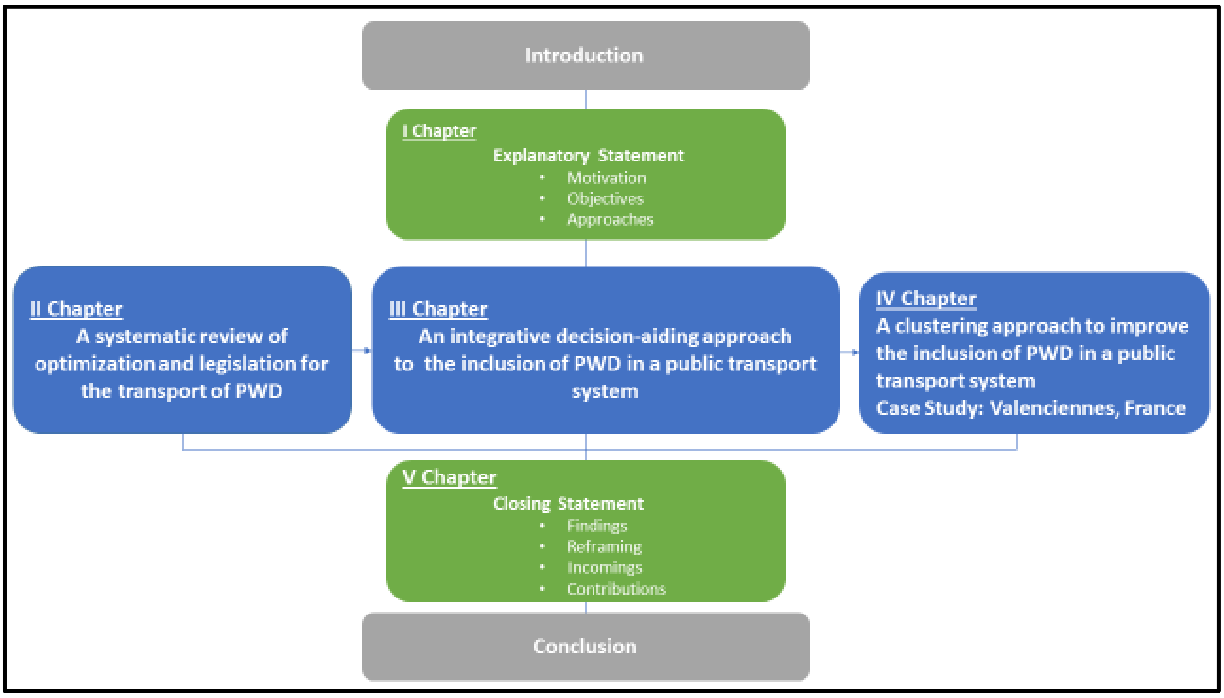

Figure 1 Flowchart of the thesis structure

The introduction provides a brief thesis overview, with the problem description, methodologies used, and contributions. Chapter I presents an explanatory statement, as mentioned here in the introduction. This chapter serves to present the multidisciplinary thesis. Chapter ll is dedicated to a systematic review. Typically, this chapter would present the literature review. In this case, we carried out a systematic review of the optimization models for PWD transport and their compatibility with the 5As.

With respect to the research problem, a review of the relevant legislation was carried out. Chapter III describes the implementation of DAP to include PWD in public transport. This chapter clarifies why a clustering approach was used, rather than some of the optimization models already analyzed. In Chapter lV, the optimization model using clustering is developed, and the final chapter provides a closing statement and a conclusion.

Chapter I

1 Explanatory statement

1.1 Introduction

Theses that employ a multidisciplinary approach do not naturally arrive at straightforward conclusions, implement methodologies or coordinate problem definitions across disciplines (Repko & Szostak, 2017). These challenges are increased when you have exceptional cases as the primary leads. Public transport is already a complex system, and of the subsystems as the transport for PWD presents a higher level of difficulties. The specifics of this thesis are the inclusion of persons with disabilities in public transport. The explanatory statement and closing statement are used to illustrate the path of this interdisciplinary dissertation(Palmer, 2013).

One explanatory statement focus is on the research's motivation, as this thesis forms part of the ValMobile project, consequently, the results obtained need to be applicable in practice. The case study subject is the public transport network in Valenciennes, a town in northern France. The research motivation is divided into three directions to address the project requirements.

The decision-aiding process (DAP) is used to structure the thesis.This chapter presents the first phase of DAP process. The first DAP step describes the problem situations, identifying the actors (participants) involved in the problem and defining their objectives (stakes) related to the problem. Research objectives are the main guidelines in the problem structuration, as it was necessary to establish the different views required by Project ValMobile, PWD needs, and analyses of the various optimization models. One part of this decision-aiding process is described in section 1.3.2 of this chapter, and the detailed presentation is provided in Chapter III.

Another explanatory statement focus is on the interdisciplinary research used in this thesis. Thus, the challenge was addressed through connection among the research motivation and problem structuration with the interdisciplinary research. The disciplines of management, the decision-aiding process, and optimization are introduced separately and their main characteristics are presented.

Chapter I is organized as follows: Section 1.2 presents the research motive, and the next part, Section 1.3, is dedicated to problem structuration whereby the three research objectives are stated. Section 1.4 demonstrates the different methodologies used in this thesis through interdisciplinary research, and Section 1.5 states the conclusion. Since we used the DAP to structure the thesis, the chapter's correlation is presented in the section on the decision-aiding process.

1.2 Research motivation

This thesis is a part of the project: "*ACCROCHE ACTIVE! Pour une jeunesse mobilisée et actrice de son avenir"* (Accroche Active, For a mobilized youth and role of its future), identified as the ValMobile action. The Valenciennes Métropole Agglomeration Community supports the project within the framework of the "*Programme d'Investissement d'Avenir Jeunesse*" (Future Investment Program for Youth), by the "*Agence nationale pour la Rénovation Urbaine - ANRU*" (National Urban Renewal Agency). The ValMobile is led by the "*Pôle De Recherche Et D'innovation En Mobilite Et Handicap de la région Hauts-de-France – PRIMoH*" (Mobility and Disability Research and Innovation Center of the Hauts-de-France region).

PRIMoH addresses disability in terms of inclusion, innovation, and the creation of economic value. In addition, PRIMoH set up a network around these themes, including various partners in the fields of care and medico-social, management and transport solutions, research and training, as well as local authorities and user associations. As we could see, we already had many participants in the project in addition to the University Polytechnique Hauts-de-France, as leader of the ValMobile action.

The ValMobile project aims to provide mobility aid tools for young people with disabilities in the Valenciennes agglomeration. The young people targeted by this tool are 13-30 years old, with a legally defined disability. We expanded this investigation to include all people with disabilities (as defined in the thesis introduction) of all ages, specifically wheelchair users. The plan is for the mobility aid tool to be incorporated in a computer application installed on smartphones, wheelchairs, etc. It provides PWD users with travel assistance, enabling them to be stakeholders in their own autonomy.

The ValMobile project is divided into three phases: i) Analysis of the existing situation and needs of PWD; ii) Development of a mobility aid tool, and iii) City test and improvement. The first phase involved an analysis of the existing situation. This phase was to identify the existing studies and support systems for mobility assistance for people with disabilities, both at the national and international level, taking different types of disabilities into account. It also included an analysis of the mobility needs and challenges for PWD in the Valenciennes agglomeration.

The development of the mobility aid tool in the second phase depends on the first phase results. One option is to develop the tool to help the mobility of PWD in the agglomeration of Valenciennes. Several propositions were made, one being the development of the optimization model suitable for PWD mobility, resulting in the improvement of their autonomy. Some of the proposed algorithms - as discussed previously - are the shortest path problem and transport-on-demand. Advanced optimization techniques such as meta-heuristics and/or hybrid approaches that combine exact and approximate methods are proposed as the solution to these two optimization problems. The last phase is the implementation and testing in the city of Valenciennes. This phase generates a real data set.

The thesis presents a task that is a single project component. Yet, the work developed here is aligned with all phases defined in the overall project. The three ValMobile phases are simultaneously three research thesis objectives.

1.3 Problem structuration

The problem structuration is the essential part of any research, as well as in the thesis (Dias & Tsoukiàs, 2003; Meinard & Tsoukiàs, 2019; Tsoukiàs, 2007, 2008). If we do not pose the problem correctly, then there is a risk that a solution is found for the wrong issue (Greco, Ehrgott, & Figueira, 2016; Hämäläinen & Lahtinen, 2016; Landry, 1995; H. Simon, 1984; H. A. Simon, 1997). The posing problem correctly is a complex process, especially when we have a diversity of participants, as is already noted in the project description. Plus, the various project aims in the broad field of implementation. When we add to this the complex transportation process and the challenge of specific needs as defined through the different transportation characteristics, problem structuring becomes a high priority.

The research problem is structured into three main areas to correlate with the ValMobile three project phases. Particular attention is paid to defining the needs of people with disabilities that are wheelchair users. The first research objective is the analysis of optimization models and legislative frameworks for the transport of PWD. The second research objective is to identify the needs of and obstacles for the inclusion of PWDsin public transport. The final objective is to develop the optimization model applied to the existing transport network. The overall objective is to bring autonomy to PWDs when using public transport.

1.3.1 Research objective I – Analysis of optimization models

The first research objective focused on analyzing the existing optimization model's components to transport persons with disabilities. PWD specific needs and the obstacles faced need to be considered from both technical and regulatory standpoints. The breakdown of various sources produced different types of information, including numerical, regulative, and bibliographic. It was essential to know which kind of data could be used to identify the appropriate optimization model. The development of the first research objective was supported by a management methodology and a systematic review.

1.3.2 Research objective II – Identification of needs and obstacles for inclusion of PWDs in public transport

Identification of PWD needs and obstacles to inclusion in public transport presents a crucial part in developing the appropriate model for integrating PWD in public transport. In addition, the relationship between all the participants in the transportation of PWD needs classification. Different decision hierarchy levels, such as strategic, tactical, and operational, generate different approaches. Different levels lead to the definition of the realm of a feasible solution, given the project's aim to develop the optimization model on the existing network. The realm of a feasible solution is an interaction of the barriers and needs across all decision levels, including the optimization models as the shortest path problem and transport-on-demand. The decision-aiding process was used as a method to achieve the second research objective.

1.3.3 Research objective III - Developing a model to include PWD in the public transport on the existing transport network

Problem structuring requires defining a precise problem position. The definition of the problem is key in the construction of the optimization model. This is the first attempt to articulate one or more of the project's concerns into formal problems. The formal problem is how we can implement the methods that already exist in decision theory or operational research. The main question to be addressed is: "What are we going to decide on?" The difficulty in setting the problem formulation is that "half of a problem is deciding what to decide." The third research objective is implemented in the Valenciennes transport network case study.

1.4 Interdisciplinary research

The inclusion of persons with disabilities in the public transport system presents a very heterogeneous system. The transport system itself is made up of a large number of participants with many crossover actions. The complexity of the PWD needs necessitates the use of Interdisciplinary research as the appropriate research methodology.

Knowledge sharing between different disciplines has always taken place in science. However, with the expansion of computer science, interdisciplinary working has matured as a priority in science design. The multidisciplinary approach brings new knowledge, which is essential in generating solutions for new, complex problems. In practice, these projects require the management of knowledge, techniques, and skills. In this context, interdisciplinary research complements rather than overrides disciplinary research.

"*Knowledge about knowledge has a peculiar multiplier or leverage effect on the growth of knowledge itself. The more we know about learning and the transmission of knowledge, and the more we know about the processes by which knowledge advances at the frontiers, the more efficient will be the use of resources, both in education and in research (*Boulding, 1970*)*"(Palmer, 2013).

In this thesis, three different methodologies were used: management, decision-aiding, and optimization models. Their combination should bring up the quality of the research.

1.4.1 Management

As mentioned in the previous section, the management of knowledge, techniques, and skills is a crucial part of the research. (Palmer, 2013) defined the interdisciplinary research mode as shown in Table 1. Through the five classes of approach, information practices, knowledge strategies, scope, and outcome, three scientific modes are identified: - collaborator, team leader, and generalist.

RESEARCH MODE	COLLABORATOR	TEAM LEADER	GENERALIST
APPROACH	Cooperative	Managerial	Individualistic
INFORMATION PRACTICES	Finding	Gathering	Probing
KNOWLEDGE STRATEGIES	Consulting	Recruiting	Learning
SCOPE	Depth	Breadth	Breadth
OUTCOME	Productive	Productive	Integrative

Table 1 Interdisciplinary research mode (Palmer, 2013)

In this case, each category of scientist is represented. Initially, the Ph.D. student is the collaborator through the ValMobile Project team leader (Spartacus et al.). The four professors represent the generalist for field management (Cimon, 2004; Véronneau & Cimon, 2007), decision-aiding process (Crévits, 2013; Crevits, Debernard, & Denecker, 2002; Crévits & Labour, 2012), and optimization (Carrizosa, Mladenović, & Todosijević, 2013; Hansen, Mladenović, Todosijević, & Hanafi, 2017). However, each individual is a team leader in his.

In addition to the participants' ideal shared role in the thesis project, management is used to analyze various sources of the literature and information. Different sources such as numerical data, regulations, and bibliography require a systematic approach.

1.4.2 Decision-aiding

The framing of decision-aiding methodology started towards the end of the 1960's (Roy, 1996). This framing came about due to the need to develop a single comprehensive method that could build a model applicable to all research disciplines. Typically, the traditional research methodology maximizes the economic function, with some feasibility constraints (D. Bouyssou, 2006). Often, within traditional operational research models, attempts are made to solve the wrong problem correctly (Ackoff, 1979; Belton & Stewart, 2002; Eppen & Gould, 1984; Rosenhead, 2006; Rosenhead & Mingers, 2001; Tsoukiàs, 2007). In addition to structuring the problem, some studies have indicated that some algorithms used to solve traditional operational research problems are not always appropriate in practice (Ehrgott, 2005; Franco & Montibeller, 2010; Greco, Ehrgott, & Figueira, 2005; Greco et al., 2016; Hartmanis & Stearns, 1965; Karp, 1975).

The decision-aiding process has been applied extensively in this thesis. Initially, it was used to structure the thesis, as shown in Figure 2. The four main steps in the decision-aiding process are: - problem situation, problem formulation, evaluation models, and final recommendation, as described in Chapters II, III, IV, and V, respectively.

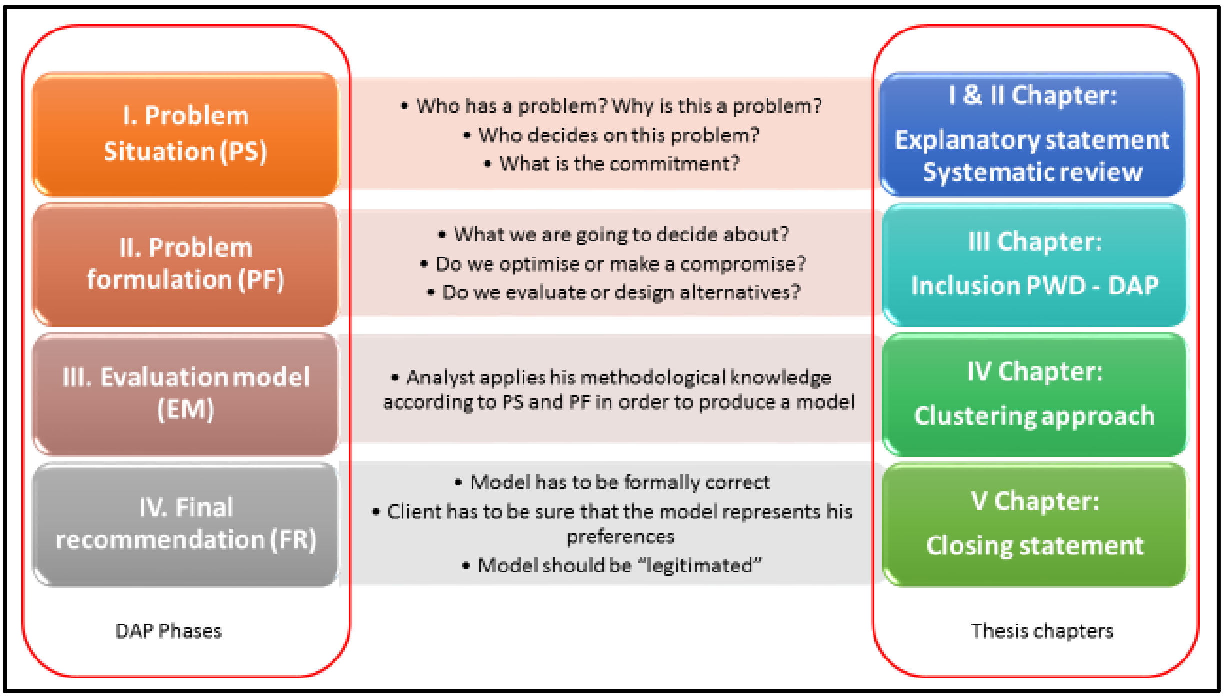

Figure 2 Connection between DAP's steps and chapters, the thesis's architecture

Chapter II, A systematic review of the literature identifies the problem situation. In Chapter III, the inclusion of persons with disabilities in public transport systems provides the thesis's problem formulation. Chapter IV - the clustering approach - is the evaluation model, and the Conclusions provide the final recommendations.

Also, every chapter follows the elementary steps of the decision-aiding process. Finally, Chapter III includes a detailed explanation of the decision-aiding methodology and its practical implementation.

1.4.3 Optimization

Mathematical optimization involves the selection of the most important element, depending on the selected criteria from a set of possible options. The objective function usually converts to a maximum or minimum.

Initially, the ValMobile project proposed optimization models, such as the shortest path (Pallottino & Scutella, 1998; Turner, 2011) or transport on-demand (Cordeau & Laporte, 2003a; Ho et al., 2018; Molenbruch et al., 2017). This functions as going from point A to point B, considering a travel network, and proposing an optimal path, given the user's characteristics.

At this point, analysis and understanding of all the mentioned optimization models' variants were carried out, including their components. Above all, the aim was to measure their compatibility against PWD needs because optimized PWD mobility starts from the home. Following these evaluations, it was discovered that the proposed optimization models only satisfied a part of the journey of the independent movement of PWDs. In order to accommodate mobility from the house, a clustering approach was introduced as the model of the primary task in exploratory data mining. The available real data set was then analyzed and classified relative to the PWD's s geo-location and existing hub centers on the network. This led again to adopting the clustering approach.

1.5 Conclusion

This explanatory statement outlines the necessary elements and steps for developing a useful transportation model for the inclusion of persons with disabilities in public transport. An in-depth analysis of the transportation models and PWD needs and obstacles was carried out, with a precise definition of the research objectives, to arrive at this thesis's findings.

Chapter II

2 A systematic review of optimization and legislation for the transport of persons with disabilities

2.1 Introduction

Public transport services have attempted to improve conditions for persons with disabilities (PWD) over time. Initially, transport-on-demand was provided, where the traditional transportation service could not assist due to cost considerations (Davison, Enoch, Ryley, Quddus, & Wang, 2014). The well-researched Dial-a-Ride model (Cordeau & Laporte, 2007; Ho et al., 2018; Molenbruch et al., 2017) has developed extended variants. Instead of private vehicles, some models proposed the operation of buses with adapted schedules in place of fixed stops (G. Dikas & Minis, 2014; Environment, 1961; Errico, Crainic, Malucelli, & Nonato, 2013). Extended variants have generated many new descriptors for these optimization models, such as demand-responsive transport, demand-responsive transit, demand-responsive service, dial-a-ride transit, and flexible transport services. The diversity of names of transport optimization models initially presented challenges in the planning of the research.

The improvement of the public network capacity and associated transportation facilities in relation to accessibility has resulted in new optimization models. To use the public infrastructure in the best quality way, science has proposed the shortest path optimization model (Pallottino & Scutella, 1998). Implementation of the shortest path model within the public transport network depends on its accessibility. One of the questions of this thesis is the inclusion of persons with disabilities in public transport. Consequently, the shortest path model has been considered in this research as a potential solution.

The range of terminology used for persons with disabilities is extensive, as is the case for transport-on-demand. In the literature, many terms are used, including disabled persons, users, persons with reduced mobility, elderly people, people with limited mobility, and people with movement disorders. This chapter explores and analyzes the optimization models serving the needs of PWD to facilitate their independent movement. The U.S. Government Accountability Office definition of PWD needs has been adopted in this research. These needs are defined as the 5As, namely Availability, Accessibility, Acceptability, Affordability and Adaptability, acknowledging key PWD requests (Shrestha et al., 2017; U.S. Government Accountability Office (GAO), 2004).

PWD includes several subgroups of impairments (physical, intellectual, motor, visual), and each group has specific needs. A clarification of these particular needs and types of disability is needed to define best the extent of personalized adaptation required and the capacity to use public transport. This thesis, as explored in this chapter, is focused exclusively on PWD wheelchair users.

There are databases with terabytes of existing literature on this topic, with extensive different web links. Similarly, the subject of transport-on-demand has been extensively studied for decades. This data is almost impossible to research without using a systematic method of review. This chapter used a systematic review as the methodology to explore optimization models for the transport of persons with disabilities, emphasizing supporting independence in PWD mobility.

In addition to the screening review of optimization models, relevant existing legislation was evaluated nationally, across Europe, and globally. The foundations for potential improvement in the transportation of persons with disabilities lie within the legislative framework, and the proposed thesis solution must comply with it.

This chapter is structured as follows: Section 2.2 describes the methodology of the systematic review. Sections 2.3 and 2.4 3 and 4 illustrate the systematic analysis of the sources and the literature, respectively. Section 2.5 summarises the legislation framework for PWD transport. Finally, Section 2.6 gives the conclusions of the research.

2.2 Systematic review

The literature review was pivotal in defining the problem and determining the research question within the guidelines that the research could be carried out (Palmer, 2013). All research projects start by conducting a literature review to identify the route through and missing links within the existing related research field. The current analysis methodology is to consider more than one field (Snyder, 2019). The current interdisciplinary approach is essential in providing the answers and solutions to complex research problems. Complex research problems consider whether the traditional literature review responds to all domains (Dijkers, 2009). The science of medicine introduced the systematic review because the conventional method did not produce satisfactory results in specific topics like data mining, comparing examination, and “translating” research between disciplinary traditions (Dijkers, 2009; Liberati et al., 2009). Some of the main features of the systematic review are: (i) systematic and comprehensive researches in order to recognize all relevant literature; (Liaw, White, & Bander) a precisely set question with predefined eligibility criteria; (Liaw et al.) data extraction and management of them; (iv) presentation and analysis of results (Badger, Nursten, Williams, & Woodward, 2000). However, for some research questions, it is better to stay within the narrative literature review. Usually, the traditional literature review is written by an expert in his field of expertise, which is an excellent choice if you deal with one discipline of research that treats a specific domain (Dijkers, 2009).

The quality of research output is a consequence of the chosen method for conducting the study. The manner in which research is carried out, and the chosen methodology on which analysis is based, has an impact on the quality of results obtained. Within this thesis, interdisciplinary research was adopted to consider the transport of PWD. This thesis's chosen methodology was for a systematic review using the Prisma statement (Cook, Mulrow, & Haynes, 1997; Fink, 2010; Gough, Oliver, & Thomas, 2012; Liberati et al.). PRISMA is an abbreviation of Preferred Reporting Items for Systematic Reviews and Meta-Analyses. PRISMA presents a minimum set of steps for reporting in systematic reviews and meta-analyses. In our research, we are only focusing on systematic analysis.

The systematic review employing the Prisma statement was adjusted for the needs of this thesis. The research was conducted using different scientific databases, including Engineering Village (EV), Web of Science (WS), EBSCO/Computers & Applied Science - EBS, and Google Scholar (GS). Engineering village was consulted as one of the key databases specific to electrical engineering and computer engineering. Engineering Village enhanced the research using the databases Inspect (EV-I) and Compednix (EV-C) as the central part of computer science. Additional value was achieved by using databases GeoBase (EV-GB), GeoRef, and Knovel (EV-K).

The Web of Science includes over 55 million records obtained from the best journals, conference proceedings, and books in science, social science, and the arts and letters on research areas of interest. EBSCO/Computer & Applied Science Complete covered the computing and applied sciences disciplines' research and development spectrum.

Navigation over the database was done with the concept plan. The concept plan for the search of databases is shown in Table 2. Three main groups were identified for the concept plan. The database rules govern the manipulation of the different combinations of the groups. The first group considers expressions about transport, the second group explains the optimization model for the transport of PWD. The third group of them provides different keywords for persons with disabilities.

OR/AND	Group I	Group II	Group III
1	Transportation	Optimization models	Persons handicapped
2	Public transport	Dial-a-ride	Persons with disabilities
3	Displacement	Transport on demand	Users
4	Mobility	Paratransit service	Persons with reduced mobility
5	Transportation systems	Demand responsive transport	Wheelchair
6	Transportation planning	Vehicle models	Elderly
7		Transport services	People with limited mobility
8		Shortest Path	People with movement disorders
9			Paratransit
10			Mobility challenges
11			Passengers

Table 2 Concept plan for research of databases

2.3 Systematic analysis of the sources

The process of screening articles included in a systematic review is presented in Figure 3. This consists of four stages: identification, screening, eligibility, and included phases (Gough, Oliver, & Thomas, 2012).

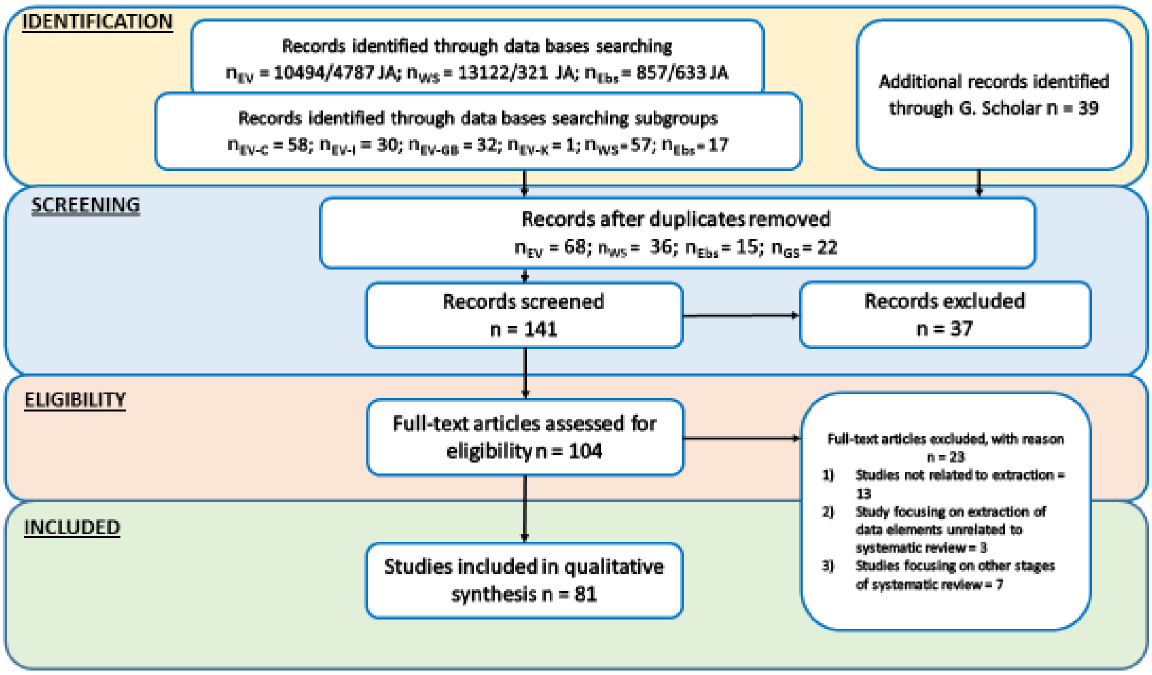

Figure 3 Prisma statement

2.3.1 Identification

The Prisma statement levels were modified in accordance with the needs of this thesis. In this case, literature identification, the first PRISMA stage, was broken into three phases. The phases represent the filtration of the articles. The extensive literature was identified in the first phaseas EV 10,494, WS 13,122, EBS 857 with the number of articles. These were the expected numbers, as transport-on-demand has been a very well-studied issue for many years. The next iteration selects only journal articles. In this situation, we have EV 4,787, WS 321, EBS 104 in the period of 1974 to 2020. The number of journal articles of EV's databases (Compendix, Inspec, GEOBASE, and GeoRef) are shown in Figure 4.

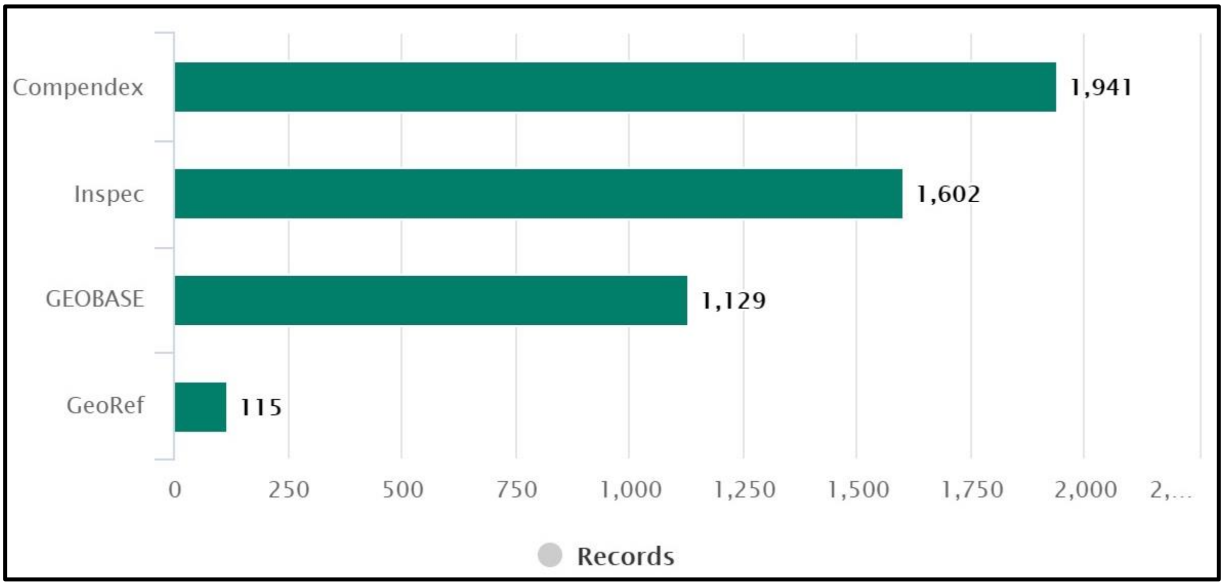

Figure 4 Ebsco databases sources: Compendix, Inspec, Geobase, GeoRef

In the second phase, the selection of journal articles in the WS database revealed different research journals in Figure 5. The most significant number is within multidisciplinary science, which validates the chosen methodology's appropriateness for this research subject. Other journals include transportation, urban studies, management and computer science, etc.

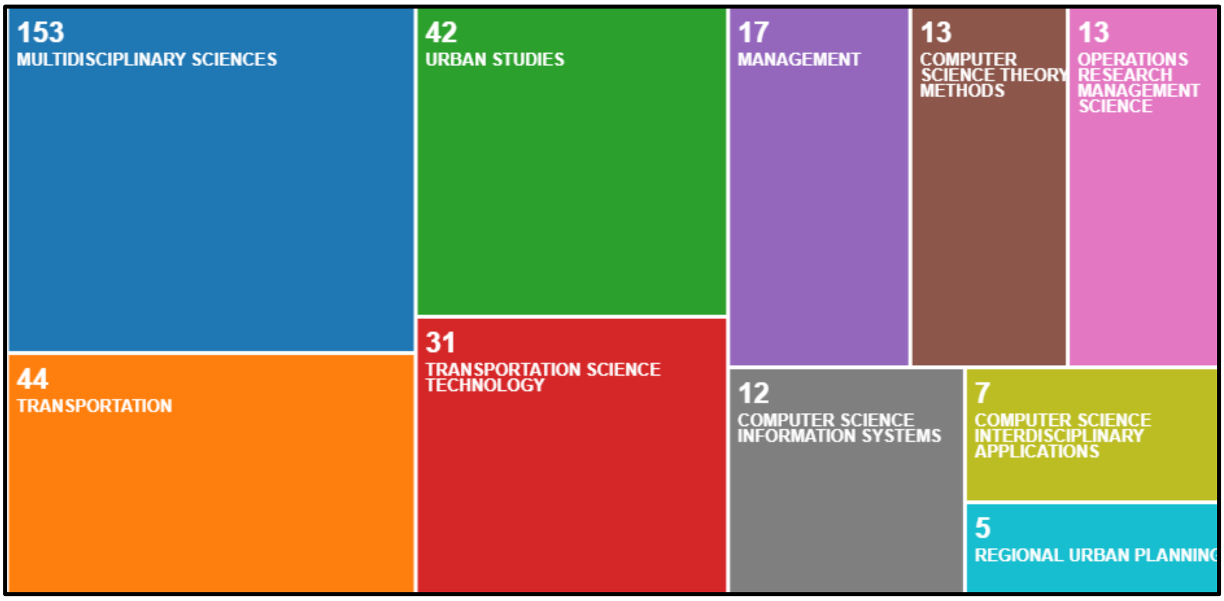

Figure 5 Web of Science database: different journals

The last step of the identification process was a more in-depth filtration of the leading group of keywords, together with their cross-fit. The new EV results were 58 articles in Compendix, 30 in the Inspect database, 32 in GeoBase, and 1 in Knovel. Figure 6 presents the results for the period 1982-2020.

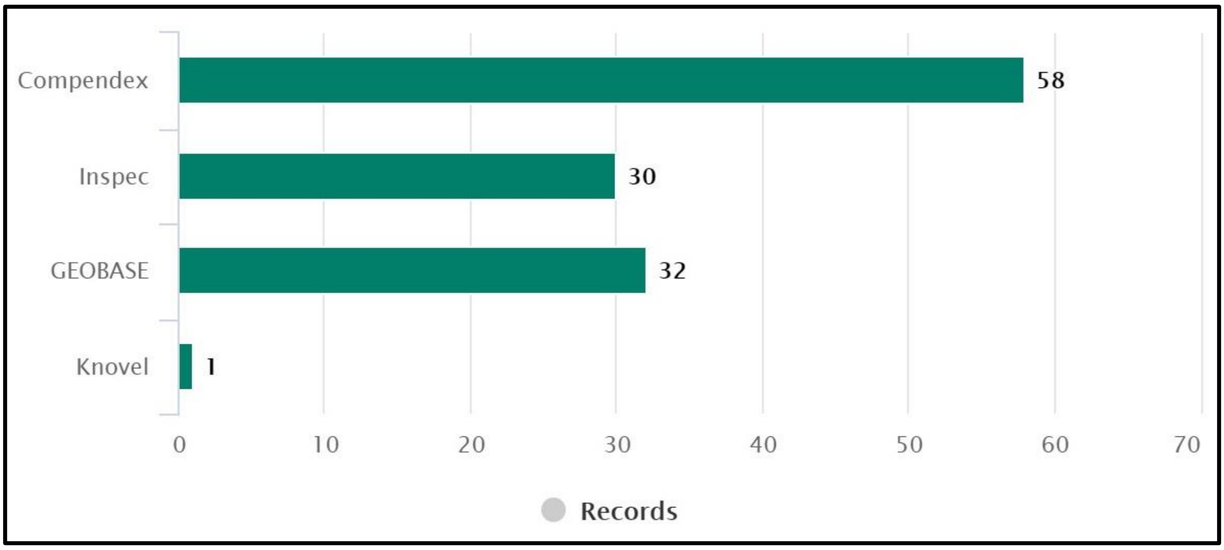

Figure 6 In-depth filtration of Engineering Village databases

Analysis of the third phase in Web of Science's research produced 57 articles matching the criteria in the period 1989-2020. Figure 7 shows the number of items in different research areas. The transportation area has taken a leading position. EBSCO/Computers & Applied

Sciences Complete had 17 articles for the period 1984-2020. The third phase of identification includes 39 records from Google Scholar.

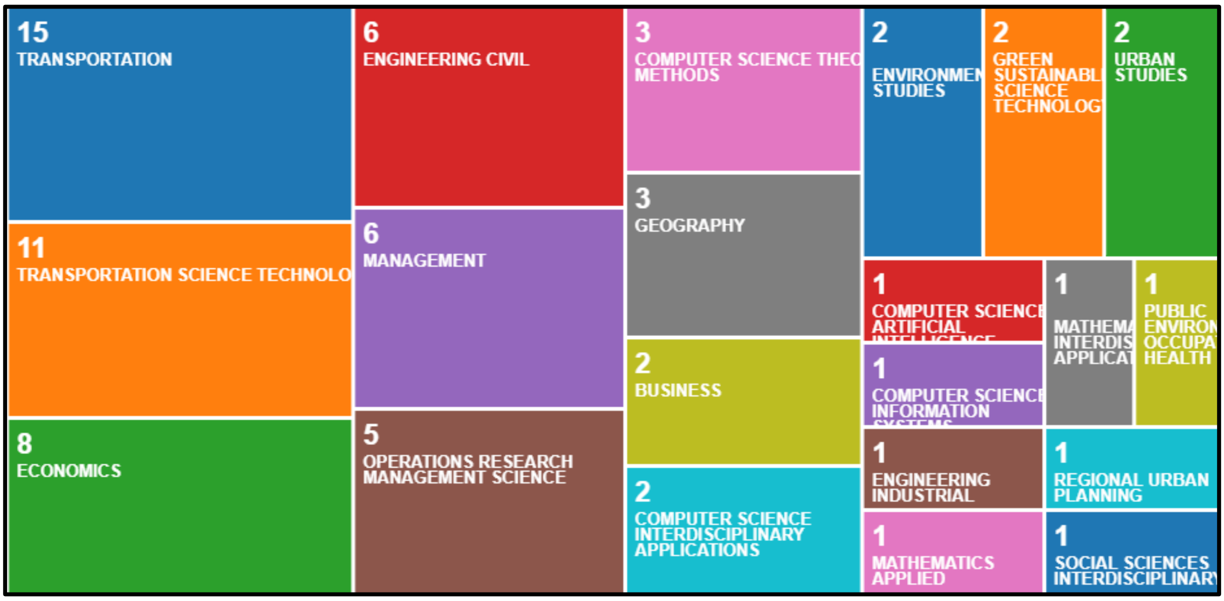

Figure 7 Web of Science database: different journals third phase

2.3.2 Screening

The second stage in the Prisma statement included screening and generated the number of records after the removal of duplicates. Sixty-eight articles came up in Engineering Village (Compendix, Inspect, Geobase and Knovel together), 36 in Web of Science, 15 in Ebsco, and 22 in Google Scholar. In total, 141 records were screened. Following analysis of the articles, 37 were excluded as they related to medical research.

In the third stage, which determined the validity of the screening review process, 104 articles were subjected to full-text examination. 23 articles were excluded from a full-text examination. In this exclusion13 of them are the studies that were unrelated to the extraction. Regarding the investigation step on removing the data unrelated to the systematic review, three articles are excluded. Seven articles were rejected because they were concentrated on other stages of the systematic review.

The last stage included a presentation of the total number of records incorporated in the analysis. Eighty-one articles were included in the systematic review.

2.4 Systematic analysis of the literature

The systematic analysis of 81 articles was divided into two parts. One part was optimization models belonging to the field of transport on-demand, and the second part was models for the shortest-path problem, highlighted with PWD needs.

2.4.1 Transport on-demand literature

Transport on-demand or dial-a-ride optimization models have proved their contribution to transporting persons with disabilities when conventional transport does not meet their needs. Many literature reviews have already been carried out on this topic, the most recent being (Ho et al., 2018; Molenbruch et al., 2017).

At this point, reference is made to the 'bible' of DARP (Cordeau & Laporte, 2003a, 2007). Ann excellent survey of a semi-flexible transit system, with a particular focus on the unifying framework for Demand Adaptive Systems (DAS) is presented by (Errico et al., 2013). The study of the flexible transit systems (FTS) (Koffman, 2004; Potts, Marshall, Crockett, & Washington, 2010), provides several descriptions of the traditional and transport-on-demand combination. In addition to these high-quality surveys, there are helpful reports and experiences in North America, Europe, Australia, Scotland and Great Britain (Brake, Mulley, Nelson, & Wright, 2007; Daniels & Mulley, 2012; Davison et al., 2014; Mulley, Nelson, Teal, Wright, & Daniels, 2012; Velaga, Nelson, Wright, & Farrington, 2012).

However, the focus of this thesis diverges somewhat from these previous studies. This research was involved in analyzing the degree of independent movement for PWD. This involved considering combining transport-on-demand and existing traditional transport and identifying the modeling elements: how they are combined and their objective function.

All these elements were analyzed using the 5A's categories of Availability, Accessibility, Acceptability, Affordability and Adaptability (U.S. Government Accountability Office (GAO), 2004). These attributes provided the framework of PWD needs for the provision of successful independent transport.

Availability provides a transport service to a destination at the time requested by PWD. A significant lack of on-demand transport needs to be overcome, resulting in the need to book the service 24 to 48 hours in advance. **Accessibility** is the primary PWD concern, including access to all transportation facilities. This is the essential requirement for the facilitation of independent transport for PWD. **Acceptability** meets PWD needs in terms of the provision of clean, safe, and user-friendly transport assistance. **Affordability** relates to financial assistance and establishing a ticketing policy adapted for the use of PWD. This criterion was modified to be regardless of whether financial aid was needed or not. This modification may require additional resources from the public ticketing system. Finally, **Adaptability** means delivery of flexible transportation service with multimodal trips and specialized equipment.

Some of the characteristics of different public transport modes (Ho et al., 2018), including bus, on-demand transit, and taxis, are summarised in the table below. These characteristics are relevant to regular users and do not address the specific needs of PWD. The closest to our analysis is on-demand transit as the term transport-on-demand. The seven characteristics identified are route, schedule, speed, cost, mode, capacity, and reservation, as shown in Table 3.

	Bus	**On-demand transit**	**Taxi**
Route	fixed	flexible	customized
Schedule	fixed	by request	by request
Speed	slow	medium	fast
Cost	low	medium	high
Mode	shared	shared	non-shared
Capacity	high	medium	low
Reservation	not needed	often needed	not needed

Table 3 A comparison of three public transport services (Ho et al., 2018)

The relationship with the 5A's can be seen in the regular features integrated into Availability, Acceptability, Affordability, Adaptability(Accessibility is not part of the traditional transport evaluation). Incorporated in availability are route, schedule, and reservation. Acceptability includes speed and capacity. Affordability relates to costs, and Adaptability is related to mode (shared or non-shared vehicles).

It is a consequence of the fact that literature reviews do not evaluate the optimization models in relation to the needs of PWD that prompted this analysis. Six different groups of models were identified:

I. **Dial-A-Ride Problem** – **DARP** (Archetti, Speranza, & Weyland, 2018; Cordeau, 2006; Cordeau & Laporte, 2003a, 2003b, 2007; Ho et al., 2018; Molenbruch et al., 2017; P. Oxley, 1980; Paquette et al., 2009; Psaraftis, 1980; Wilson, Sussman, Wong, & Higonnet, 1971; Wilson, Weissberg, & Hauser, 1976);
II. **Demand Adaptive System – DAS** (Crainic, Errico, Malucelli, & Nonato, 2012; Crainic, Malucelli, Nonato, & Guertin, 2005; Daganzo, 1978, 1984; Errico et al., 2013; Malucelli, Nonato, Crainic, & Guertin, 2001; Malucelli, Nonato, & Pallottino, 1999a);
III. **Flexible Transport System – FTS** (Bakas, Drakoulis, Floudas, Lytrivis, & Amditis, 2016; Brake et al., 2007; Chandra, Bari, Devarasetty, & Vadali, 2013; Cortés & Jayakrishnan, 2002; Daniels & Mulley, 2012; Davison et al., 2014; Errico et al., 2013; Kim, Levy, & Schonfeld, 2019; Kim & Schonfeld, 2014; Koffman, 2004; Mulley et al., 2012; Potts et al., 2010; Qiu, Shen, Zhang, & An, 2015; Velaga et al., 2012);
IV. **Scheduled Paratransit Transport System – SPTS** (Georgios Dikas, 2014; G. Dikas & Minis, 2014; George Dikas & Minis, 2018);
V. **Mobility Allowance Shuttle Transit – MAST** (Quadrifoglio & Dessouky, 2008; Quadrifoglio, Dessouky, & Ordóñez, 2008a, 2008b; Quadrifoglio, Dessouky, & Palmer, 2007; Quadrifoglio, Hall, & Dessouky, 2006; Zhao & Dessouky, 2008);
VI. **Integrated Dial-a-Ride – IDARP** (Aldaihani & Dessouky, 2003; Broome, Worrall, Fleming, & Boldy, 2012; Daganzo, 1984; Carl Henrik Häll, 2006; Carl H. Häll, Andersson, Lundgren, & Värbrand, 2009; M. Hickman & K. Blume, 2001; M. D. Hickman & K. L. Blume, 2001; Liaw et al., 1996; Posada, Andersson, & Häll, 2017).

2.4.1.1 Dial A Ride Problem – DARP

The DARP provides the ultimate on-demand service with specific pickup and delivery challenges. A multi-vehicle routing problem, also categorized as a Vehicle Routing Problem, with Pickup and Delivery and Time Windows, is a more precise description of DARP (Cordeau, Laporte, Savelsbergh, & Vigo, 2007; Doerner & Salazar-González, 2014; Jozefowiez, Semet, & Talbi, 2008; Toth & Vigo, 2002, 2014). The aim is to produce suitable timetable schedules and vehicle routes within the constraints of the pickup and delivery problem (Parragh, Doerner, & Hartl, 2008a, 2008b). The objective functions can be divided into two groups: to minimize or maximize (Ho et al., 2018; Molenbruch et al., 2017):

I. Minimize
    a. the total distance
    b. the total routing costs
    c. the total vehicle travel time
    d. the total tour time

e. the fleet size
f. the number of vehicles
g. the maximum flow time
h. vehicle timeout
i. travel time of each user
j. user waiting time

II. Maximize

a. the number of requests served
b. the number of requests served on time
c. quality of service
d. the satisfaction of flexible constraints

With respect to the needs of PWD and objective functions, it is clear that DARP provides a quality of service in addressing PWD challenges, such as the travel time of each user, user waiting time, etc. Nevertheless, the main goal is to minimize the operators' travel costs. Although some PWD needs are addressed within the objective function, there is a lack of literature that addresses the issue of quality of service. To the best of our knowledge, only (Paquette et al., 2009) addresses this subject. The advanced service design of DARP is presented in Figure 8.

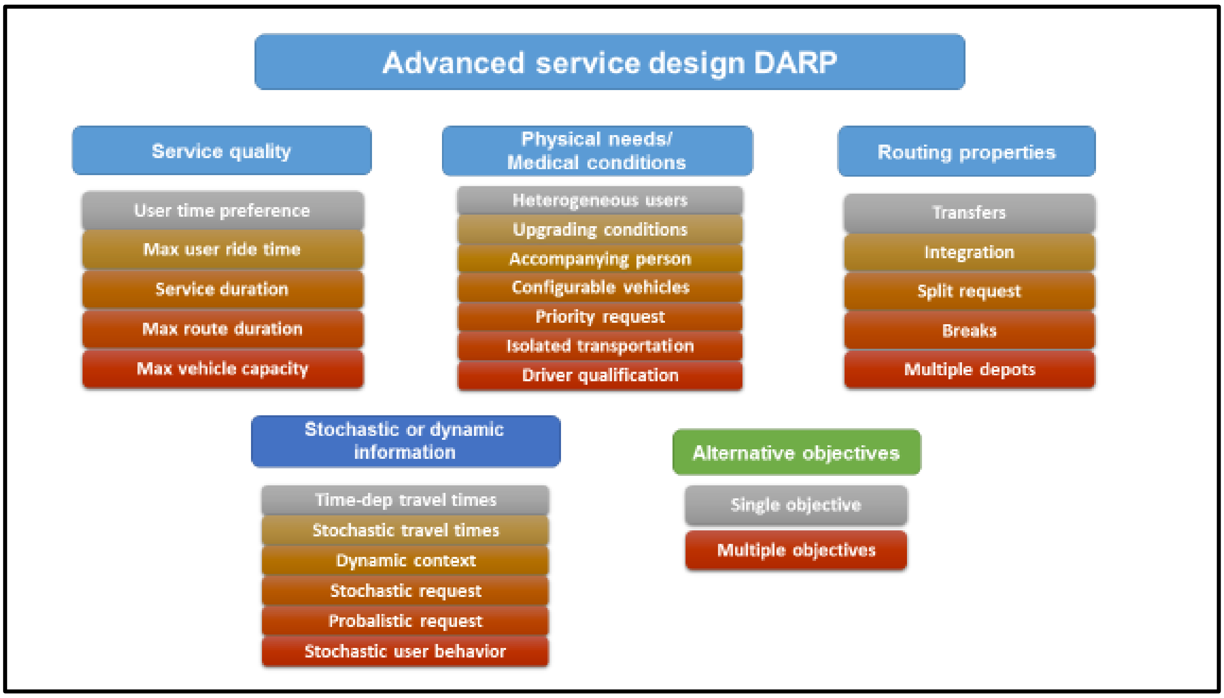

Figure 8 Advanced service design DARP, inspired by (Molenbruch et al., 2017)

Model/5As	Availability		Accessibility		Acceptability	Affordability	Adaptability
	Time	Place	Infrastructure	Vehicles			
DARP	0,5	1	0	1	1	0	0,5
DAS	0,5	0,5	0	0,5	0,5	0,5	0,5
FTS	0,5	0,5	0	0,5	0,5	0,5	0,5
SPTS	0,5	1	0	0,5	0,5	0,5	0,5
MAST	0,5	0,5	0	0,5	0,5	0,5	0,5
IDARP	0,5	1	0,5	0,5	0,5	0,5	0,5

Table 4, we compare the level of satisfaction of PWD needs. The levels of satisfaction (low, medium, and high) are designated with three colors (red, orange, and green, respectively) and with three weights (0, 0.5, and 1, respectively). The DARP evaluation shows high satisfaction in the Availability of place, Accessibility of vehicles, and Acceptability.

Place Availability is the most prominent advantage of DARP. Until now, the DARP is the only model that provides the precise delivery location for PWD. By contrast, Time Availability provides medium satisfaction, but in practice, this is more towards low than medium because of the need to book the trip 24h to 48h in advance. The medium category is given because PWD obtains access at the time requested, but planning is required, which is not required for regular users.

DARP takes a different form in different cities. DARP is a part of classic on-demand transport and is not just for persons with disabilities (Cordeau et al., 2007). In all cases, users must call to book their journey. Generally, the ticket is booked in advance, as the routes are provided several times a week (regular service). Another form is the trip-on-demand (occasional service) or spontaneous trips within a few hours (casual dynamic service) (Paquette et al., 2009).

To the best of the authors' knowledge, all DARP vehicles are user-friendly for PWD. In addition, Availability of the place, vehicle accessibility is one of the highest DARP attributes. Acceptability takes a high position in the DARP ranking, as this type of service is guaranteed to be clean, safe, and user-friendly. Adaptability achieves a medium score, as DARP vehicles usually provide specialized equipment, but they do not offer a flexible service. The infrastructure Accessibility and Affordabilityearn the lowest rating, as DARP does not address network Accessibility, and the cost of the service is usually very high or receives some form of government subsidy.

Model/5As	Availability		Accessibility		Acceptability	Affordability	Adaptability
	Time	Place	Infrastructure	Vehicles			
DARP	0,5	1	0	1	1	0	0,5
DAS	0,5	0,5	0	0,5	0,5	0,5	0,5
FTS	0,5	0,5	0	0,5	0,5	0,5	0,5
SPTS	0,5	1	0	0,5	0,5	0,5	0,5
MAST	0,5	0,5	0	0,5	0,5	0,5	0,5
IDARP	0,5	1	0,5	0,5	0,5	0,5	0,5

Table 4 Transport on-demand optimization models in relation to 5A's

2.4.1.2 Demand Adaptive System – DAS

All the transport on-demand variants became as a result of better serving the client using different transportation capacities. One of these variants is the Demand Adaptive System (DAS), a specific form of demand-responsive transport (Crainic et al., 2012). The DAP presents the combination of classic DARP and the conventional fix–line bus service. The DAS model is built through fixed bus stops designed in advance, with the possibility of adjusting the bus route when and responding to user demands (Crainic et al., 2005). In fact, DAS generalizes the semy-flexible systems highlighting the conventional bus scheduling features.

In the 5As ranking, the DAS achieves medium in six of seven attributes. Time availability is 0.5 because, as in the DARP variant, PWD needs to book the journey in advance. Place availability is going to 0.5 since they can use some bus stops, which is not precisely the place where PWD wants to arrive. Again, as with DARP, Accessibility is not considered and is rated 0, or low satisfaction. The vehicle accessibility is 0.5 because PWD uses the bus lines, which is not sure they are accessible. The acceptability depends on the quality of the transport carrier, since we have in this situation a combination of buses and DAPR vehicles, we can not guarantee if the service is clean, safe, and user-friendly, so this attribute is noted as 0.5. In DARP variants, affordability is ranked the lowest, yet DAS deal with the public lines in one part, and according to this, DAS has got 0.5 for affordability. The meaning of adaptability is that service is flexible to use multiple trip types or specialized equipment. DAS used two modes, bus lines, and DARP vehicles, and got the remark 0.5.

2.4.1.3 Flexible Transport System – FTS

In cases where one of the conventional transport components is not fixed (e.g., route, vehicle, schedule, passenger, and payment system), for transport modeling, we consider it to be a semi-flexible transport service (Mulley et al., 2012). Within the group of FTS, in the literature, we found various expressions, such as Checkpoint dial-a-ride systems (Daganzo, 1984), Feeder Transit Service (Li & Quadrifoglio, 2010), or High Coverage Point to Point Transit System (Cortés & Jayakrishnan, 2002).

FTS combines the flexibility of DARP and the rigidity of traditional transport, with the emphasis on avoiding the general drawbacks of DARP (Errico et al., 2013). The main feature of the FTS model is the use of the same transport system, as presented in Figure 9. (Koffman, 2004; Potts et al., 2010) and (Errico et al., 2013) made a classification of FTS into the groups: route deviation, point deviation, demand-responsive connector, request stops, flexible route segments, and zone routes. For the route deviation, the schedule of vehicles is regular with the defined routes and deviates from completing optional requests and in the zone around the route. The point deviation is similar to the route deviation, and the only difference is that the schedule path is not defined in advance, yet some stops. In the case of the demand-responsive connector, vehicles serve in a demand-responsive form in a zone with at least one scheduled shift point that presents a connection with a fixed path. For the request stops, everything is regular in the operation of vehicles, conventional fixed-route, fixed-schedule mode with serving some stops where existing a requests. The flexible route segments present the part of the route that is a flexible and where the vehicles operate out of the conventional fixed route and schedule. The last one, the zone routes, present the vehicles that serve in the given zone with two points corresponding to the departure and the end of the line. In the 5As analysis, this has an impact on the time and place availability.

As the FTS is a forerunner of DAS models, where DAS has improved scheduling tools compared to FTS, it matches DAS in the 5As ranking. If we just consider DAS and FTS, a difference for Time Availability could be observed. Then DAS goes to 0.7 and FTS to 0.3 for on more in-depth analysis. FTS loses time functionality in providing a more flexible service, as the vehicles must follow pre-determined schedules and need more time to make a deviation in routing.

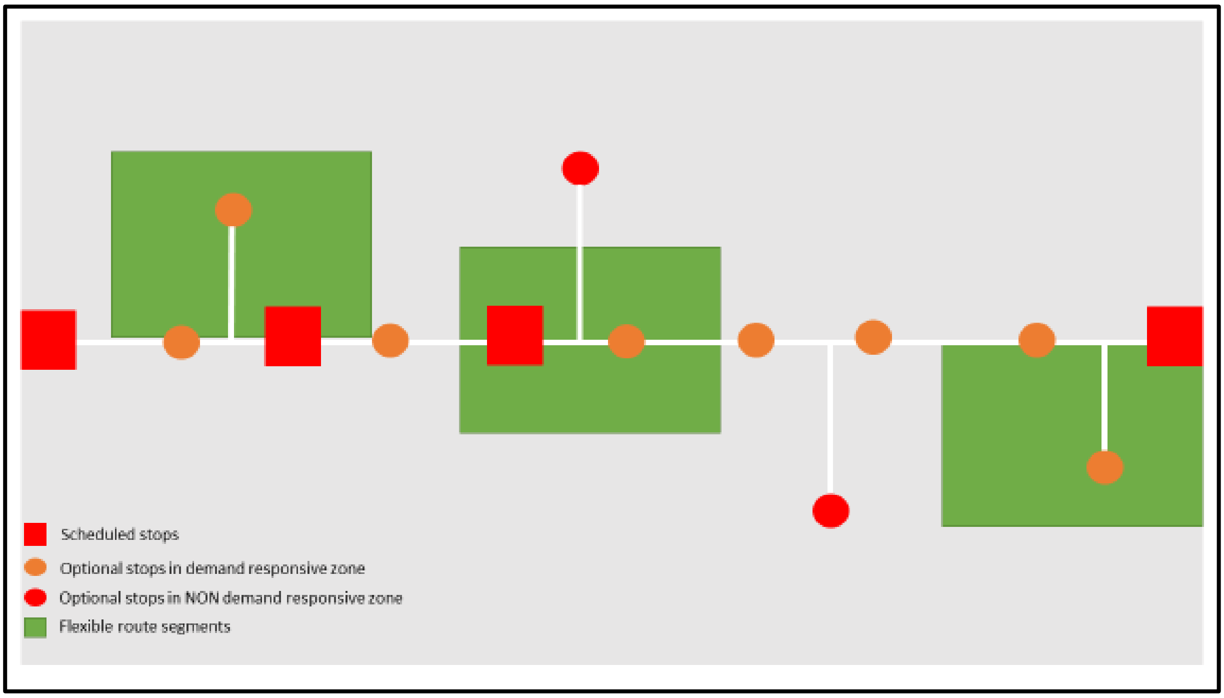

Figure 9 Functionality of Flexible transport systems, inspired by (Errico et al., 2013; Koffman, 2004), adapted by the author

2.4.1.4 Scheduled Paratransit Transport System - SPTS

The fourth group of identified optimization models relates to Scheduled Paratransit Transport System (SPTS). In SPTS, bus routes are modified from scheduled pathways to meet PWD demand and requests for locations to pick up and deliver (G. Dikas & Minis, 2014). In addition to FTS, SPTS attempts to solve the problematic "first-last leg" in the transportation journey of PWD. The public transport journey is composed by the "first-last leg" of any journey. The first leg presents the distance between the point of origin (International Conference on Smart, Health, & Abdulrazak) and the departure (bus, railway, metro stops, etc.). The last leg is opposite, from the public arrival station (bus, railway, metro stops, etc.) to the destination (working place, hospital, etc). In order to solve this "first-last leg," bus lines deviate from the fixed, regular route when they have demanded of PWD. In this case, one of the vehicles or several of them deviates from the route to pick up PWD to their point of origin and preferably leaves them to a regular bus stop or demanded destination. This kind of deviation is limited by a certain distance, of course.

In the 5As evaluation, SPTS has similar characteristics as DAS, FTS, and MAST. Time availability is ranked as 0.5 because the buses are working on demand, meaning they are not on a regular schedule. Place Availability has gotten 1 as one of the promising attributes since they are trying to solve the most significant issue in the transportation journey of PWD, “first-last leg. ” In comparison SPTS to DARP, SPTS dominates only in affordability, and the price is more affordable. And equal to the Place Availability. This characteristic could be seen in the IDARP model.

2.4.1.5 Mobility Allowance Shuttle Transit - MAST

Another relevant model for analysis is Mobility Allowance Shuttle Transit (MAST), as shown in Figure 10**Erreur ! Source du renvoi introuvable.** This model looks at running vehicles on repeat, on the same route, with proposed intermediate bus stops (checkpoints) (Quadrifoglio & Dessouky, 2008; Quadrifoglio et al., 2008a). MAST is characterized by vehicles that serve in regular fixed routes and serving in predefined specific zones. Concurrently, route derogations can be assigned in specific zones when vehicles have slack time. According to the authors (Zhao & Dessouky, 2008) of this model, they succeeded to decreased the operative bus cost by setting the length of a service zone to half the travel speed of the shuttle multiplied by the cycle time.

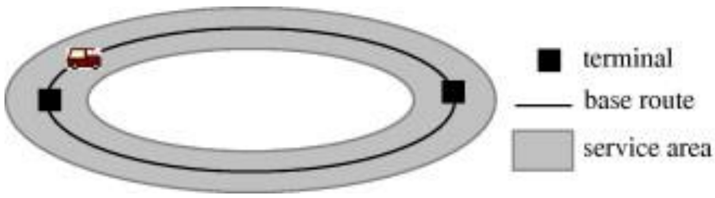

Figure 10 General presentation of MAST systems (Zhao & Dessouky, 2008)

In the concern of PWD users and in our 5As analysis, MAST has similarities with FTS and DAS. The difference is in the repeat vehicles service, which could increase the capacities for the specific PWD demands. The 5As evaluation is the same, and the ranking is equal. MAST could reach 0.7 for the Time Availability in more sensitive analysis because PWD doesn’t need to book the journey in advance and with the increased vehicles capacities, in comparison to FTS and DAS. However, in global, this time, MAST reached 0.5.

2.4.1.6 Integrated Dial-a-Ride Problem - IDARP

The final group is Integrated Dial-a-Ride Problem (IDARP), also known as the Bimodal dial-a-ride problem (Liaw et al., 1996). IDARP is probably the most compatible with existing models for the inclusion of PWD in public transport. IDARP is developed for intermittent vehicle routes and improves DARP by occasionally using a part of fixed paths (Carl H. Häll et al., 2009). The advantage of this model is that PWD could ride by the fixed-route public transport system for one part of his journey. This model assumes that the fixed routes are already known. The IDARP uses fixed routes at an optimal level while responding to the requests of PWD. The network optimization model is used for the formulation of IDARP.

In relation to the features of the 5As, IDARP is the only model that achieves an infrastructure Accessibility rating of 0.5. The IDARP model considers the entry point to the public transport network where PWD are delivered. In addition, place availability achieves a high rating of 1. The other characteristics reach a medium satisfaction level. Another advantage of IDARP is that it can use all transport modes, including bus, train and tram, while the other referenced optimization models only include buses.

The objective functions of DAS, FTS, SPTS, MAST, and IDARP models are included in the comprehensive analysis of DARP functions.

2.4.2 The shortest-path problem literature

As stated in the previous section on transport on-demand, the shortest path problem (SPP) is thoroughly researched in the literature, particularly for network flow optimization problems (Ahuja, Magnanti, & Orlin, 1993; Gallo & Pallottino, 1986; Pallottino & Scutella, 1998). SPP has a widespread application in transportation. Developing the networks at a large scale and transport analysis and planning needs so it supports the preference for applying the shortest-path method. The shortest-path problem belongs in the domain of graph theory.

In general, SPP finds a path between two vertices (or nodes) in a graph with different weighting criteria, such as minimum distance, minimum travel time minimum costs, etc. Some surveys about SPP are found in other fields, such as route planning, transportation models, graphs, networks flow, or telecommunications (Ahuja et al., 1993; Bast et al., 2016; Deo & Pang, 1984; Duin & Volgenant, 1991; Festa, 2006; Minoux, 1989; Pallottino & Scutella, 1998;

Turner, 2011; Zwick, 2001). (Turner, 2011) summarized variants of shortest-path problems with the following objective functions:

a) Bottleneck - can be presented as maximum capacity problem path, or minimum (the largest edge cost);
b) Balanced – where the difference between the largest and smallest edge cost is minimized;
c) Minimum deviation – can be presented as the difference between maximum and average weight in solution which should be minimized;
d) Algebraic sum - the sum of bottleneck objective function (Min-Max) and sum linear objective functions (Min-Sum), based on different cost functions;
e) K-sum and k-max objectives – can be presented as minimum sum of k largest edge costs, K-max as K^{th} largest edge cost;
f) Trimmed-mean objectives – don't treat the k^{th} largest and K^{th} smallest cost edge, but they add the costs of remaining edges.

The shortest path problem can be considered on different types of graphs. It can be a directed graph, a weighted graph, a directed weighted graph, or a tree graph, as shown in Figure 11 (Nuanmeesri, 2019).

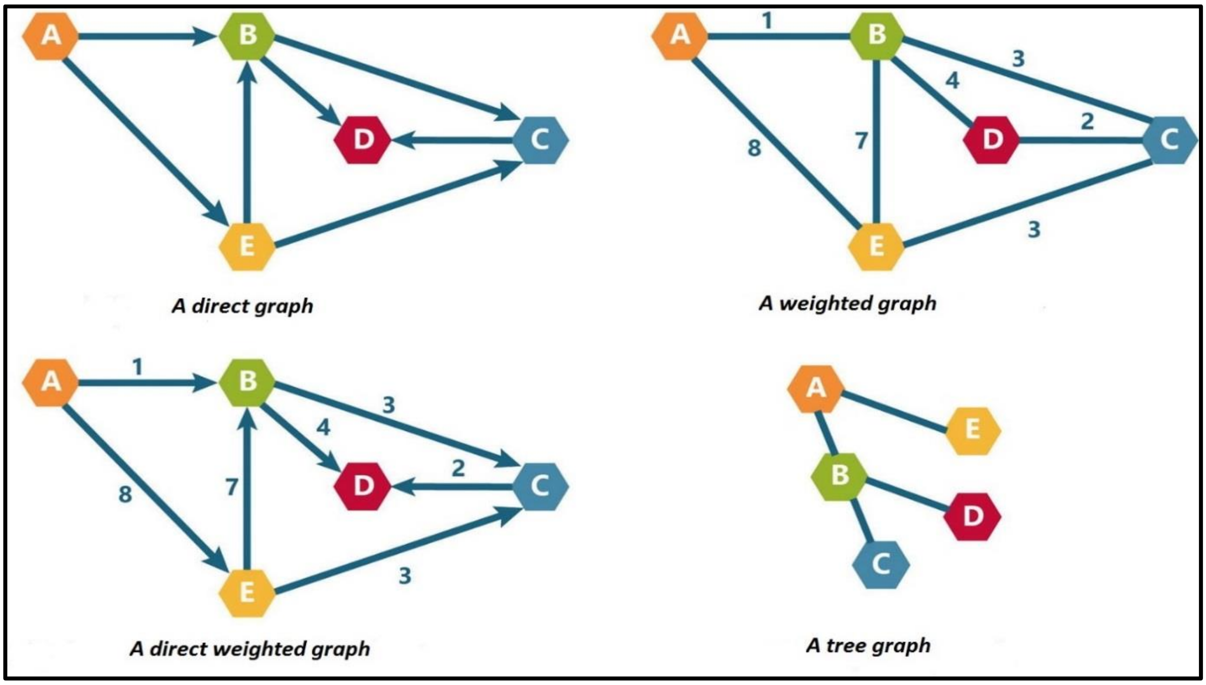

Figure 11 Different type of graphs in shortest path problems (Nuanmeesri, 2019)

The same evaluation criteria are applied to the shortest path optimization models – the 5As of Availability, Accessibility, Acceptability, Affordability and Adaptability (U.S. Government Accountability Office (GAO), 2004). The difference here is that the shortest path optimization models cannot provide full independence in PWD transport because the SPP is applicable only on public transport networks where accessibility exists.

The shortest path problems are grouped into four groups; see **Erreur ! Source du r envoi introuvable.**. where characteristics concerning the 5As are given.

I. **Multimodal shortest path problem – MSPP** (J. R. Current, Re Velle, & Cohon, 1985; John R Current, Revelle, & Cohon, 1987; Lozano & Storchi, 2001; Modesti & Sciomachen, 1998);

II. **Time-dependent shortest path problem – TDSPP** (Franceschetti, Honhon, Laporte, & Van Woensel, 2018; He, Boland, Nemhauser, & Savelsbergh, 2020; Ichoua, Gendreau, & Potvin, 2003; Nachtigall, 1995; Orda & Rom, 1990, 1991);

III. **Resource-Constrained Shortest Path Problem – RCSPP** (Beasley & Christofides, 1989; Ferone, Festa, Guerriero, & Laganà, 2016; Garcia, 2009; Joksch, 1966; Turner, 2011);

IV. **Multi-objective shortest path problem – MOSPP** (Granat & Guerriero, 2003; Guerriero & Musmanno, 2001; Liu, Mu, Luo, & Li, 2012; Maria, Pangilinan, & Janssens, 2007).

Standard SPP is very simple and so is excluded from the 5As analysis.

Model/5As	Availability		Accessibility		Acceptability	Affordability	Adaptability
	Time	Place	Infrastructure	Vehicles			
MSPP	0,5	0	1	0,5	0,5	1	0,5
TDSPP	1	0	1	0,5	0,5	1	0,5
RCSPP	0,5	0	0,5	0,5	0,5	1	0,5
MOSPP	0,5	0	1	0,5	0,5	1	0,5

Table 5 Shortest path optimization models in correspondence with 5As

2.4.2.1 Multi-modal shortest path problem - MSPP

The first group analyzed was the Multi-modal shortest path problem (MOSPP). The MOSPP considers the different modes of transport (Lozano & Storchi, 2001). The main issue with this kind of model is that they cannot provide the level of satisfaction for Place Availability. In fact, they can only offer a delivery place that is on the public transport network. However, the criteria for Infrastructure Accessibility and Affordability are highly rated.

For Time Availability, a medium rating was achieved, as PWD needs to use the standard timetable. Vehicles Acceptability depends on fleet characteristics, so it is not possible to know the percentage of accessible vehicles in advance. A medium rating, with a score of 0.5, was given to Acceptability, which is dependent on the quality of the service provider. Affordability achieved the highest level of satisfaction, and the regular public service is used with the same price ticketing. Adaptability matches well with MOSPP, as the primary demand for Adaptability is to provide a flexible service with multiple trips (multimodal). This issue should take MOSPP to a high-level rating. However, it was decided to rate it as a medium, as the other component of the Adaptability criteria is to provide specialized equipment, and the data was not available in MOSPP.

2.4.2.2 Time-dependent shortest path problem - TDSPP

The following group is the Time-dependent shortest path problem (TDSPP) (Orda & Rom, 1990). This kind of model is employed on the road network, usually in understanding the problem of congestion (Franceschetti et al., 2018). We also found an application on the railway network (Nachtigall, 1995), where the author changed the general approach in calculating the shortest path. The calculation is often made from all possible starting times independently, and, in this case, the desired transit function was proposed for the count.

Interestingly, our study of the TDSPP could make it possible for PWD to achieve the desired journey time on the network. In relation to this TDSPP peculiarity, the 5As feature Time Availability achieved a high level of satisfaction. In all analyzed models, only TDSSP achieved this high rating. Although the other models which used regular time-tabling are similar, yet we wanted to reward effort and the potential to offer PWD their desired journey time. Additionally, TDSPP achieved the highest level of satisfaction for Time Availability, Infrastructure Accessibility, and Affordability.

This is the only model that achieved these scores in SPP, and is equal to DARP. Vehicles Accessibility, Acceptability, Adaptability achieved medium level satisfaction, as in the previous model MOSPP, for the same reasons. Only the Place Availability attribute ranked as zero,

2.4.2.3 Resource-Constrained Shortest Path Problem – RCSPP

Resource-Constrained Shortest Path Problem (RCSPP) forms part of the constrained group of SPP. When assessing the shortest path between two points on a network and on route, some of a vertex absorbs the particular resources (Beasley & Christofides, 1989)

RCSPP was ranked in the 5As evaluation due to limited resources. PWD are faced daily with multiple transport limitations. To the best of our knowledge, the literature does not include the shortest path model that considers accessibility for PWD. It is assumed that the RCSPP has the potential to address this.

The primary constraint of RCSPP is the cost. It depends on the variant considered and can include fuel costs, routing costs, crew wages, etc. RCSPP is the only mode in SPP variants with a 0.5 score for Infrastructure. Accessibility achieved a medium level of satisfaction.

As with all SPP models, RCSPP was rated 0, or low level, for, Place Availability, and one of the highest Affordability ratings. Time Availability, Vehicles Accessibility, Acceptability, and Adaptability achieved medium ratings, with 0.5 scores.

2.4.2.4 Multi-objective shortest path problem – MOSPP

As the name Multi-objective shortest path problem (MOSPP) suggests, this model considers the traditional shortest path problem in relation to multiple objective functions that are often in conflict (Liu et al., 2012). MOSPP is a popular research subject, particularly in route planning, transportation and network design etc. (Granat & Guerriero, 2003). The positive aspect of MOSPP is its approach to address different objective functions. This is appropriate for a very complex transport system, and this complexity arises in the case of transporting persons with disabilities. The same applies to the 5As evaluation model.

The MOSPP achieved the same ratings as the MSPP model. Affordability is rated high, as with all SPP variants. A high rate is also achieved for Infrastructure Accessibility. Place

Availability gets zero, a low level of satisfaction. Time Availability, Vehicles Accessibility, Acceptability, and Adaptability reach a medium level, with 0.5 ratings.

2.5 Legislation literature review

In the screening review of optimization models, particular attention was given to transport legislative frameworks for persons with disabilities and their rights. The current legislation was considered at three different levels: Mondial, European, and national (France and Canada). The intention was to establish an ideal approach for the development of a new transport model for PWD, and identify new constraints that could be improved. A vital part of improving transportation for persons with disabilities exists within the legislative framework, and the proposed thesis solution needs to comply with it. Additionally, the model's formatting depends on the available data structure and should be consistent with information standards.

2.5.1 World-level

Two essential documents were reviewed at a global level: the first is legally binding, and the second is a presentation of reports. The United Nations Convention on the Rights of People with Disabilities (United Nations, 2006) and the World Report of Disability (World Health Organization, 2011) are reviewed in this section.

2.5.1.1 United Nations Convention on the rights of persons with disabilities

The reference point for all studies and the legal basis for further legislation is the United Nations Convention on the Rights of Persons with Disabilities (United Nations, 2006). The United Nations (UN) Convention on the Rights of People with Disabilities (UNCRPD) was adopted in December 2006, submitted for sign-off in March 2007, and came into force in May 2008.

The UNCRPD is the first international legislative obligatory instrument that establishes the minimum criteria for the rights of people with disabilities. The intention is to "promote, protect and ensure the full and equal enjoyment of all human rights and fundamental freedoms by all persons with disabilities, and to promote respect for their inherent dignity"(United Nations, 2006, p. 3).

Article 1 of UNCRPD defines persons with disabilities as "those who have long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others"(United Nations, 2006, p. 3).

In Article 10, UNCRPD proposes that countries ensure that persons with disabilities have their inherent right to life on an equal basis with others, without consideration for age and gender (Articles 6 and 7).

The key article for our research is Article 9, where the issue of accessibility is addressed. UNCRDR requires countries to identify and eliminate obstacles and barriers and guarantee that persons with disabilities have access to their environment, transportation, public facilities and services, and information and communications technologies. Articles 19 and 20 validate the relevance of our research by requesting that PWDs have access to in-home, residential, and community support services to foster personal mobility and independence.

2.5.1.2 World Health Organization

The World Health Organization (WHO) and World Bank Group (WB) collaborated to produce the World Report on Disability (WRD). The purpose of WRD was to provide data on new policies and programs for the improvement of life for PWD. Particular focus was given to expediting and facilitating the implementation of UNCRDR. The WRD recommends that all stakeholders, including governments, civil society organizations, and disabled people's organizations, be consulted. Suggestions include the design of enabling environments, developing rehabilitation and support centers, providing fair social protection, and enforcing new and existing standards and legislation.

Furthermore, the WRD definition of disability is the one used in this thesis, and introduces the *International Classification of Functioning, Disability, and Health* (ICF). "Disability is the umbrella term for impairments, activity limitations, and participation restrictions, referring to the negative aspects of the interaction between an individual (with a health condition) and that individual's contextual factors (environmental and personal factors) (World Health Organization, 2011, p. 4).” ICF has improved the understanding and measurement of disability.

2.5.2 European level

The EU Legal Framework consists of European regulation, directives, communication, and standards. In addition, the EU Legal Framework includes Treaties, Charters, and Strategies. All elements of European regulations are presented within three categories, based on accessibility requirement categories (Bekiaris et al., 2018; The Academic Network of European Disability Experts (ANED)):

- General - declaring that a product or service should be made accessible to persons with disabilities;
- Specific - addressing special measures for a product or service to be accessible to persons with disabilities;
- Detailed - providing full guidelines for the provision of a product or service.

The European legislative framework for transporting persons with disabilities is described in Table 6 (High resolution in Appendix A). Comprehensive analyses are provided for all transportation modes, divided into multimodal (all modes), air, rail, intelligent road (intelligent transport systems), road, intelligent communication (mobile application and the web), and maritime. Different colors indicate different categories of demand accessibility: green is general, yellow is specific and pink is detailed accessibility requirements.

No	Reference	Title	Transport mode	Accessiblity requirements
1	European Union Charter 2012/C 326/02	Charter of Fundamental Rights of the European Union	MULTIMODAL	General
2	Commission communication 2010/0636	European disability strategy 2010-2020	MULTIMODAL	General
3	Commission proposal for a Directive 2015/0278 (COD)	Approximation of the laws, Regulations and administrative provisions of the Member States as regards the accessibility requirements for products and services - European Accessibilty Act	MULTIMODAL	General
4	Commission Regulation (EC) No 1107/2006	Rights of disabled persons and persons with reduced mobility when travelling by air	AIR	Specific
5	Commission Regulation (EC) No 1371/2007	Rail passengers' rights and obligations	RAIL	Specific
6	Commission regulaiton (EC) No 454/2011	Technical specification for interoperability relating to the sub-system “telematics applications for passengers’ services” of the trans-European rail system (TAP-TSI)	RAIL	Detailed
7	Commission Regulation (EC) No 1300/2014	Technical specifications for interoperability relating to the accessibility of the Union's rail system for persons with disabilities and persons with reduced mobility (TSI-PRM)	RAIL	Detailed
8	Commission Directive (EU) No 2016/797	Interoperability of the rail system within the European Union (recast)	RAIL	Specific
9	Commission Directive (EU) No 2010/40	Framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport	MULTIMODAL	Specific
10	Commission implementing decision (EU) 2016/209	Standardization request to the European standardization organizations as regards Intelligent Transport Systems (ITS) in urban areas in support of Directive 2010/40/EU	INTELLIGENT - ROAD	Specific
11	Commission Regulation (EC) No 181/2011	Concerning the rights of passengers in bus and coach transport	ROAD	Specific
12	Commission Directive (EC) No 2001/85	Special provisions for vehicles used for the carriage of passengers comprising more than eight seats in addition to the driver's seat	ROAD	Specific
13	Commission Directive (EU) NO 2016/2102	Accessibility of the websites and mobile applications of public sector bodies	INTELLIGENT - COMMUNICATION	Specific
14	Commission Regulation (EU) 1177/2010	Rights of passengers when travelling by sea and inland waterway	MARITIME	Specific
15	Council Directive 98/18/EC	Safety rules and standards for passenger ships	MARITIME	Specific
16	European Standard EN 16584	Infrastructure and rolling stock - Railway applications - Design for PRM Users	RAIL	Detailed
17	European Standard EN 16585	Rolling Stock-Railway Applications - Design for PRM Use - Equipment and Components On Board Rolling Stock	RAIL	Detailed
18	European Standard EN 16586	Railway applications - Design for PRM Use - Accessibility of persons with reduced mobility rolling stock	RAIL	Detailed
19	European Standard EN 16587	Railway applications - Design for PRM Use - Requirements for obstacle free routes for infrastructure	RAIL	Detailed
20	European Standard EN 12896	TRANSMODEL - Reference Data Model For Public Transport	MULTIMODAL	Detailed

Table 6 European legislative framework for transport of PWD

2.5.2.1 General framework

The following group of documents creates a general framework: Charter on Fundamental Rights, European disability strategy 2010-202, and the European Accessibility Act. The Charter of Fundamental Rights of the EU defines a fundamental set of rights that should be under protection in the EU. EU activities and initiatives supporting PWD inclusion in society fall under the Fundamental Rights of the EU. The Charter contains rights and freedoms such as dignity, equality, solidarity, citizen's rights, and justice. In December 2000, the Charter was an initiative that was not legally binding. However, after nine years, in 2009, it came into force. The EU's Charter of Fundamental Rights prohibits discrimination on the ground of disability and recognizes the right of disabled people to be integrated (European Union, 2012).

The European Disability Strategy 2010–2020 (European Union, 2010) is based on the UN's Convention. The strategy addresses eight areas:

I. Accessibility: goods and services to be designed to be accessible to PWD, and businesses to be supported in the provision of assistive tools;
II. Participation: guarantee that PWD have all the advantages of EU citizenship; elimination of obstacles to allow equal participation in public life and recreational activities;
III. Equality: promotion of equal opportunities;
IV. Employment: increase employment of persons with disabilities;
V. Education and training: promote education and lifelong learning;
VI. Social protection;
VII. Health: promote equal access to health services and related facilities;
VIII. External action: promote the rights of PWD in the EU's enlargement and international development programs.

Our research is in accordance with the commitment to Participation and Equality informs of the provision of full independence in PWD transport.

The European Accessibility Act is a bill proposal that would increase the accessibility of numerous products and services in the European Union (EU) for persons with disabilities. The proposal relates to products and services, including smartphones, tablets, and computers; ticketing machines and check-in machines; televisions and TV programs; banking and ATMs; e-books; online shopping websites and mobile applications.

2.5.2.2 Specific framework

As mentioned above, the Specific framework considers the special factors for a product or service to be accessible to persons with disabilities. This categorization belongs to the EU regulations, directives, and technical specifications for interoperability – TSI. In this respect, there are ten documents that define particular transport mode variants such as rail, road, air, maritime, multimodal and intelligent systems. Below is a general view.

This specific framework concerns the rights of PWD when traveling by air, rail, bus, coach, and maritime and defines the terms of assistance to be provided by airports, airlines, railway operators, railway infrastructure managers, and bus services, including the non-discrimination principle. PWD rights are also defined in the case of delay or cancellation. Additionally, it covers specific requirements for the accessibility of vehicles used in urban passenger transport, obligations concerning disability accessible signs, and information for all transportation modes.

2.5.2.3 Detailed framework

The detailed framework provides the technical specification for interoperability applicable to transport modes and infrastructure in railway systems, establishing technical standards.

A universal approach is applied to the operation of railway transport across all countries and member states of the EU. This approach makes it particularly applicable for persons with disabilities. This framework defines technical specifications for interoperability relating to subsystem “telematics applications for passenger services” of the trans-European rail system (TAP-TSI), as well as TSI relating to the accessibility of the Union's rail system for PWD (TSI-PRM). TSI-PRM states the requirements for railway services and means of access using lifts, ramps, boarding facilities, information systems, etc.

Additional detailed documents are included in the European Standards (EN), wherein the railway system leads again with four standards. These all relate to railway applications designed for PWD use. EN 16584 covers infrastructure and rolling stock - General requirements; EN 16585 relates to rolling stock - part of Equipment and Components On Board

Rolling Stock; EN 16586 Accessibility of PWD on rolling stock; and EN 16587 defines requirements for obstacle-free routes for infrastructure.

The last EN standard on our list in Table 6 is TRANSMODEL, Reference Data Model For Public Transport. Public transport services depend on information systems, and this standard defines a uniform way of gathering, saving and marking data systems. TRANSMODEL meets those needs, and covers the entire domain of public transport operations. This standard is composed of several subdomains such as: transport network infrastructure and topology, public transport schedules, journey planning, fares, fare validation, real-time passenger information and operational aspects of public transport.

2.5.3 National legislations

The thesis research project was carried out at two laboratories in France and Canada, so their respective national legislation applies in both cases.

2.5.3.1 The French law for PWD transport

The French framework for PWD transportation has been legally binding since 2005, and relates to the accessibility of facilities open to the public, public transport, residential buildings and roads for persons with disabilities (JORF, 2015). This legislation has had several amendments since 2005, the most recent being in 2015. Transport accessibility is defined under Title IV “Accessibility,” chapter 3) Built environment, Transport, and New technologies.

In order to ensure the implementation of the law, the French government established in 2010the Inter-Ministerial Observatory for accessibility and universal design (*Observatoire interministériel de l’accessibilité et de la conception universelle).* Regarding transportation, principles were developed to implement accessibility schemes for transport services (*Schéma Directeur d’Accessibilité des services de transports, SDA*). SDA helped to refine the program of transportation accessibility, recognized challenges, and defined the accessibility modes of various transportation types, as well as maintenance (The Academic Network of European Disability Experts (ANED)).

2.5.3.2 Canada Transportation Act

In Canada, the current relevant legislation is the Canada Transportation Act (Canada Gazette, 1996), which states that the transport system is to be accessible without unnecessary obstacles to the movement of persons, including persons with disabilities. Recently, the Canadian transport agency proposed the legal basis of the Canada Transportation Act, the Accessible Transportation for Persons with Disabilities Regulations (ATPDR), which was adopted in 2019 (Canada Gazette, 2019).

ATPDR includes some voluntary codes of practice such as: Aircraft Accessibility for Persons with Disabilities; Passenger Rail Car Accessibility and Terms and Conditions of Carriage by Rail of Persons with Disabilities; Ferry Accessibility for Persons with Disabilities; Removing Communication Barriers for Travellers with Disabilities; Passenger Terminal Accessibility; and Accessibility of Non-National Airports System Air Terminals.

ATPDR aims to support the inclusion and participation of PWD in society by defining inclusive and accessible transportation requirements for all transportation modes. ATPDR covers the following eight generic areas: Application, definitions, and interpretation; service requirements in the accessibility of transportation; technical provisions for facilities and equipment; terminals; security screening and border clearance; training; communication; administrative monetary penalties for non-compliance.

2.6 Conclusion

The comprehensive analysis of the key components for the independent transport of PWD is completed. This analysis was divided into three parts: transport on-demand optimization models, shortest path optimization models, and legislative framework.

The systematic review directed the first two parts: transport on-demand and shortest path. The screening results recognized six models in transport on-demand optimization models such as: Dial A Ride Problem - DARP; Demand Adaptive System - DAS; Flexible Transport System - FTS; Scheduled Paratransit Transport System – SPTS; Mobility Allowance Shuttle Transit - MAST, and Integrated Dial-a-Ride - IDAR. The shortest path optimization models generated four models: Multimodal Shortest Path Problem - MSPP; Time Dependent Shortest Path Problem - TDSPP; Resource Constrained Shortest Path Problem - RCSPP; and

Multi Objective Shortest Path Problem - MOSPP. It has been demonstrated that these optimization models are suitable for the transport of persons with disabilities.

In addition to the classification contribution, all models are described and evaluated for the first time in relation to the 5As attributes. A ranking list, with detailed studies of every model component, is provided. A thorough examination has shown that existing optimization models cannot provide transport for persons with disabilities to ensure their full independence.

Finally, the chapter provided an extensive review of legislation globally, across Europe, and nationally (France and Canada). This enables us to establish the transport legislative framework for PWD, and identifies a potential new approach that could allow PWD to come closer to achieving unobstructed travel in line with existing recommendations.

Chapter III

3 An integrative decision-aiding approach to the inclusion of persons with disabilities in a public transport system

3.1 Introduction

Accessibility is one of the prerequisites for ensuring an adequate transport level for persons with disabilities (United Nations, 2014). It is already well recognized that providing accessibility for everyone is a lengthy process requiring many investments. The combination of cost issues, and a very complex transport system with a vast spectrum of different participants, raises the question of how to provide the best service that meets PWD needs.

However, from another perspective, transport-on-demand evolved at a time when public transport could not provide appropriate access for PWD to transport facilities (Davison et al., 2014; Environment, 1961; Ryley, Stanley, Enoch, Zanni, & Quddus, 2014), either due to the mode of transport or the network itself.

Currently, the situation is quite different. Improvements have been made to comply with legislation committed to providing equal service for all, which benefitted from significant public transport investment. In this way, the public transport aptitude has raised and encouraged meeting the PWD's needs. The challenge is to identify the best model that will provide the optimal PWD integration in public transport, as indicated above.

The decision-aiding process (DAP) (Tsoukiàs, 2007) helped clarify the key issues already reported and considered by PWD. This was consequently adopted as a framework for integrating the challenges of PWD in transport systems. The DAP is presented through its four stages, namely: problem situation, problem formulation, evaluation model, and final recommendations. These stages integrate the legal framework, stakeholders involved in the process, and PWD needs and obstacles they face to define the problem statement. The problem statement is proposed using several potential actions by the client in relation to the problem situation. The beneficiaries are persons with disabilities (wheelchair users), and the procuring entity is the public institution at a community level.

This chapter is structured as follows: Section 3.2 describes the DAP methodology used. Section 3.3 describes the practical implementation of this methodology. In this section, a model was designed that ran through the phases of the decision-aiding process. Subsection 3.3.1 gives an overview of the participants in the transportation system and describes problem scenarios. The next DAP stage, subsection 3.3.2, processes the problem formulation with the developed matrix of relations. Section 3.3.3 presents several optimization models as evaluation models. Final recommendations of the proposed methodology are given in Section 3.3.4. Finally, section 3.4 offers the conclusion

3.2 Decision-aiding process

The framing of decision-aiding methodology started around the end of the 1960's (Roy, 1996). This framing arose because of the need to develop a single comprehensive method that could build a model applicable to all research disciplines. In general, traditional operational research has intended to optimize economic function within given feasibility constraints (D. Bouyssou, 2006). For example, in conventional operational research models, attempts are frequently made to develop solutions to the wrong problem (Ackoff, 1979; Belton & Stewart, 2002; Eppen & Gould, 1984; Rosenhead, 2006; Rosenhead & Mingers, 2001; Tsoukiàs, 2007). In addition to the challenge of structuring the problem, some studies have demonstrated that the algorithms selected to solve traditional operational research problems have not been particularly useful in practice (Ehrgott, 2005; Franco & Montibeller, 2010; Greco et al., 2005; Greco et al., 2016; Hartmanis & Stearns, 1965; Karp, 1975). Developing an optimal solution usually arrives through cognitive, theoretical, and epistemic problems, but now we can say that we are addressing a practical, real-world problem (Jackson & Keys, 1984; Papadimitrou & Steiglitz, 1982; Tsoukiàs, 2008).

For a better understanding of the decision-aiding process, we start with its definition. The author Bernard Roy, who established the European school of Decision Aiding (Roy & Vanderpooten, 1997), gives his definition: "Decision aiding is the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps obtain elements of responses to the questions posed by a stakeholder of a decision process. These elements work towards clarifying the decision and usually towards recommending, or simply favoring, a behavior that will increase the consistency between the evolution of the process and this stakeholder's objectives and value system"(Roy, 1985, p. 10; 1996, p. 10).

The decision-aiding process is a method that provides help to the "client," which can be any entity (person, company, etc.) in getting a rational solution to the problem. The main characteristic of this tool is that we have to have a minimum of two participants: the client (who can be a decision-maker) and the analyst (D. Bouyssou, 2000, 2006). Another feature is the existing interaction between the client and the analyst inside the DAP methodological framework. This interaction allows the client and analyst to control the DAP formally (Tsoukiàs, 2007).

The decision-aiding process demonstrates that a particular problem is not within a decision process, but that the process of setting and solving a problem forms part of the same exercise (H. A. Simon, 1983). From this point of view, we implemented our solution to the problem already incorporated within its construction. This resulted in our naming of the methodology used as an integrative decision-aiding approach.

3.2.1 Decision-aiding approaches

Different decision approaches focus on different disciplinary interests. Initially, this implied two approaches: normative and descriptive. Then, the prescriptive approach was added, and finally the constructive approach (Bell, Raiffa, & Tversky, 1988; R. Brown & Vari, 1992; R. V. Brown, 1989; Franco & Montibeller, 2010; Keller, 1989; Koehler & Harvey, 2008; Luce & Von Winterfeldt, 1994; Roy, 1996; Starmer, 2000; Tsoukiàs, 2008). In the literature, they are associated with approaches to decision theory. However, the later work of Roy, Tsoukiàs, and others (D. Bouyssou, 2000, 2006; Dias & Tsoukiàs, 2003; Roy, 1985, 1996; Roy & Bouyssou, 1993) has identified them as four approaches of decision-aiding.

Brown developed a scientific view that analyzed normative and descriptive approaches (R. Brown & Vari, 1992; R. V. Brown, 1989; Fischer, 1989). Statistical decision theory, traditional operational research are appropriate for the normative approach. This approach considers how idealized people would arrive at their decisions. It proposes a perfect, abstract process. Research from mathematics and organizational theory are more inclined toward the descriptive approach, which shows how people make their decisions. In contrast to the normative approach, here is a real process that attempts to present the world as it is.

The prescriptive approach includes both normative and descriptive approaches. The path of this approach is to unveil clients' values system through answers to the preference questions. The issue in this approach is how people should best make their decisions. The constructive approach builds a model based on the interaction between the client and analyst. In this scenario, the structuring and formulation of the problem are effectively aligned with the process of solving it. (Belton & Stewart, 2002; Denis Bouyssou et al., 2012; Marttunen, Lienert, & Belton, 2017; Rosenhead, 2006; Rosenhead & Mingers, 2001; Roy et al., 2002; H. A. Simon, 1973).

Differences among the decision-aiding approaches come from the process used to obtain the model (D. Bouyssou, 2000, 2006; Dias & Tsoukiàs, 2003; Tsoukiàs, 2007, 2008) as presented in Figure 12. The normative approach postulates the model, the descriptive approach observes it, the prescriptive approach exposes the model, and the constructive approach arrives at a consensus.

Approach	Characteristics		Process to obtain the model
Normative	Exogenous rationality, ideal economic behavior	How ideal people ***would make up*** their minds	To postulate
Descriptive	Exogenous rationality, empirical behavior models	How people ***do make up*** their minds	To observe
Prescriptive	Endogenous rationality, coherence with the decision situation	How people ***should make up*** their minds	To unveil
Constructive	Learning process, coherence with the decision process	Interaction between the client and analyst	To reach a consensus

Figure 12 Different decision aiding approaches

Our work is consistent with the principles of Bouyssou et al. (D. Bouyssou, 2006), stating that decision-aiding approaches do not use a single exclusive method or set of methods concurrently. Equally, the chosen method does not determine the decision-aiding approach. One of the contributions of this thesis is the practical implementation of the decision-aiding process. This chapter has used the constructive approach. A detailed explanation of the stages is provided at every step of our model.

3.2.2 Description of the model of the decision-aiding process

There are four phases in the decision aiding process: problem situation, problem formulation, evaluation model, and final recommendation (D. Bouyssou, 2000, 2006; Tsoukiàs, 2007). Each phase is presented separately with its main characteristics.

3.2.2.1 Problem situation

The first phase of the DAP is the problem situation. The problem situation aims to define: the origin of the client's problem and involvement, identify the consequences of a decision, and the most rational way of providing a solution. The latter is also useful for the analyst to precisely define where and how assistance could be provided.

At this stage, the objective is to identify the problem but not to fix it. It enables improved evaluation of the client's demands for assistance and associates them with possible responses (Crévits, 2013). Some of the questions requiring an answer in the problem situations include: Who has a problem? Why is this a problem? Who decides on this problem? What is the commitment of the client to this problem? Who is going to pay for the consequences of a decision?

The problem situation $\mathcal{P}$ is a triplet of $\langle \mathcal{A}, \mathcal{O}, \mathcal{S} \rangle$, where:

- $\mathcal{A}$ represents all participants (actors) included in the decision process;
- $\mathcal{O}$ represents all objects (stakes) that participants from $\mathcal{A}$ could bring to the process;
- $\mathcal{S}$ represents all resources that participants from $\mathcal{A}$ are ready to commit to their stakes from $\mathcal{O}$, and the other participants' stakes.

One example from the book (D. Bouyssou, 2006), which will be used here, is the construction of a new highway intending to improve the connection between two cities through a particular region. In this case, the actors are the potential constructors of the highway, the local, regional, and national institutions (including the "National Road Agency"). All of them have particular concerns, such as the highway construction, the environmental impact, the socio-economic impact, the transformation of the land use, the transportation policy, the environmental policy. The resources and commitments which each of those participants should bring are: potential constructors commit money and demand knowledge and authorization; the regional authority commits authorization and political legitimation and demands infrastructures and political legitimation, etc.

3.2.2.2 Problem formulation

The next phase in DAP is the problem formulation, with Γ represented by a triplet $\langle \mathrm{A}, \mathrm{V}, \Pi \rangle$, where:

- A represents the set of potential actions that the client could perform within the frame of the problem situation $\mathscr{P}$;
- V represents the set of points of view under which the potential actions will be observed, analyzed, evaluated, and compared;
- Π represents the **Problem statement**, which is the decision problem: - the possible application of set A within the anticipation of what the client expects.

To continue with the construction of a highway from the previous sections, some of the possible presentations of problem formulation are: build the highway or not; freeway a toll-highway; which route; what the procedure to approve the route should be(D. Bouyssou, 2006).

The problem's formulation is an essential step in constructing the interface between the client and analyst. In fact, this is the first attempt to reframe one or more of the client's concerns into formal problems. It creates the link between the decision problem, as seen implicitly by the client, and a representation manipulated by assistance to produce a result. The formulation of the issue by explaining the decision problem allows the analyst to prepare the modeling work to the client in an intelligible way, thus acknowledging the expression of his/her point of view and his/her intervention.

The formal problem is the result on which we can implement existing methods in decision theory and operational research. The key question needing a response is: “What are we going to decide about?”. The statement summarizes the degree of difficulty in defining the problem formulation: “Half of a problem is deciding what to decide”(Tsoukiàs, 2007, p. 16).

Another factor to consider is what does makes the decision-aiding process a powerful tool. Usually, some decision-aiding approaches stop here, after the problem formulation or the problem settings have been established. The doctrine followed is an equivalence between problem formulation and problem solving. In this way, the decision-aiding process is restricted to formulating problems, accepting the formulation as given, or a particular client's concern.

As mentioned above, this thesis applied the constructive decision-aiding approach, and the problem formulation is one of the outcomes. Furthermore, the problem formulation should be used in the construction of the evaluation model.

3.2.2.3 Evaluation model

The evaluation model aims to accurately estimate the impact of the solution envisaged in the problem formulation. As with the problem situation and formulation, the evaluation model has five parts: $\mathcal{M} = \langle \boldsymbol{A}, \{\boldsymbol{D}, \boldsymbol{E}\}, \boldsymbol{H}, \mathcal{U}, \mathcal{R} \rangle$, where:

- ***A*** represents the set of alternatives on which the evaluation model is based;
- ***D*** gives the set of dimensions, possibly provided with structural properties, by which the model manipulates the potential actions of ***A***;
- ***E*** represents the set of scales associated with each element of ***D***;
- ***H*** represents the set of criteria on which the factors of ***A*** are evaluated in order to take into account the preferences of the client, restricted to each criteria;
- $\mathcal{U}$ represents the set of uncertainty distributions associated with ***D*** and ***H,*** or only ***H***;
- $\mathcal{R}$ offers the set of information synthesis operators of the elements of ***A*** or ***AxA,*** notably the aggregation operators.

This kind of model representation is highly consistent with the decision-aiding models conventionally used in (Crévits, 2013), also widely used in traditional operational research, decision support, and artificial intelligence (Tsoukiàs, 2007). Also, the main feature of these models is that they are generally generate numbers. Usually, evaluation is understood by most people by using a number (D. Bouyssou, 2006). However, what is not so well appreciated, and will be proved in this thesis, is that numbers do not necessarily represent the evaluation models. Different types of evaluation models include sets, relationships, geometrical figures, logic languages, algorithms, and graphical interpretations (D. Bouyssou, 2006; Cimon, 2004; Crevits et al., 2002; Lapointe & Cimon, 2009; Véronneau & Cimon, 2007). This thesis proposes the concept of relationships among different optimization models and proposes the algorithm that governs their interactions, depending on network information.

Validation of the evaluation model

The evaluation model can be subjected to several internal validations: - logical consistency of the elements of the model, experimental validation, and external validations relating to the reality of the problem and decision (Crévits, 2013). Model validation is recognized as a critical element of operational research from the origin of this discipline.

Even at the beginning of operational research, the validation is recognized among the six phases that should consist of one operation research project (Churchman, 1957; Sargent & Balci, 2017). Our research interest is the validation processes of the evaluation model, as defined by Landry et al. (Barlas, 1996; Déry, Landry, & Banville, 1993; Eker, Rovenskaya, Obersteiner, & Langan, 2018; Landry, Banville, & Oral, 1996; Landry, Malouin, & Oral, 1983).

One of the disadvantages of these types of model validations is that the presented analyses anticipate that a valid model would deliver a logical process. This approach fails to take into account the interaction between analyst and client (Hämäläinen & Lahtinen, 2016; Hämäläinen, Luoma, & Saarinen, 2013). This lack of process validation (Landry et al., 1983) is overcome in the DAP as the critical element of these processes is precisely the interaction between analyst and client. Consequently, we modified the process validation scheme carried out by Landry and used it effectively in our research. Types of validation processes (conceptual, logical, experimental, and operational validation) and their location are presented in Figure 13. Between the steps of the problem situation and problem formulation should be applied a conceptual validity. The conceptual validation checks if the model is in coherence with the client's concerns and problem situation. Between the problem formulation and model evaluation is a checkpoint for the logical validation. The logical validation checks if the concepts and tools used in the model are reasonably compatible and meaningful. The next verification point is between the model evaluation and final recommendations. This is names as the experimental validity and serves to test the model with the experimental data. The last checkpoint is the operational validity, located between the final recommendation and the problem situation.

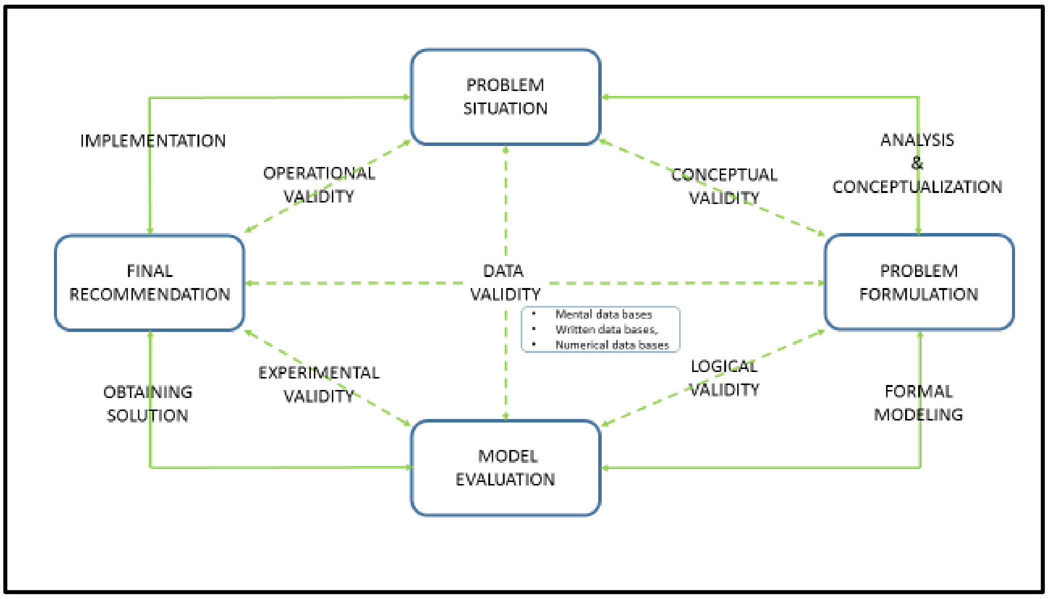

Figure 13 Validation process

3.2.2.4 Final recommendation

The final recommendation Φ reports the result of the evaluation model in the context of the client's language, based on three questions:

- meaning: the ability of the recommendation to respond to all the customer's concerns;
- operational completeness: the potential of the recommendation to be implemented; and:
- legitimacy: coherence of the recommendation in the decision context that is usually not treated in the evaluation model (D. Bouyssou, 2000, 2006; Crévits, 2013; Landry et al., 1996; Tsoukiàs, 2007).

3.2.2.5 Fulfillment of the decision-aiding process

In order to complete this illustration of the decision-aiding process, a detailed presentation of DAP (Tsoukiàs, 2007) shows the construction hierarchy of artifacts and sub-artifacts, as described in Figure 14. The preceding links should not be seen as strictly sequential stages following from $\mathcal{P}$ to Φ. Instead, they are intended to guide the client and analyst to the questions that arise during the designing decision aid. However, backward and forward steps are quite possible if progress in DAP shows that thinking about an artifact requires going back to previously defined options or adding to them. The participants, potential actions, and the alternatives provide several starting points for the construction of the problem situation, the formulation of the problem, and the evaluation model. It is noted that Π and $\mathcal{U}$ are exclusively contributed by the analyst (Crévits, 2013; Crevits et al., 2002; Crévits & Labour, 2012).

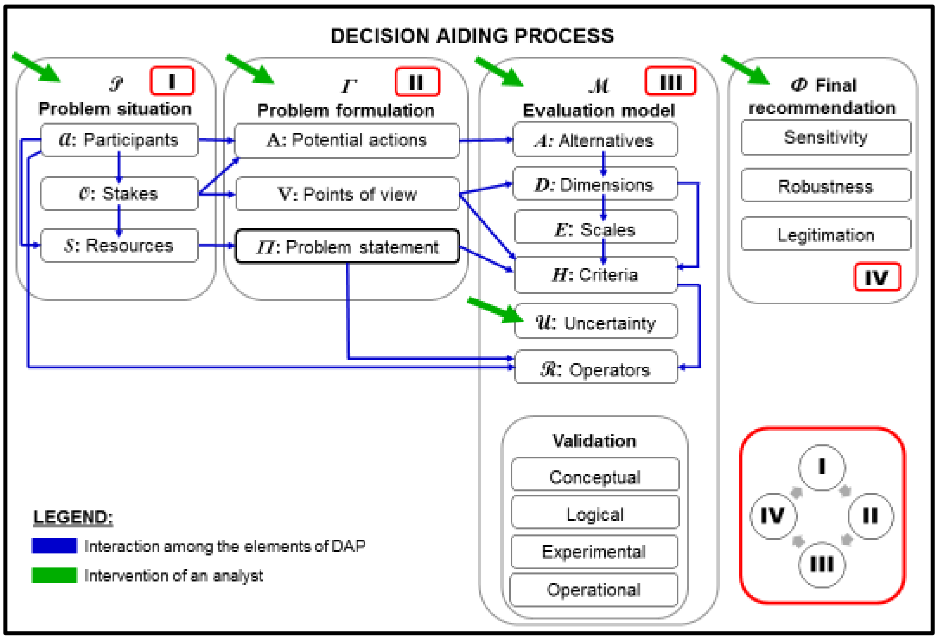

Figure 14 Decision aiding process

3.3 Model design – practical DAP performance

In this section, the decision-aiding process is applied to a practical problem. All phases are implemented and presented, as explained in the methodology. The client is a public institution, and PWD is the beneficiary. The experts provide the decision-aiding function within three different research fields: optimization, management, and decision-aiding. This means that all possible issues arising within the framing of the model will be familiar to people who deal with these types of issues on a daily basis.

Article 20 of the Convention on the Rights of Persons with Disabilities defines the mobility of a person with disabilities, which is to optimize the independence for PWD through: "(i) Facilitating the personal mobility of persons with disabilities in the manner and at the time of their choice, and at affordable cost. (ii)Facilitating access by persons with disabilities to quality mobility aids, devices, assistive technologies, and forms of live assistance and intermediaries, including by making them available at an affordable cost (iii)Providing training in mobility skills to persons with disabilities and specialist staff working with persons with disabilities; (iv) Encouraging entities that produce mobility aids, devices and assistive technologies to take into account all aspects of mobility for PWD (United Nations, 2006, p. 12)"(Barton, 2006; Iriarte, McConkey, & Gilligan, 2015; MacLachlan & Swartz, 2009). The research in this thesis is aligned with this statement.

3.3.1 Problem situation

The first phase of the decision-aiding process is to identify the actors (participants) involved in the problem and define their objectives (stakes) within the issue. The third figure (element) of the triplet is the resources that participants are prepared to commit. The transportation chain presents one extensive system with many participants. To start, we used participants involved in transportation projects, as defined by the study supported by the European Commission (Kelly et al., 2004). They are classified into three groups: Government/Authorities, Business/Operators, and Communities/Local Neighborhoods.

Decision levels provide a more detailed classification of participants: strategic level relates to the Government and Authorities, tactical level to Business and Operators, and operational level to Communities and Local neighborhoods. The detailed list is presented in Table 7 with the rest of the parameters for the problem situation (Cascetta, Carteni, Pagliara, & Montanino, 2015; Council of Canadian Academies, 2017; Erkul, Yitmen, & Çelik, 2016; Meyer

& Miller, 2001; Roberts & Babinard, 2004; Weiner, 1999). Each participant presented in Table 7 is associated with the objects and stakes. We could see a large specter of different concerns for the inclusion of PWD in public transport.

Among the participants, our client belongs to two groups: Local Authorities and Local Transport Authorities. The objects and stakes that participants could bring to the problem are: deployment of implementation instruments and resources; improved communication within government, regional government and project; offering of expertise and advice; and effective management of traffic and transport demand. The beneficiary's possible actions (PWD) are defined as the individual needs of different types of disability.

a	*o*	*s*
Actors/Participants	**Objects/Stakes**	**Resources**
Government/Authorities		
International organizations (United Nations, World Health Organization, World bank)	Contributing resources (information, ideas and financial resources)	Staff capacity
	Expertise in good practice	Staff knowledge
	Legitimation, validation	Sharing information and data
	Promoting the value of the project	Project funding
	Support and promotion of Research & Development in the field of universal design (goods, services, equipment, and facilities)	Regularly budgeted publicity
	Provide the criteria for PWD to have an equal level of access with others (physical environment and transportation)	Funding for new studies
European Union (Institutions of European Union: European Commission, European parliament, Agencies of European Union in the appropriate field, European Investment Bank, European Regional Development Fund)	More efficient, safe and secure transport in technical and regulatory areas	Working groups
	Financial support through the different frames of the projects (research and innovations, cross-border cooperation, founds for regional development)	Planned annual budget
	Better understanding and promotion of transport for PWD	New studies and presentations within annual budget
	Legitimation, validation	Sharing information and data

	Unique market - better integration of project within the EU single market (retain the possibility of buying new vehicles, building new infrastructure, etc)	Investments planned annual budget
	Promote universal design and universal access	Advertising
National ministries (Transport, Social Care, Equality, Public Works, Environment)	Legal and technical obligations	Improving legislation
	Linking legislative framework from different fields of work for PWD	Working groups
	Financial support, possible subventions, and budget planning	Annual budget
	Promotion and integration with other government projects	Advertising
Regional Government (City/regional authorities)	Lobbying, advocacy, advertising	Staff resourcing
	Technical expertise, monitoring implementation	Staff resourcing
	Validation of compliance with national legislation and technical standards	Working groups
	Connection between different regional projects	Participating in common interest groups
	Financial support: (Fund/support local concessionary fares/services for PWD)	Implementation of legislation
Local Authorities	Deploying implementation instruments and resources	Annual budget
	Improving communication between government, regional government and project	Staff resourcing, Working groups
Neighboring Cities	Better transportation network integration	Common projects
Local Transport Authority	Expertise, advice	Staff capacity
	Effective management of traffic and transport demand	New studies

Businesses/Operators		
National Business Associations	Improving business performance	Staff resourcing, annual budget
	Inclusive design standards to be produced, promoted, and shared "Best accessibility practices" to be recognized and classified	Sharing information and data New studies
	Work with PWD to develop need-focused products/services	Working groups
Major Employers	Improving business performance	Staff resourcing, yearly budget
Regional and National Businesses - state-owned/public companies (Rail/bus operators/infrastructure managers)	Improving business performance regionally and country-wide	Staff resourcing, annual budget
	Delivery of accessible transport services and infrastructure	Annual budget
	Provision of concessionary fares/services for PWD	Staff resourcing, annual budget
	Training of employees, raising awareness of PWD's transport needs	Annual budget
Private Financiers	Create synergies between public transport and private companies	Working groups
Local Business Associations	Improving business performance - the connection between private business and national institutions within	Staff resourcing
Town Centre Retailers/Hospitals/Medical and rehabilitation centers	Feedback on the scope of data and demands of PWD	Sharing information and data
Small Businesses	Taxis and other private enterprises	Investments planned by annual budget
Communities/Local Neighborhoods		
National Environmental NGOs - Non-Governmental Organisations (NGOs) (Disability and special interest groups, lobbyists, advocates)	Develop, share and promote inclusive design standards	Sharing information and data
	Advocate accessibility for PWD to national and local government, transport operators, professional bodies and delivery agents	Staff resourcing
	Record and monitor impact of accessibility actions	Working groups
	Provide and promote disability awareness training, including consultation for service design accessibility issues	Advertising
	Undertake accessibility audits of existing infrastructure/services	New studies

Motorist Associations	Promote the best conditions	Sharing information and data
Trade Unions	Promote the needs of major employers	Sharing information and data
Media	Education, information	Advertising
Local Authority Forums	Implementation	Staff resourcing
Local Community Organizations - Delivery consultants (e.g. Transport/Construction/Development consultancies)	Integrate inclusive design standards in projects	Staff resourcing
	Engage local PWD stakeholders and NGOs in project design	Staff resourcing
	Incorporate the public/private sector in defining accessible operational and maintenance management	Working groups
Local Interest Groups	Implementation	Staff resourcing
Cycle/Walking Groups	Implementation	Staff resourcing
Public Transport User Groups	Implementation, feedback information	Sharing information and data
Transport Users	Implementation, feedback information	Sharing information and data
Citizens	Implementation, feedback information	Sharing information and data
Visitors	Implementation, feedback information	Sharing information and data
Citizens in Neighbouring Cities	Implementation, feedback information	Sharing information and data
Disabled People	Different needs of different types of disability	Participating in groups of common interests
Transport Staff	Implementation	Working hours

Table 7 Problem situation

3.3.2 Problem formulation – Matrix

Before applying the problem formulation using the triplet$\langle$A, V, $\Pi\rangle$ PWD needs must be defined. Then research is conducted more deeply into studies that analyze and make recommendations for the successful transport of PWD. In addition to PWD needs, some obstacles compromise the access of PWD to public transportation. Awareness of the complex diversity of both needs and constraints is derived from the enormous number of participants already defined in Section 3.3.1. In this phase, a matrix of relationships was developed with associated potential actions. The matrix also generates a feasible solution to the problem, to be defined as the problem formulation. The matrix is composed of all three elements of the problem formulation $\Gamma = \langle \mathrm{A}, \mathrm{V}, \Pi \rangle$.

The outcomes of the generally known study carried out by the Beverly Foundation (Beverly Foundation and Community Transportation Association of America, 2004) and accepted by the U.S. Government Accountability Office (U.S. Government Accountability Office (GAO)) have been incorporated. The detailed matrix is presented in Appendix B, Table 16. The study is for the elderly, but this thesis used it as a reference point for people with disabilities. This approach is validated by the definition of disability, which recognizes senior people as persons with disabilities. The first column of the matrix defines 5As: availability, accessibility, acceptability, adaptability, and affordability (U.S. Government Accountability Office (GAO), 2004).

Availability relates to providing a transport service at the time and place requested by PWD, one of the key concerns with transport on demand being that PWD has to book the service at least a day in advance. Accessibility is the most important issue and links to access to all transportation facilities. Acceptability is meeting the needs of PWD by providing a clean, safe, and user-friendly transport service. Affordability is the need for financial support to establish a ticketing policy that is adapted for PWD. Finally, Adaptability is the delivery of a flexible transport service that includes multimodal trips and specialized equipment.

The second column of the matrix identifies more specific needs of PWD. In this section, 5A's are associated with themes such as:

1. Availability
   a. Time
   b. Place

2. Accessibility
    a. Information and travel training
        i. Pre-journey planning information
        ii. Information at transport stops and stations
        iii. On-board information
        iv. Travel training
        v. Disability awareness training

    b. Pedestrian footways and street crossing
        i. Footways and sidewalks
        ii. Dropped curbs and street crossings

    c. Public transport stops and station infrastructure
        i. Bus stops
        ii. BRT (Bus Rapid Transit) and light rail stops
        iii. Major bus/train/metro interchanges and terminals

    d. Public vehicles
        i. Buses and Mass Transit Vehicles
        ii. Trains

    e. Private modes of transportation
        i. Adapted vehicles
        ii. Parking facilities and associated concessions
        iii. Taxis and minivans

3. Acceptability
4. Affordability
5. Adaptability

The subclassification of 5As has been adapted for this research and includes the World Bank study (World Bank, 2013). The second column mentioned earlier suggests technical details for improving accessibility for PWD to transport, which forms part of our research. The further technical information given in this thesis is drawn from the study "Survey of information for people with reduced mobility in the field of public transport" (Institut für barrierefreie Gestaltung und Mobilität GmbH, 2003).

This research was conducted through European, French, Canadian, American legislation (Canada Gazette, 2019; European Parliament and of the Council, 2007, 2011; European Union, 2014; France, 2014; United States Congress, 1990), studies, research papers concerning people with disabilities. These have been used as a database for establishing the matrix presented in Appendix B (Belter & Gerike, 2008; Bühler, Heck, Sischka, & Becker, 2006; Council of Canadian Academies, 2017; Litman, 2017; Lubin & Deka, 2012; Nuworsoo, 2009; Suen & Mitchell, 2000; Velho, 2019; Verseckienė, Meškauskas, & Batarlienė, 2016; Wasfi, Steinmetz-Wood, & Levinson, 2017).

The first row indicates the level of decision and presents a different point of view. The strategic level is Institutional and Economic barriers; the tactical level is Operator and community attitudes, and Information and education obstacles; and the operation level relates to operational issues. A simplified version of the matrix is presented in Table 8. since that detailed matrix in Table 16. needs a lot of space.

The second row in the matrix identifies obstacles, which are defined as Institutional framework - Legislation - Conceptual outlook - Policy; Economic issues - Finance - Budget – Fundings; Operational issues; Operator and community attitudes - Stakeholders approaches; Information and education - Human and Social resources (Daniels & Mulley, 2012; Mulley et al., 2012).

Received input from the client excludes new investment that produces a feasible solution to the problem formulation within the existing transportation network. The above information determines the problem formulation setting at the operational level. However, the tactical and strategic level helps define possible future actions or new client strategies. This clearly demonstrates DAP's potential, as it enables the client to gain insights beyond their perceived problem, providing a better position on the market. An additional benefit is the leverage of information between the levels. This thesis does not address potential actions beyond the client realm. Besides the leverage of information, the other zones provide alignment between the participants in a transportation system. After an in-depth analysis, four feasible zones were identified for Problem formulation Table 8 (in red).

The first zone associates the elements of availability, time and place, with potential actions:

- Fleet capacities - Scheduling - Minimizing total vehicle travel time; the overall journey time; the fleet size; the number of vehicles; maximum flow time; vehicle time out; travel time of each user - Maximizing the number of requests served; the number of applications served on time (Molenbruch et al., 2017);
- Network capacities - Involved additional service through door-to-door service - Minimizing the total distance traveled; the total route costs - Maximize the number of requests served; the number of applications served on time (Alumur & Kara, 2008; Gelareh & Nickel, 2011).

The second zone relates to accessibility to public vehicles, Buses and Mass Transit Vehicles, and Trains:

- Fleet efficiency - Flexible route - Vehicle routing problem - Demand adaptive system - Mobile allowance shuttle transit - Demand Responsive Bus Routing Problem (G. Dikas & Minis, 2014; Molenbruch et al., 2017);
- Line planning (maximize passenger service, minimize operational costs of the railway system) - Timetabling - Platforming - Rolling stock circulation - Shunting - Real-time traffic control - Number of direct connections, frequencies, and reliability (Caprara, Kroon, Monaci, Peeters, & Toth, 2007; Lusby, Larsen, & Bull, 2018);
- Integrate transit and feeder services - Real-time response to changing demand - New personalized public transit - Define hub center to bring PWD to the public network (Farahani, Hekmatfar, Arabani, & Nikbakhsh, 2013).

The third zone relates to accessibility in private modes (taxis and minivans):

- Integrate transit and feeder services - Real-time response to changing demand - New personalized public transit - Define hub center to bring PWD to a public network - Dial-a-ride problem - Transport on demand (Gupta, Chen, Miller, & Surya, 2010).

The last zone is adaptability:

- Quality of service - Always provide a seat - Service assistance by a person, with proper support if required - PWD can book by phone, by SMS, or on-line - Transport chain without interruption (Finn, 2012; Paquette et al., 2009).

		Strategic level		Operational level	Tactical level	
Needs	Levels	Institutional framework	Economic issues	Operational issues	Operator and community attitudes	Information and education - Human and Social resources
Availability	Time			I		
	Place					
Accessibility	Information and travel training					
	Pedestrian footways and street crossing					
	Public transport stop and station infrastructure					
	Public transportation vehicles			II		
	Private modes of transportation					
				III		
Acceptability						
Affordability						
Adaptability				IV		

Table 8 The simple version of Matrix (feasible solutions)

The French national railway company “SNCF Réseau.” runs railway transport in France. Our client does not run this mode of transportation, so the part in the matrix dedicated to the accessibility of trains is excluded from further analysis.

The stated potential actions indicate the objective functions and constraints of some optimization models in transportation. This leads to the conclusion that the problem statement is to optimize, rather than rank, existing optimization models. Therefore, according to the problem statement, the problem formulation is defined as **How to frame current optimization models that fit the characteristics of a public network to enable full autonomy for PWD, without interrupting the transport journey.**

3.3.3 Evaluation model

In order to understand the uninterrupted transportation journey, we need to know what forms the process of public transportation (Meyer & Miller, 2001). In our case, we start by breaking down the public transportation journey with an example of a public transportation journey for a PWD.

The PWD leaves the point of origin (International Conference on Smart et al.), reaches a bus stop (if the pavement meets the needs of the wheelchair user), and uses the local bus service to get to a suburban subway station (tram, metro, train station), where a change in the transport mode takes place. This phase is called a trip collection process. The next stage is the transfer process, where the PWD proceeds through the station to the subway (tram, metro, train) platform. Then, the PWD alights the subway (or another mode of public transport) to a downtown station (any station within the public network's core). This is called a line-haul process. The last phase is a distribution process where the PWD arrives at a destination (e.g., place of employment).

We note that the trip collection process and distribution process occur in the same type of zones, where the public network probably does not exist. Figure 15 Transport process of PWD with zones shows the public transportation process, including zones, illustrating what the proposed model should do and its barriers. The three types of different zone are marked in the transportation process. Zone 1 is at the core of the transport network with all transportation modes and usually with the highest grade of accessibility. Zone 2 is divided into two parts, around zone 1. This zone's characteristics with the density transport network with the medium grade of accessibility. The last one, zone 3 is outside of the central transport network with few transportation modes and the lowest grade of accessibility. The different line colors, in this case, indicate different modes of transport. This means that the PWD - at the point marked by a pink star - needs to change the transport mode or keep using the same mode, but needs to change line.

In this example of a PWD trip, red point 7 is the start of the PWD trip, and green point 7 is where he/she finishes the journey. On this trip, the PWD changes the mode of transport six times. In each of these six situations, accessibility issues come up, presenting challenges to the PWD.

Optimization models which can help reduce accessibility problems that arise within the public transport network include: the Shortest path problem (Bast et al., 2016; Pallottino & Scutella, 1998; Turner, 2011): Multimodal shortest path (J. R. Current et al., 1985; John R Current et al., 1987; Lozano & Storchi, 2001; Modesti & Sciomachen, 1998), Time-dependent shortest path (Orda & Rom, 1990); Multi-objective shortest path (Maria et al., 2007), Resource-Constrained Shortest Path Problem (Turner, Punnen, Aneja, & Hamacher, 2011). They operate in zones 1 and 2.

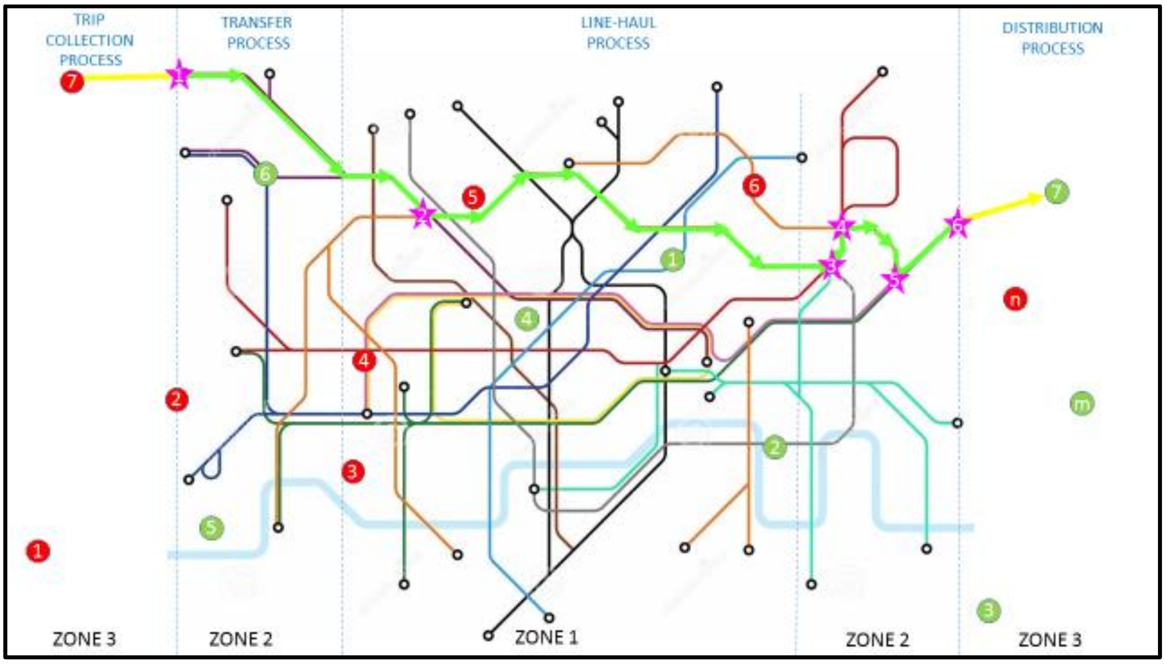

Figure 15 Transport process of PWD with zones

Zones 2 and 3 are examples of the second type of optimization models, which helps avoid accessibility issues. However, they address use of the public bus as the mode of transport. These are categorized as Transport on-demand or Demand Responsive Transport and Flexible transport service in the literature. We recognized them also in public transport. This identification arose because fixed bus routes were modified to meet PWD needs.

The first model is the Integrated Dial-a-Ride Problem (IDARP), which presents a combination of DARP and public transport service. IDARP frames the vehicle routes and schedules for a dial-a-ride service, but some parts of each request may be responded to by the regular public service (Carl H. Häll et al., 2009; M. D. Hickman & K. L. Blume, 2001). From the PWD perspective, IDARP enables to alternate from a DAR vehicle to conventional transit and, potentially again, to a DAR vehicle.

The Demand Adaptive System is a model where the bus stops are confirmed in advance, and the bus changes its route when a request is made (Crainic et al., 2012; Malucelli, Nonato, & Pallottino, 1999b). The predecessor of the DAS model is the Semi-Flexible System (Errico et al., 2013). Another optimization model that addresses this type of problem is Mobility Allowance Shuttle Transit (MAST).

The Scheduled Paratransit Transport System (SPTS) "allows the bus route to deviate from its original pathway to meet the needs of PWD, providing the service where the PWD requested it (G. Dikas & Minis, 2014). SPTS is similar to DAS and MAST, except it focuses only on the first and last phase of the journey, referred to as “first - last leg.”

The main idea behind optimization models for zones 2 and 3 is to bring the public network closer to PWD, by adjusting bus scheduling and routing. The earlier models discussed present the acceptable solution for PWD transport; however, they do not provide for the inclusion of PWD in public transport. Additionally, PWD are not able to have autonomy in movement.

Zone 3 is reserved for the familiar Dial-a-Ride Problem (DARP) (Cordeau & Laporte, 2007; Ho et al., 2018). DARP is a door-to-door service that provides full accessibility for PWD. However, the main drawbacks of the DARP are the need to book a long time in advance and the high cost.

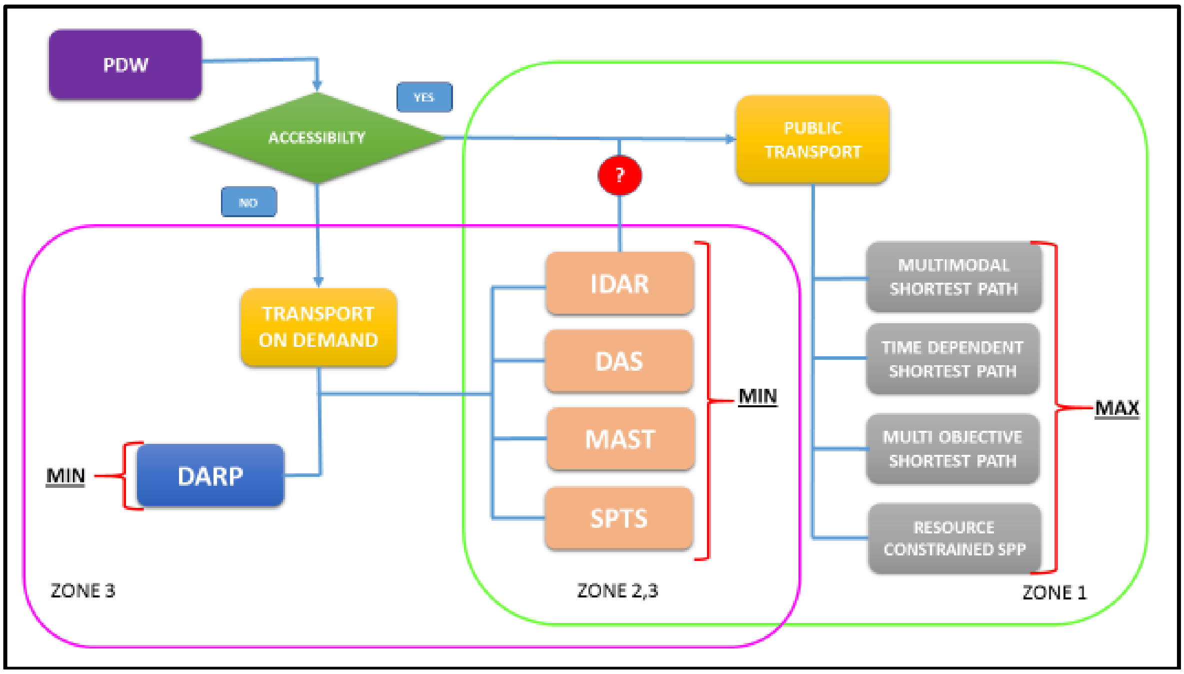

Figure 16 An integrative framework of optimization models’ correlations according to network accessibility

The scheme of the relationship between existing optimization models, depending on the public network information, specifically on the current accessibility of the public network, is shown in Figure 16 the algorithm's main question is the PWD destination. The response to this question is given in the final recommendation.

In addition to the decision scheme, a mathematical formulation is provided, clarifying each element of the evaluation formula. The evaluation model is written as $\mathcal{M} = \langle \boldsymbol{A}, \{\boldsymbol{D}, \boldsymbol{E}\}, \boldsymbol{H}, \mathcal{U}, \mathcal{R} \rangle$, and the definition of these elements is presented below:

A is the set of alternatives:

A_1 - Multimodal shortest path;
A_2 - Time-dependent shortest path;
A_3 - Multi-objective shortest path;
A_4 - Resource-Constrained Shortest Path Problem;
A_5 - Integrated Dial-a-Ride Problem (IDAR);
A_6 - Demand Adaptive System (DAS);
A_7 - Mobility Allowance Shuttle Transit (MAST);
A_8 – Scheduled Paratransit Transport System (SPTS);
A_9 – Dial-a-Ride Problem (DARP).

D presents the set of dimensions, possibly with structural properties, by which the model manipulates the potential actions of ***A***; - presents the measurement of the public network:

D_1 – number of bus stations;
D_2 – number of bus stations with accessibility to PWD;
D_3 – number of tram stations;
D_4 – number of tram stations with accessibility to PWD;
D_5 – number of train stations;
D_6 – number of train stations with accessibility to PWD;
D_7 – number of bus lines;
D_8 – number of tram lines;
D_9 – number of train lines;
D_{10} – length of bus lines;
D_{11} – length of tram lines;
D_{12} – length of train lines;
D_{13} – number of intersection points between bus and tram;
D_{14} – number of intersection points between bus and train;
D_{15} – number of intersection points between tram and train;
D_{16} – number of intersection points (nodes) between bus and tram, accessible to PWD;
D_{17} – number of the intersection point (nodes) between bus and train, accessible to PWD;
D_{18} – number of the intersection point (nodes) between tram and train, accessible to PWD.

E presents the set of scales associated with each element of ***D***:

E_1 – number of bus vehicles;
E_2 – number of bus vehicles accessible to PWD;
E_3 – number of tram vehicles;
E_4 – number of tram vehicles accessible to PWD;
E_5 – number of train vehicles;

E_6 – number of train vehicles accessible to PWD;
E_7 – number of cars, vans (public);
E_8 – number of cars, vans (private).

H represents the set of criteria on which the elements of ***A*** are evaluated, in order to take into account client preferences, resepcting each criterion:

H_1 – Availability;
H_2 – Accessibility;
H_3 – Acceptability;
H_4 – Adaptability;
H_5 – Affordability.

$\mathcal{U}$ represents the set of uncertainty distributions associated with ***D*** and ***H,*** or only ***H***; it is considered empty in this case.

$\mathcal{R}$ represents the set of information synthesis operators of the elements of ***A*** or ***AxA,*** notably the aggregation operators. Since $\mathcal{R}$ can perform a multiple-criteria classification procedure, and our problem statement is to optimize rather than rank, this is empty.

The mathematical formulation is divided into three evaluation parts (Equation 1, Equation 2, Equation 3). The final evaluation model is presented in equation (4), where the first part is maximized, and the second and third parts are minimized.

$$\mathcal{M}_1 = \langle \sum_{i=1}^{4} A_i \{\boldsymbol{D}, \boldsymbol{E}\}, \boldsymbol{H}, \mathcal{U}, \mathcal{R} \rangle$$

Equation 1 Evaluation model for the shortest path variants

$$\mathcal{M}_2 = \langle \sum_{i=5}^{8} A_i \{\boldsymbol{D}, \boldsymbol{E}\}, \boldsymbol{H}, \mathcal{U}, \mathcal{R} \rangle$$

Equation 2 Evaluation model for transport on-demand variants

$$\mathcal{M}_3 = \langle \boldsymbol{A_9} \{\boldsymbol{D}, \boldsymbol{E}\}, \boldsymbol{H}, \mathcal{U}, \mathcal{R} \rangle$$

Equation 3 Evaluation model for Dial-a-ride transport

$$\mathcal{M} = \max \mathcal{M}_1 + \min (\mathcal{M}_2, \mathcal{M}_3)$$

Equation 4 Evaluation model for the whole system

The evaluation model is itself subject to validation, as described in Section 3.2.2.3. In order to validate the evaluation model, it must satisfy four criteria: conceptual, logical, experimental, and operational. The conceptual validation is arrived at by the reported quarterly progress, which is approved by the client and the project evaluation team. The issue of logical verification is met, as it satisfies the characteristics of a public transport network. The same network already accepts and governs the type of model which is defined. The experimental validation was not run, as the model's sub-parts involve commonly understood optimization models in the literature, which are already proven by validated data.

3.3.4 Final recommendation

For an analyst, providing the final recommendation Φ generates the result of the decision-aiding process. The key part is to communicate the final proposals in the client's language in a meaningful, totally operational, and legitimate way. If the final instructions are not clear to the client, there is a risk that the preceding work will have no effect. Thus, the analyst must highlight the key issues. As the research approached the problem situation and problem formulation on three levels - strategic, tactical, and operational - the final recommendations are made in the same way.

Φ_1 – Operational level – The problem formulation has shown that optimization models (Transport on-demand and SPP) are the primary components for obtaining an efficient solution to one part of the problem. Initially, these two basic models were competitors, yet this research has resulted in their unification. However, the network access issue in the independent transport journey persists and represents the main obstacle in achieving full autonomy for PWD movement. To overcome this issue and establish the missing link between the departure starting point (International Conference on Smart et al.) and the public transport network, the use of cluster centers is recommended. These centers provide the closest access to the interface with existing exchange poles (hubs). The center of the cluster is the average of all points (elements) that belong to that cluster. In our case, the elements are the PWD geolocation. The exchange poles (hubs) mean a transportation hub that presents a place where passengers exchange between vehicles and/or between transport modes. Public transport hubs include train stations, metro stations, bus stops, tram stops, airports and ferry slips. The next stage of the analysis enables the clusters to bring most PWD to the nearest station in an accessible way. Within the solutions obtained from the clusters approach, the first user's requirement is satisfied. The network remains unchanged, but the model analyzes two axes: i) correlation between the exchange poles and the PWD position; and ii) future exchanges pole positions in the function of demanded numbers of clusters and PWD locations. The proposed model requires the availability of data. The different types of data could bring about organizational change and the information system. Here, clustering has been approached as a Data Analytics Tool to assess organizational arrangements' consistency when integrating the two models, transport on-demand and the shortest path.

Φ_2 – Tactical level – The possible consolidation of the stakeholder's network, the participants in the transportation journey, is identified in the zones colored red in the matrix of the problem. The further incorporation is met by the optimization models that operate in these zones.. Additionally, other aspects that were not initially planned are satisfied. These models generate new data and information that can be shared, particularly amongst transport users, citizens, visitors, etc., in communication with the other stakeholders, particularly with organizations and associations that promote PWD's needs and develop information and communication systems. Additionally, social networks and mobile phone applications can track supply and demand to ensure that PWD needs are met.

Φ_3 – Strategic level – Respond to the community of users and citizens (PWD), and include them in the operational decision-making process. As part of the decision-making process, PWD are temporary stakeholders in transport, particularly in data gathering. This makes it necessary to put in place means to control the entry and exit of decision-making processes. Disability organizations need to consolidate existing provisions to take care of PWD, by setting up information systems that can provide information continuously, define the sector and public policy guidelines, and responsibly address various other issues related to the data.

3.4 Conclusion

One of the challenges of this chapter was how to improve the living conditions of persons with disabilities. In this study, this relates to their inclusion in a public transport network. A second aim was to provide tools to assist in the process of decision-making for the client, *“Communauté d'agglomération Valenciennes Métropole.”*

Considering and understanding the needs and obstacles faced by PWD in daily transportation, the first challenge of this chapter is satisfied and brings the most important elements for the inclusion of PWD in public transport. This chapter summarizes the literature from different disciplines, including the legislation in different countries, studies, and international organizations' analysis, medical examinations, etc. This helps analyze optimization models from two different perspectives: that of PWD needs, and (Liaw et al.) of the company that provides the transport.

In the latter case, the process of decision-aiding is comprehensively explained, emphasizing the useful tools in the methodology clearly to both client and analyst Also, byapplying the methodology, each phase generates examples and clarifies the process associated with the appropriate transportation optimization model. Ultimately, the proposed model enables the provision of a transport service that gives full autonomy to PDW.

However, there is always room for further improvement, and the final recommendations address this issue. Future work should define the cluster centers, which would improve the accessibility of the transport network. In addition, the mobile applications and the information service should also be areas for improvement.

Chapter IV

4 A clustering approach to improve the inclusion of persons with disabilities in a public transport system – Case Study: Valenciennes, France

4.1 Introduction

This chapter is dedicated to applying the ideas elaborated in previous chapters. Various dictionaries (Stevenson, 2010; Urbandictionary.com & Peckham, 2012; Walter, 2008) have defined this application as an act of putting something into operation. Alternatively, some use it as an act of committing to a particular purpose. Our specific objective is the inclusion of persons with disabilities into the public transport system of Metropole Valenciennes. However, first, there are some questions to which we should provide clear answers with respect to the implementation of our research findings. The first task is to define the specific type of transport system and its characteristics. The second task is to identify what actions should be taken and how they should be carried out. The key question is: what are the relevant optimization problems to account for these particularities and deliver better solutions with the available data sources?

The principal constituents of the work carried out here are summarised in the outputs of Chapter III – Methodology. They present key information and proposals for direct implementation at the operational level. The summary of the final recommendations for the operational level as defined previously is, “The network access issue in independent transport journey persists and represents the main obstacle in getting full autonomy for PWD movement. To overcome this issue and establish the missing link between the departure starting point (International Conference on Smart et al.) and the public transport network, the use of cluster centers is recommended. The center of the cluster is the average of all points (elements) that belong to that cluster. In our case, the elements are the PWD geolocation. The exchange poles (hubs) mean a transportation hub that presents a place where passengers exchange between vehicles and/or between transport modes. Public transport hubs include train stations, metro stations, bus stops, tram stops, airports, and ferry slips. These centers provide the closest access to the interface with existing exchange poles (hubs). The next analysis stage enables the clusters to bring most PWD to the nearest station in an accessible way. Within the solutions obtained from the clustering approach, the first user's requirement is satisfied. The network remains unchanged, but the model analyzes two axes: i) correlation between the exchange poles and the PWD position, and ii) future exchanges pole positions in the function of demanded numbers of clusters and PWD locations. The proposed model requires the availability of data. The different types of data could bring about organizational change and the information system. Here, clustering has been approached as a Data Analytics Tool to assess organizational arrangements' consistency when integrating the two models, transport on-demand and the shortest path.”

In other words, the previous analysis demonstrated that transportation optimization models, transport on-demand, and the shortest path provided partial independence for PWD. Improving the companies’ organizational outputs is the main focus of these models. Advanced PWD mobility independence is not the central issue, and the focus remains more on satisfying the companies' needs. These two models have different ways of providing the solution to PWDs transport with different organizational structures.

Concerning the managerial characteristics of the transport on-demand and the shortest path, the goal is completely different. Transport-on-demand gathers resources to meet demand, while the shortest path allows an outside request and relies on a network configuration. One forms a part of centralized management transport network models and the other results in a decentralized transport organization. The integration of these two models along the PWD transport journey produced the appropriate operating data and identified the missing link in the transportation chain, leading to the clustering approach.

The clustering approach functions in two directions by employing both network and user data. From the real data set of “on-demand” service transport, clustering provides an analysis of PWD transport flow, with the geo-location of PWD using existing hub locations on the network. Furthermore, the optimal number of clusters was sought to check the compatibility with the number of existing poles on the network.

Generally, this chapter demonstrates how different research approaches can be used to have a socio-economic impact. Specifically, the synergy between the decision-aiding process and optimization techniques have been used here for this purpose. Decision-aiding is used to identify and locate the problem, while an optimization technique, in this case, clustering, is used to resolve identified issues. In particular, our primary focus is on the public transport network in Valenciennes, a city in the north of France.

In the decision-aiding process, the transport network map characteristics are analyzed, focusing on existing hubs and services for persons with disabilities. Then, in the clustering phase, a detailed analysis is performed by varying the number of required clusters, offering different recommendations on how PWD can be included.

This chapter is structured as follows: Section 4.2 presents the Valenciennes public transport network's characteristics as the background for Section 4.3, which describes the problem. Section 4.4 describes the clustering approach as a methodology. Section 4.5 provides computational results based on real data. Finally, Section 4.6 presents the conclusion and discussion of the improvement of Valenciennes public transport.

4.2 The transport network in Valenciennes

This section presents a detailed description of the Valenciennes metropolitan area, its transport network system configuration, and the layout of its public transport, emphasizing the organization of transport services for persons with disabilities within Valenciennes. All this information serves to understand and define the challenges faced by persons with disabilities, which is crucial for developing a decision-aiding process.

4.2.1 Transport network presentation

Valenciennes is a town in the north of France, in the region Hauts-de-France, north department. In 2016 the population of Metropole Valenciennes was around 350,000 (L'Institut national de la statistique et des études économiques France, 2016).

The public transportation network in the Valenciennes region includes three major sub-networks, each of which falls under the responsibility of a particular organization:

- **Urban transport** is run by the Transvilles network (https://www.transvilles.com), which in turn sits under the responsibility of Inter-municipal Syndicate of Urban Transport of the Valenciennes Region (SIMOUV - *Syndicat Intercommunal de Mobilité et d'Organisation Urbaine du Valenciennois)*. Transvilles also forms part of the “Autonomous Parisian Transportation Administration” (*Régie Autonome des Transports Parisiens* – RATP-Dev), a state-owned public transport operator and maintainer;
- **Interurban road transport** is managed by the Department of the North;
- **TER intercity rail transport** (Regional Express Train) and **regional inter-urban lines** are run by the Hauts-de-France Region and operated by the French national railway company (SNCF).

The network map, see Figure 4.3 (for higher resolution, see Annex B), includes:

- 1,570 stops/stations;
- 2 tramway lines;
- 38 bus lines;
- 37 school bus lines;
- 5 zones of transport-on-demand (Taxival);
- 3 shuttle buses;
- 1 service for PWD (*Sésame*);
- 10 lines for integration with the "*Arc-en-Ciel*" regional network;
- 3 commercial agencies; and
- 7 parking relays

For clarity, Transvilles distinguishes "transport-on-demand" and "Sésame service." "Transport-on-demand" is for regular users that live in areas that are remote from regular lines. "Sésame service" is also a transport-on-demand service, but available exclusively for persons with disabilities.

The network includes 9,500,000 km of lines. There are five exchange hubs, "*pôles d'échanges*" on the network. These are shown in Figure 17 colored lavender, including the primary transport lines:

I. Station Anzin-Hôtel de Ville;
II. Station Denain-Espace Villars (terminus);
III. Station Famars Université (terminus);
IV. Station Gare;
V. Station Saint Waast.

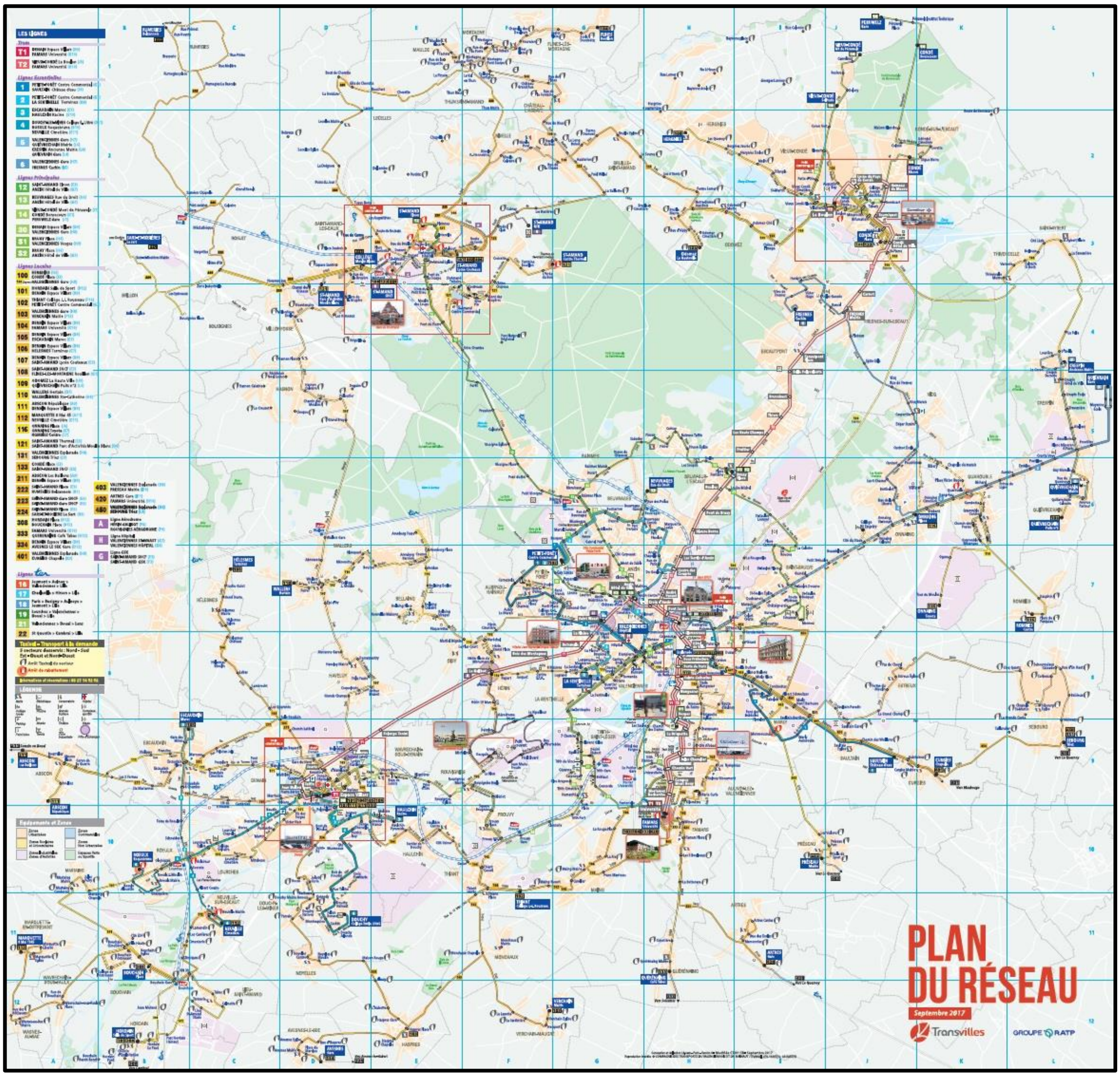

Figure 17 Public transport network map, Valenciennes, France

(Source: https://www.transvilles.com/plan-reseau

Three of these hubs - Station Anzin-Hôtel de Ville, Station Gare and Station Saint Waast - are located in the town center within a close distance of each other. The hubs Station Denain-Espace Villars and Station-Famars Université are on the city's outskirts and form the terminus for tram lines and some bus lines. The details of these hubs, including their facilities, number of lines, and accessibility, are given in Appendix C. Figure 18 is the public transport network plan run by Transvilles in Valenciennes.

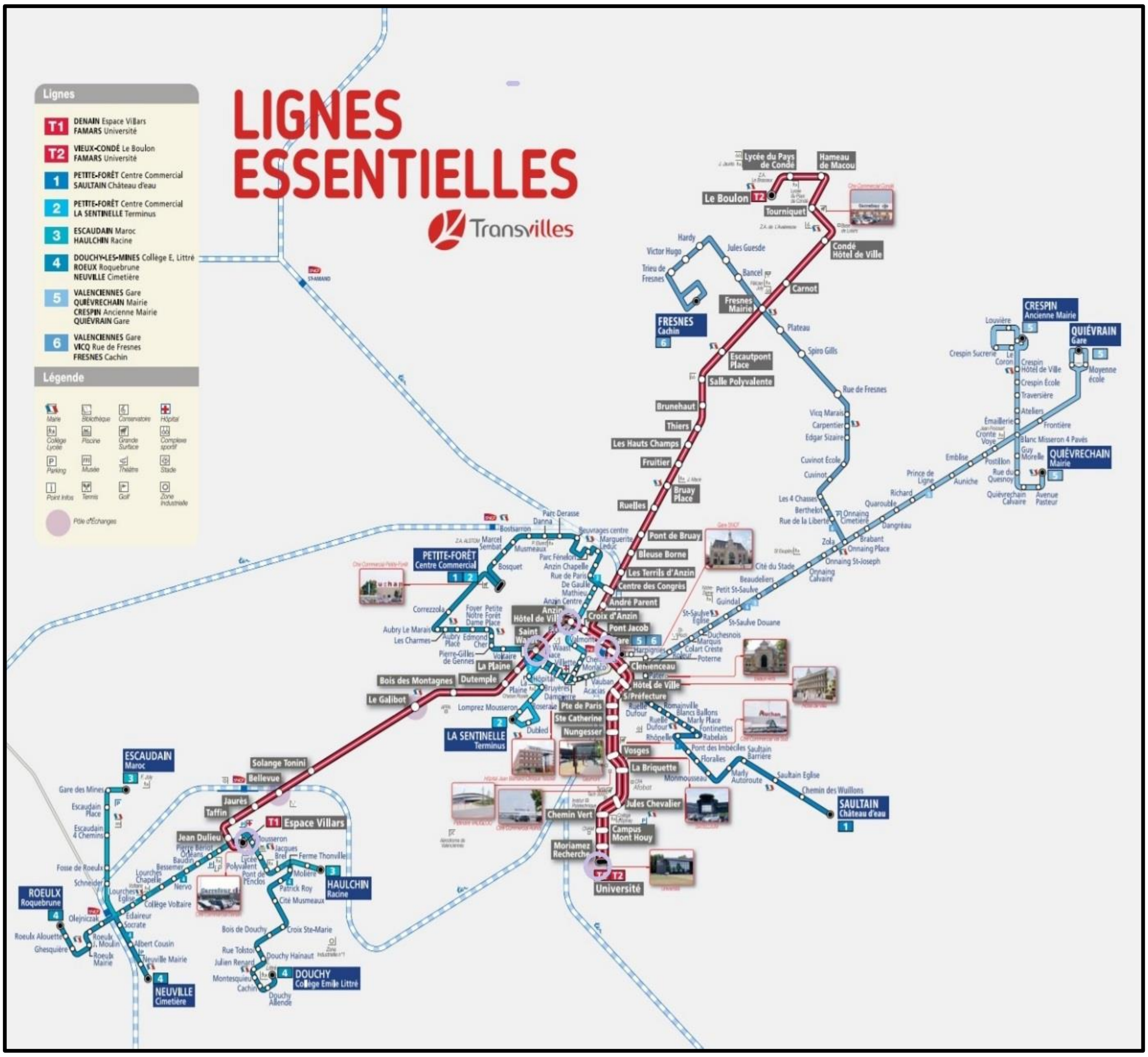

Figure 18 Primary transport lines in Valenciennes and exchange hubs

(Source: https://www.transvilles.com/lignes-essentielles)

The total volume of transport users is around 17,000,000 passengers per year. Table 9 shows the number of passengers per year and the number of passengers using the "transport-on-demand" service.Table 9. shows the number of regular users decreasing year after In 2018, however, there was an increase in the number of PWD that used the Sésame service. Unfortunately, we do not have data on PWD use of other modes of transportation provided by Transviles, such as bus and tram, etc.

Year	Passenger	Transport on demand
2014	17155033	
2015	16667534	10548
2016	16870412	11120
2017	15519879	10237
2018	13 220 479	9 793

Table 9 The volume of transport per year (Source: https://www.simouv.fr/)

Various modes of transport operate in Valenciennes, including a tramway, bus, and transport-on-demand. The volume of users per kilometer and per mode is shown in Table 10.

Year	Tramway	Bus	Transport on demand Sésame Propres
2014	1724573	4513462	306622
2015	1770854	3976076	352375
2016	1756200	3890325	348493
2017	1509902	3531151	366016
2018	1369649	3598443	461083

Table 10 Evolution of kilometers by users and mode (Source: https://www.simouv.fr/)

According to the SIMOUV 2018 activity report (SIMOUV, 2018), there is the following transport distribution: 16% Tramway; 44% Bus; 6% Transport-on-demand (*Sésame Propres*); 27% Shuttle bus (*Bus affrétés*); 1% Transport-on-demand (outsourced) (*Sésame sous-traités*); 2% Taxival and 4% Regional lines (*Lignes régionales sous convention SIMOUV*). So buses are the dominant mode of transport.

2018	%
Tramway	16
Bus	44
Transport on-demande (*Sésame Propres*)	6
Shuttle bus (*Bus affrétés*)	27
Transport-on-demand (outsourced) (*Sésame sous-traités)*	1
Taxi Val	2
Regional lines	4

Table 11 Transport distribution in 2018

4.2.2 Transport organization for PWD – "*Sésame*"

"*Sésame*" - the current transport organization for PWD - holds a fleet of 14 vehicles. The vehicle depot of Transville is positioned in Saint Saulve, which is not one of the hubs. Only one of 14 vehicles is located in hub Station Denain-Espace Villars. The "*Sésame*" service is organized by routes, which group people whenever possible. These routes are offered for access to work, internships, higher education, and leisure travel.

This service is based on the "reservation ahead" principle: each transportation request needs to be sent at least two weeks before planned travel; Transvilles examines the request and notifies the user about the decision within 48 hours. Besides integrating PWD to public transport, we also notice a problem in the transport on-demand organization Valenciennes is more rural than urban, and there has been a move towards urbanization (*périurbanisation*). The associated changes have led to adverse outcomes for the organization of co-ordinated travel that favors individual modes. A further issue is that each group responsible for organizing transport (SIMOUV, Department of North, or TER) has its own particular plans, particularly on the provision of accessibility for PWD. As a result, all documents have to be aligned to enable collaboration on different levels of decisions.

Public transport for PWD needs to be improved, although Valenciennes public transport is generally efficient. The network is experiencing an increasingly marked imbalance in the services offered. There is a good frequency of use of the tramways, but dissatisfaction with the rest of the network. Valenciennes has a diversity of transport offerings (TER, Tram, Bus, Transport-on-demand Sésame), which must serve the development of public transport in the area.

The entire travel infrastructure needs improvements (buildings, roads, public spaces, transportation, and housing). A solution must be developed for rural areas and sidewalks accessibility. Evidently, re-organizing an entire transport network needs a lot of time, effort, and resources. Consequently, we will focus here on an approach that can be implemented in the short term to address the challenges of integrating PWD into the public transport system.

This chapter drew most elements from a real-life database to analyze the possible application of location models to the Valenciennes transport network. The data configuration indicates that the potential application of a clustering model could result in better dial-a-ride solutions, which could significantly impact the organizations of buses. One of the constraints of organizing transport by coaches is the number of vehicles that are accessible to PWD. In addition to accessibility, another critical parameter is availability. Availability relates to the provision of a service in the locality adjacent to PWD's intended journey destination.

4.3 Problem description

In recent years, public transport systems have been required to accommodate an increasing diversity of users, and in parallel, the number of users has generally increased, particularly persons with disabilities.

As stated previously, the World Health Organization reported one billion PDW, which represents 15% of the total population (World Health Organization, 2011). In addition, French demographic trends have been characterized by a rapid increase in the number of people who have mobility difficulties, with a forecast of 17 million people aged 60 and over, and 4 million people aged 80 and over after 2020. From 2010, the French people aged over 60 have exceeded those under 20 (Egis France Villes & Transport). A similar study of Egis France has shown that the overall population of Valenciennes is aging. The percentage of young people decreases, while the number of elderly people increases, particularly those aged over 75 years.

Public transport systems are required to comply with increasingly demanding regulations to meet the needs of PWD. Meanwhile, the design of transport systems has not fundamentally changed. The default consideration is still on the standard user, while PWD users do not yet have full recognition as a new potential source of clients. PWD has yet to be recognized by transport companies in terms of its potential as a source of additional revenue. The quantities of users and the diversity of their needs make transport planning very complex. This complexity increases when the specific needs of PWD have to be met. The range of disabilities includes physical, intellectual, motor, and visual, and each category's needs have to be defined. This huge range of criteria meant that we limited our investigation to PWD wheelchair users - the physical group. In addition to the number and diversity of PWD involved, PWD transport is limited by the factors such as the infrastructure's particular characteristics: – the network, routes, vehicles, etc.

Several combined complex optimization problems arise in the network's design,) when routes across - or flows through - the network are required. Familiar routing challenges include the *shortest path* problem, *minimum spanning tree problem, traveling salesman* problem, *vehicle routing problem*; amongst other interesting optimization problems that have additional practical constraints (Bast et al., 2016; Feremans, Labbé, & Laporte, 2003; Turner, 2011).

In addition to the network design, studies have recognized several optimization problems that could potentially deliver better transport services to persons with disabilities. For example, the *transport- on-demand* problem, otherwise known as *dial-a-ride* problem (Archetti et al., 2018; Cordeau & Laporte, 2007; Molenbruch et al., 2017). Section 3.3.3 describes in detail existing optimization models in the transport journey for PWD.

The intention here, as stated previously, is to improve the inclusion of PWD in an existing public system using different optimization models. In this section, the focus is simplified by considering specifically the transport organization for PWD in Valenciennes (Section 4.2.3). The mode of transport for PWD is exclusively transport on-demand referred to as “Sésame.” The transport-on-demand provides a service for PWD moving from origin A to destination B without using the regular public network.

Alternatively, the “shortest path” applies to Valenciennes’s regular public network once PWD reaches it. PWD can move through the public network following the shortest path from where they enter the network to the point where they left. The Transvilles application and website provide access to the itinerary that does not include a specific option for PWD.

It is generally known that all tram lines are fully accessible for PWD. All stations along their routes and their associated fleets can accommodate PWD. On the other hand, in the bus system, the problem is the accessibility of PWD to the stations since the accessibility to the vehicles is provided.

However, the interchanges between different modes of transport and various lines take place at the hubs. These locations are the key points for the independent mobility of PWD.

Here, we consider how these two models, transport on-demand and the shortest path - can be used simultaneously to design routes for PWD that partially involve the public transport network. Specifically, suppose PWD wants to travel from point A to B. In that case, PWD can initially transfer to the public network (using transport on-demand), then travel through the system using the shortest path, and finally, transfer to destination B (transport on-demand).

In order to integrate these two optimization problems, the geo-position of hubs is defined to determine the best routing methodology. The identification of hubs occurs in the first leg of the transportation trip (where PWD enters the network) and the last leg of the transportation trip (where PWD leaves the network). To solve this problem and resolve the first and last transport legs' challenge, a clustering analysis of the Sésame's data set is carried out. The "Sésame" data set provides information on the users' departure and arrival location. The other data set contain information on the geo-location of the network, accessibility to stations (stops), and the location of existing hubs. In order to make use of this data for this scenario, the cluster analysis model is proposed (Hartigan, 1975; Kaufman & Rousseeuw, 2009; Meyer & Miller, 2001). The following section provides more details on the clustering methodology.

4.4 Clustering approach

Cluster analysis is the classification of objects according to their similarities and organizing objects into groups (L. Kaufman & P. J. Rousseeuw, 1990; Kaufman & Rousseeuw, 2009; Späth, 1980). Clustering techniques belong to the group of unsupervised methods within the class identifiers that do not use existing knowledge. The main aim of clustering is to identify the fundamental structure in a given set of objects (also called data). Besides the classification and pattern recognition, the model placing and optimization present other attributes of the grouping.

Classification is the primary component of exploratory data mining. Clustering is a standard statistical data analysis technique used in many fields, particularly for the data sets in complex systems. It could be said that clustering is a persuasive generator for the computerized analysis of data (Everitt, Landau, Leese, & Stahl, 2011; Han, Kamber, & Tung, 2001). This persuasive generator has features that incorporate a range of methods to arrive at a correct and feasible solution. These methods have been demonstrated to be useful in a wide range of applications.

Practical models are employed to illustrate the theory's application, and figures are used broadly to describe graphic techniques (Everitt et al., 2011). As already stated, clustering can help identify the characteristics of any structure or patterns present in a given data set. It is a useful approach that emerged from anthropology and psychology to understand relations within groups. This is the field where clustering was initially discovered (Driver & Kroeber, 1932; Zubin, 1938).

Many equivalent terms are used for clustering, as revealed in the literature, such as data classification, grouping, numerical taxonomy, etc. Clustering helps in assessment, prediction, and then arriving at a decision. These diverse classifications are the result of different scenarios and different data types. Depending on the particular aim, techniques can be employed, such as partitioning, hierarchical, graph-theory methods, and methods based on mathematical programming formulations (Carrizosa et al., 2013; Hanafi & Yanev, 2011).

The focus is on partition techniques, which separate objects into particular group representations by minimizing or maximizing a given objective function (Everitt et al., 2011). Examples of these techniques include K-means and K-medoids algorithms, which try to minimize average squared distance, generating so-called centroids. K-means and K-medoids algorithms allocate each object to one of the K clusters from a given set of objects, minimizing the within-cluster sum of squared distances. In this case, we used the K-medoids method, as it is more robust in relation to outliers, and also because this method deals with both interval-scaled sizes and vague variation coefficients (Balasko, Abonyi, & Feil, 2014; Đorić, El Cadi, Hanafi, Mladenović, & Artiba, 2017; Everitt et al., 2011).

The K-medoids method relies on the minimum sum-of-squares criterion (MSSC). The minimum sum-of-squares criterion is one of the favourite among various models used for cluster analysis, as it expresses both homogeneity and separation. Using the MSSC, K-medoids partition a given set of *n* objects into K clusters, minimizing the total squared distance from the objects to their cluster's centroid. The *n* objects to be clustered are represented as points $x^i \in \Re^s$, $i = 1, \dots, n$; while K cluster centers are chosen among points x^i. The squared distance between two points is defined as the squared Euclidean distance between the two points x^i and x^j, in the s -dimensional space under consideration: $d(x^i, x^j)$ = $\sum_{k=1}^{s}(x_{ik} - x_{jk})^2$. In our case, the data set is the geographical position (geo-location) of PWD present by the longitude and longitude. The data set is later translated in the Euclidean space.

Mathematically, the K-medoids may be expressed as a mixed-integer programming (MIP) model, which uses the binary decision variables w_{ic}which express the assignment of the object i to the cluster c, with the center at x^c and binary decision variable y_c which indicates if a centroid is located in point x^c or not.

So a MIP formulation of K-medoids can be expressed as follows:

$$\min_{w,y} \sum\nolimits_{i=1}^{n} \sum\nolimits_{c=1}^{n} w_{ic}\, d(x^i, x^c)$$

Subject to:

$$\sum_{c=1}^{n} y_c = K,$$

$$\sum_{c=1}^{n} w_{ic} = 1, \qquad \forall i \in \{1,2,\dots,n\}$$

$$w_{ic} \le y_c, \forall i, c \in \{1,2,\dots,n\}$$

$$w_{ic}, y_c \in \{0,1\}, \forall\, i, c \in \{1,\dots,n\}.$$

The objective function expresses the minimum sum-of-squares criterion. The first constraint ensures that exactly *K* points are chosen to be centroids. The next constraints allow each point to be assigned to precisely one centroid (cluster), while the third set of constraints guarantees that each point is awarded only to an established centroid.

Regarding computational complexity, K-medoids in the Euclidean metric for general values of *K* and *s* have been shown to be NP-hard (Aloise, Deshpande, Hansen, & Popat, 2009).

. In our case, we apply the k-medoids approach on the data set available for the public network of Valenciennes. The objects in the real data set are the geo-location of PWD. The objective is to analyze transportation flow with their geo-location of clusters in the departure and/or arrival of PWD. We are also interested in seeing how these clusters are positioned concerning the existing network and examining cluster centers' position relative to the existing hubs on the network. The Clustering – nodes - network example is shown in Figure 19, where points belonging to the same cluster are marked in the same color.

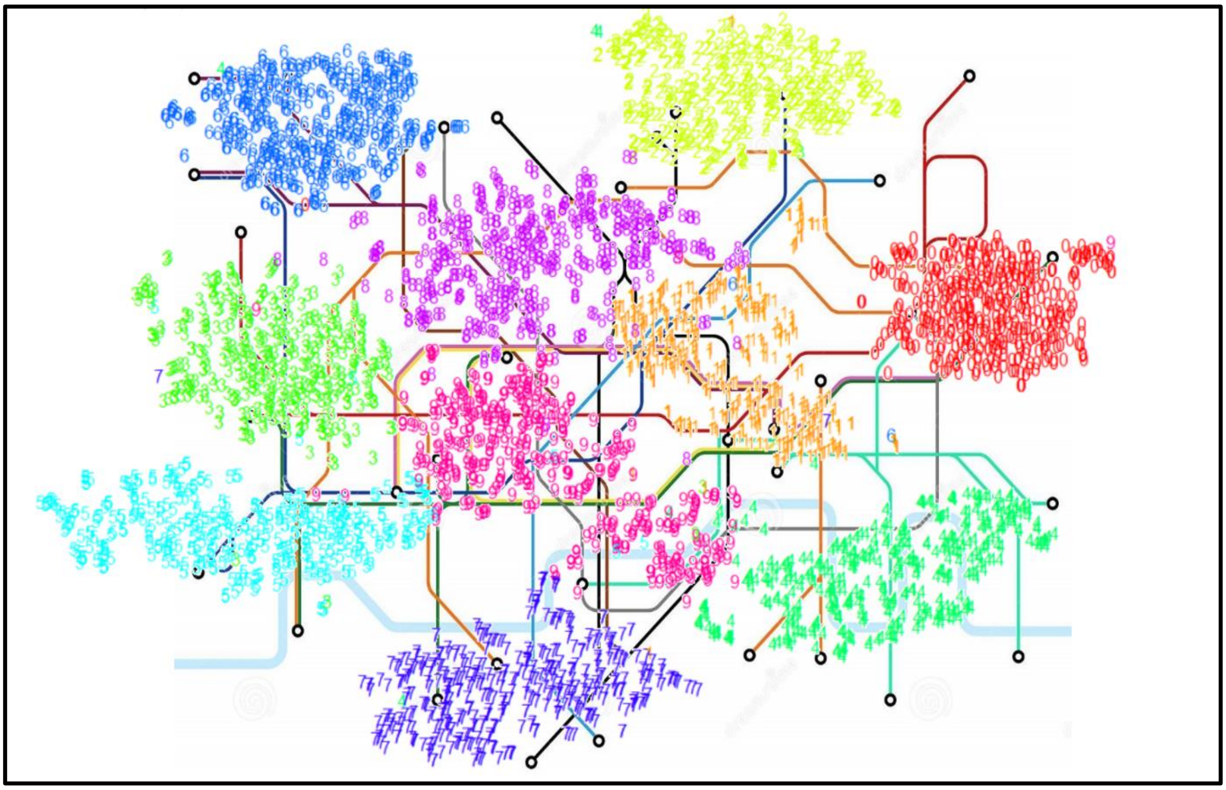

Figure 19 Clustering – hubs - network example

4.5 Computational experiments

In this section, we present the outcome of experiments obtained by applying the clustering approach to the public transport network in the city of Valenciennes. The public transport network, transport flow, and position of existing hubs in Valenciennes are analyzed and compared. For the analysis, real examples are used to perform k-medoids clustering (L. Kaufman & P. Rousseeuw, 1990; MacQueen, 1967; Pelleg & Moore, 1999; Rdusseeun & Kaufman, 1987) with a different number of clusters. In addition, the optimal number of clusters was sought. All tests were run in the MATLAB R2016b, on machine Hp Zbook, Intel® Xeon® Processor E3-1505M v5 2.80 GHz.

In addition, we performed a retrospective analysis of the obtained clusters. We examined the number of "satisfied" PWD users within each cluster. A user is "satisfied" if he/she is not more than 1000, 400, or 150 meters away from the center of the cluster he/she belongs to. The distance of 1000 meters is assumed for regular users. It is routinely suggested in transport and town planning literature that all people should have access to a bus service that stops within 400 meters (¼ mile) of their home and destination (Broome et al., 2012; Murray, 2003; Murray, Davis, Stimson, & Ferreira, 1998). Some references even proposed 150 meters as a recommended walking distance without rest for wheelchair users (P. R. Oxley &

Britain, 2002). In the figures presented in sections 4.5.3.1 and 4.5.3.2, the “satisfied” PWD users are those belonging to a circle with a proposed radius of meters originating at a cluster center

Since we performed clustering based on data from transport-on-demand users and wanted to compare with the existing network, we set a radius of 1000m for the graphical analysis. Also, we performed numerical analysis for the 1000m, 400m, and 150m distances.

4.5.1 Data set

Transvilles provided real-time data sets in two formats. The first is the General Transit Feed Specification (GTFS). It is known that GTFS is making public transit data universally accessible (Wong, 2013). GTFS is divided into static and real-time segments. The first component contains schedule, fare, geographic transit information, and the second component contains arrival predictions, vehicle positions, and service advisories. According to the GTFS model, we have the data of agency, calendar, calendar_dates, routes, shapes, stop_times, stops, and trips. This data describes the network and stops (stations) with their location presented as longitude and latitude.

The other data set is from the transport-on-demand “Sésame” database taken from 1st January 2019 to 31st December 2019. In order to respect users' privacy, the data set contains only street, house number, zip code at departure, and the same information at arrival. It was necessary to change this format to the one used for GTFS. So, the translation from traditional address information to the longitude and latitude format was carried out.

4.5.2 The optimal number of clusters

The optimal number of clusters was done by the k-medoids in Matlab. The function idx = kmedoids (X,k) performs k-medoids Clustering to partition the observations of the n-by-p matrix X into k clusters and returns an n-by-1 vector idx containing cluster indices of each observation. Rows of X correspond to points and columns correspond to variables. By default, k-medoids use the squared Euclidean distance metric and the k-means++ algorithm for choosing initial cluster medoid positions. Since that, the function k-medoids in Matlab demand the number of clusters (k) in advance. The tests were run for the following number of clusters: 5, 7, 9, 12, 25, 50, 105, 210, and 420. There are 420 stations on the Valenciennes’s public transport network with accessibility. In accordance with the MATLAB performances, the maximum number of iterations is set at 10000, 100000, and 1000000 with 1, 100, 1000, 10000 replications. Additionally, all tests are run ten times to get an average number. The detailed tables are presented in Appendix E (Table 17, Table 18, and Table 19) presents the results for the total number of PWD at departure and arrival, which is 5537. Results show that the optimal number of clusters is close to the maximum number of clusters.

The same conclusion applies to the departure and arrival cases, which are presented in Table 18 and Table 19. Table 12 only shows the results for 1 000 000 iterations and 10 000 replications which are the most precise. When the maximum number of clusters is set at 9, 7 and 5 clusters for the arrivals, the optimal number of clusters is 7, 5, and 4, respectively. For the departures, the optimal number is 8, 6, and 4, while for both arrivals and departures, we obtain 7, 5, and 4, respectively, the same as the arrivals.

Instances	MaxIteration	Replicates	No of stations= Max no of cluster	1	2	3	4	5	6	7	8	9	10	Avg
ARRIVAL	1 000 000	10 000	420	416	419	418	420	419	419	419	415	420	417	**418**
			210	207	209	208	204	209	209	197	210	210	200	**206**
			105	104	96	94	104	104	102	100	99	105	104	**101**
			50	49	46	50	47	46	49	48	48	48	45	**48**
			25	22	20	25	22	20	18	17	23	24	22	**21**
			12	9	11	8	12	12	8	7	7	8	8	**9**
			9	7	8	9	7	4	4	9	4	9	7	**7**
			7	6	4	4	4	6	6	4	4	4	7	**5**
			5	5	4	4	4	4	4	4	4	4	4	**4**
DEPARTURE	1 000 000	10 000	420	420	418	420	411	415	412	418	417	419	419	**417**
			210	194	203	210	210	206	207	206	210	210	204	**206**
			105	104	104	100	104	102	102	105	104	102	104	**103**
			50	49	44	50	40	49	50	50	45	50	50	**48**
			25	23	21	24	25	21	22	21	22	20	25	**22**
			12	10	12	12	11	8	9	12	10	9	12	**11**
			9	8	9	7	9	9	7	9	7	7	9	**8**
			7	6	6	6	4	7	6	7	4	4	6	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
ALL	1 000 000	10 000	420	416	419	417	416	415	420	417	420	417	419	**418**
			210	210	208	208	210	210	210	210	210	207	204	**209**
			105	96	99	103	103	101	100	105	101	94	101	**100**
			50	45	50	50	50	50	46	50	48	48	50	**49**
			25	20	20	25	22	19	25	24	23	25	22	**23**
			12	12	10	12	8	9	11	12	10	12	7	**10**
			9	9	4	7	6	4	9	4	8	9		**7**
			7	4	4	4	6	6	6	4	7	4	6	**5**
			5	4	4	4	4	4	4	4	4	4	4	**4**

Table 12 Optimal number of clusters

4.5.3 Clustering of the geographical positions of PWD

The purpose of clustering in this research is to provide data analysis. The optimal number of clusters provided in section 4.5.2. with the experiment results in Appendix E, is used as the input for further analysis. Since the number of clusters produced by k-medoids tends to get close to the maximum number, we have chosen to analyze the situation with five, seven, and nine clusters, as it is explained below.

As well, for the k-medoids method, the number of clusters sought needed to be defined in advance. There are five hubs on the public transport network map (*Station Anzin-Hôtel de Ville, Station Denain-Espace Villars, Station-Famars Université, Station Gare, Station Saint Waas*t). In the first series of experiments, we set the parameter K to five, i.e., the requested number of clusters is five. In this way, we could check if the situation on the ground corresponds to the demands of PWD. That is, whether the hubs are well located or not in relation to PWD requests. Also, we examined how an increase in the number of clusters impacts the relationship between PWD demands and hub locations. In this regard, additional tests were carried out with the value of parameter *K* set to seven and nine. The geo-position data sets in departure and arrival were processed, and all tests were run for both geo-positions, respectively. The test for the complete database with departures and arrivals is reported numerically. The results are presented both numerically and graphically for departures only and arrivals only.

4.5.3.1 Clustering of the geographical positions of PWD at departure

For departures, clustering is applied to 2,763 users. The number of searched clusters, *K*, varies from 5 to 9, as previously explained. The results of clustering for three different values of K are shown in Table 13. For each value of *K*, the number of users per cluster (Columns "Size of cluster") are reported, and the number of satisfied PWD users in each cluster (Columns "Satisfied"). Also, for each cluster, the percentage of satisfied users in relation to the total number of users in that cluster is calculated. Results are given in columns "%."

The results show for the case of 5 clusters and 1000m radius an average of 18% satisfied users, with the percentage per cluster ranging from 4% to 49%. For 7 clusters, there is a 4% increase, which represents an average of 22% of satisfied users. Nevertheless, now, the percentage per cluster ranges from 3% to 53%. A significant percentage of satisfied users is noted in the 9 clusters case. An average of 35% of users is satisfied, with the percentage per cluster ranging from 11% to 70%. For 400m, the percent of the satisfied users are 1, 6, and 8 % for 5,7, and 9 clusters percent and around 1%, respectively. In a case of 150m, the percent of satisfied users for all situations is 1%.

DEPARTURE	5 Clusters			7 Clusters			9 Clusters		
1000m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	185	90	49%	177	94	53%	302	33	11%
Cluster 2	955	223	23%	330	84	25%	310	60	19%
Cluster 3	390	14	4%	173	6	3%	327	84	26%
Cluster 4	887	89	10%	723	182	25%	123	27	22%
Cluster 5	346	84	24%	863	207	24%	753	337	45%
Cluster 6	N/A	N/A	N/A	176	9	5%	79	55	70%
Cluster 7	N/A	N/A	N/A	321	33	10%	509	256	50%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	171	94	55%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	189	24	13%
Total	2763	500	18%	2763	615	22%	2763	970	35%
400m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	887	12	1%	863	22	3%	675	60	9%
Cluster 2	185	8	4%	177	58	33%	309	5	2%
Cluster 3	955	3	0%	173	3	2%	173	36	21%
Cluster 4	346	6	2%	330	6	2%	343	3	1%
Cluster 5	390	3	1%	176	5	3%	695	79	11%
Cluster 6	N/A	N/A	N/A	321	5	2%	123	21	17%
Cluster 7	N/A	N/A	N/A	723	79	11%	105	1	1%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	88	14	16%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	252	9	4%
Total	2763	32	1%	2763	178	6%	2763	228	8%
150m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	955	1	0%	863	2	0%	123	1	1%
Cluster 2	185	5	3%	177	4	2%	753	1	0%
Cluster 3	390	2	1%	173	3	2%	171	3	2%
Cluster 4	346	4	1%	723	2	0%	509	18	4%
Cluster 5	887	5	1%	176	5	3%	327	4	1%
Cluster 6	N/A	N/A	N/A	330	4	1%	302	4	1%
Cluster 7	N/A	N/A	N/A	321	4	1%	189	11	6%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	79	2	3%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	310	1	0%
Total	2763	17	1%	2763	24	1%	2763	45	2%

Table 13 Results of clustering at departure, K= 5, 7, 9

Figure 20 shows the result of clustering in the geo-situation departure for five clusters. The first ones (the five hubs already on the network) are shown in grey rectangles. New clusters are indicated by blue rectangles, and red circles centered at a centroid with a radius of 1,000 meters indicate satisfied users. PWD users, or the point where "Sésame" picks them up, are small dots in blue, red, cyan, green, and pink. Higher resolution versions of Figure 20, Figure 21, and Figure 22 can be found in Appendix F (Figure 33, Figure 34, and Figure 35). Note that users in the same cluster appear in the same color.

Having applied the clustering, Figure 20 shows that only three hubs fall into the circles of satisfied users, and there is no match between an existing hub and a cluster center. Also, it is clear that two hubs (*Station Anzin Hôtel de Ville and Station Saint Waast*) are inside the new cluster. Consequently, matching between existing hubs and clusters happens in only two of five cases.

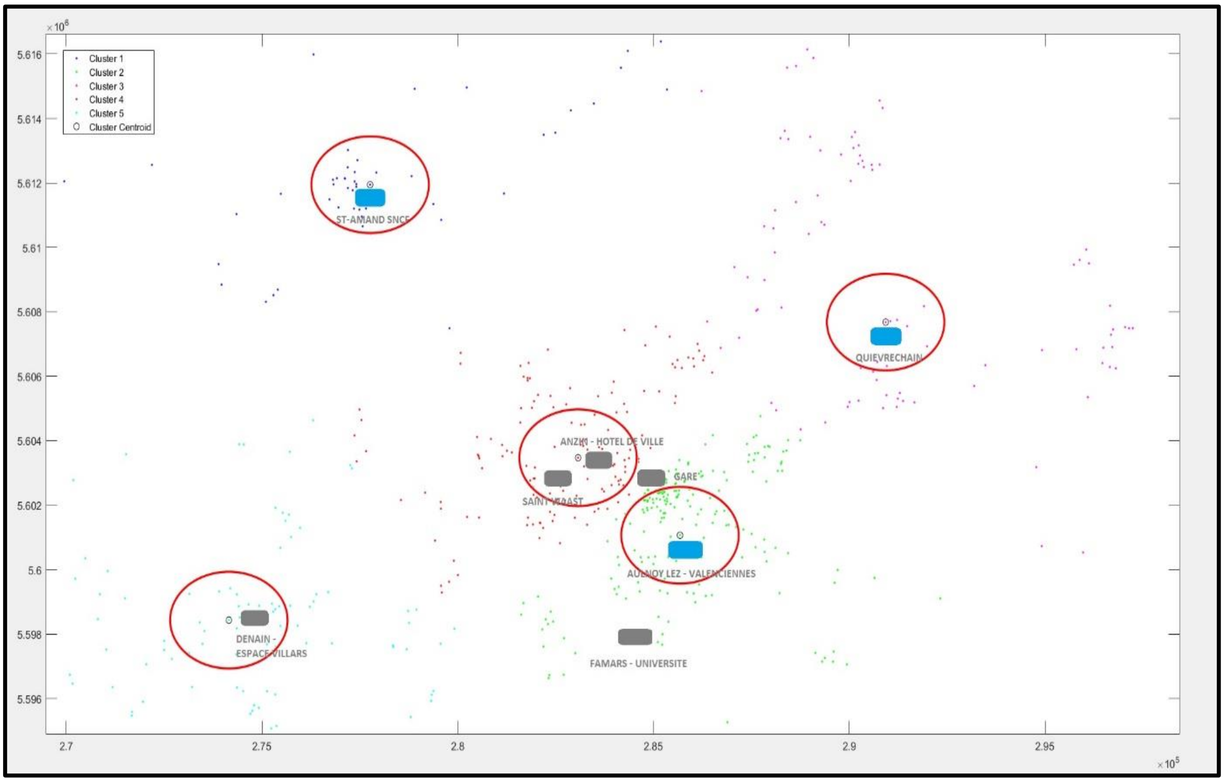

Figure 20 Geographical position at departure: 5 clusters

Interestingly, the *Station Gare* and *Station Famars Université* hubs sit outside the circles. For *Station Gare* this could be because there are three adjacent hubs in a small area in the city center. Alternatively, the *Station Famars Université* is replaced by the nearest new one at *Aulnoy-lez-Valenciennes.* This may be because *Station Famars Université* is located at the end of Valencinnes's public transport network, and clustering suggests moving this hub more centrally. Also, there are two new clusters in Quiévrechain and St-Amand SNCF's geo-location at the border of Valenciennes Metropole. It is anticipated that this is to improve the Valenciennes Metropole area.

The 7 clusters scenario is shown in Figure 21. The same indication as the previous case applies here. Again, in the city center, two hubs (Station Saint Waast and Station Anzin Hôtel de Ville) sit within the same circle. However, now we have met all existing hubs. The hub Gare is also part of one circle, unlike the previous case with five clusters. Also, this time, there is no new hub at *Aulnoz-lez-Valenciennes,* but instead at *Conde – Le Boulon*, which is also the terminus for tramline 2. Alternately, *Quiévrechain* and *St-Amand SNCF* are the same as the 5 cluster cases.

The nine clusters example is shown in Figure 22. Existing hubs are located as for the seven clusters case. Nothing has changed. Inevitably, there are new clusters. Some of these are in related positions, as previously. The two new centers are at *Bouchain* and *Escaupont.*

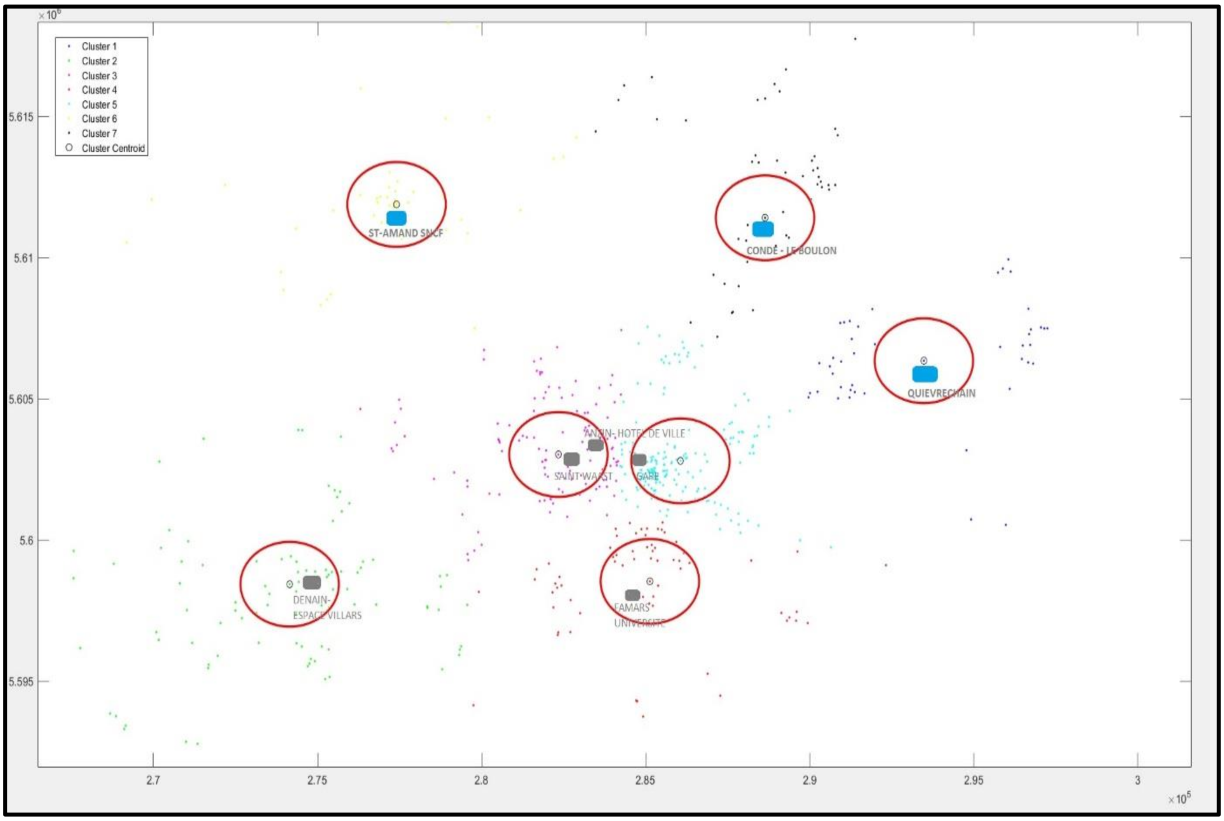

Figure 21 Geographical position at departure:7 clusters

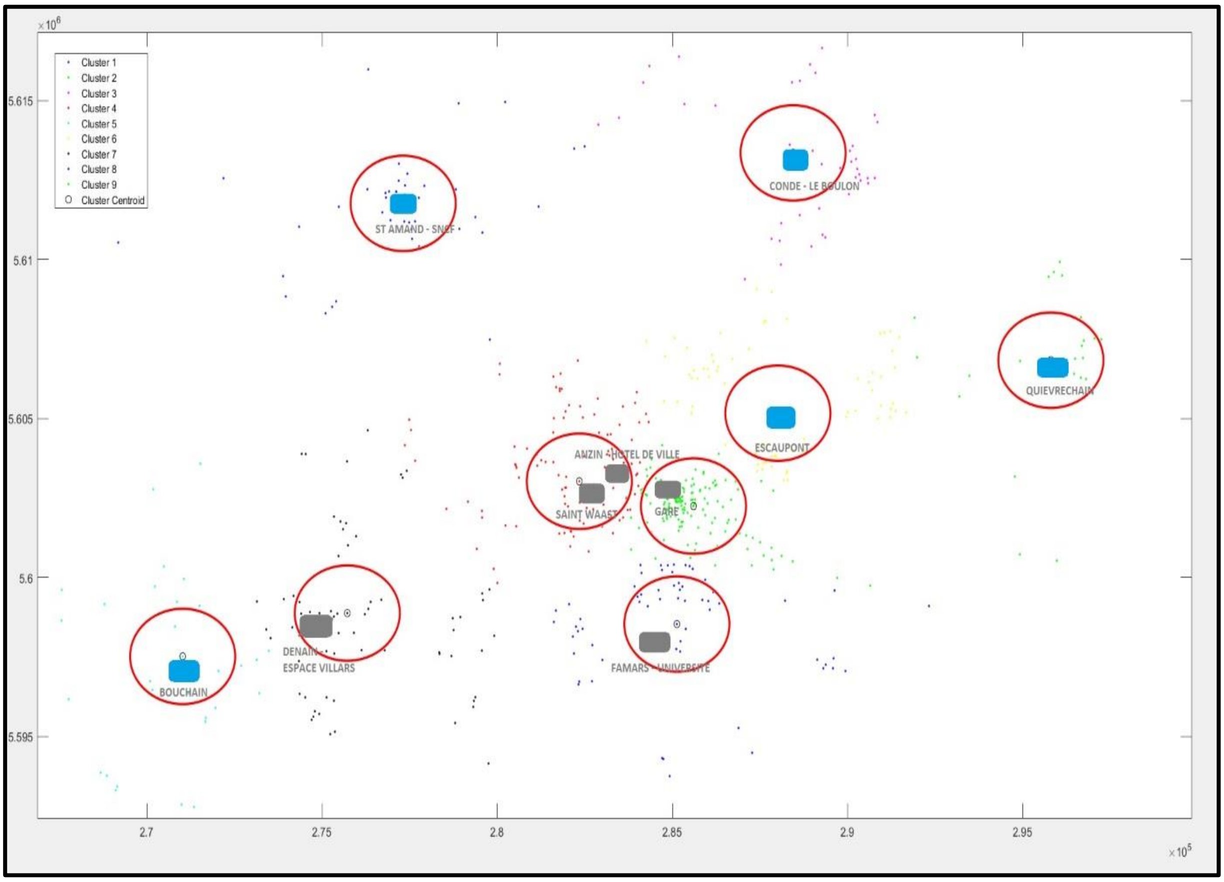

Figure 22 Geographical position at departure: 9 clusters

4.5.3.2 Clustering of the geographical positions of PWD at arrival

As already mentioned, the previous tests have been studied in the case of departure when the vehicle takes PWD users. The arrival event is when the vehicle delivers the user to the requested address. Table 14 shows the clustering results applied to 2,747 users, with the number of requested clusters set at five, seven, and nine. There are 16 fewer users at arrival because some users get out at the same place.

In the case of 5 clusters, the results are equal in the departure and the arrival leading to the same average percentage of satisfied users. The same applies to the case with 7 clusters. However, for the case of 9 clusters, there are some differences. There are 24% satisfied users, which is 9% less than for the departure situation. Also, the minimum rate of satisfied users in a cluster is now 4%, compared to the departure situation, which was 11%. The radius of 400m reported 2% of satisfied users with 5 clusters, 6% within 7 clusters, and 8% in the case of 9 clusters. Radius 150m shows an improvement of 1% in 5 and 7 clusters and 2% for9 clusters.

ARRIVAL	5 Clusters			7 Clusters			9 Clusters		
1000m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	390	14	4%	173	6	3%	171	6	4%
Cluster 2	953	222	23%	330	84	25%	703	182	26%
Cluster 3	171	76	44%	723	182	25%	159	80	50%
Cluster 4	346	84	24%	319	33	10%	272	57	21%
Cluster 5	887	89	10%	863	207	24%	302	25	8%
Cluster 6	N/A	N/A	N/A	163	80	49%	174	37	21%
Cluster 7	N/A	N/A	N/A	176	9	5%	741	246	33%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	121	27	22%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	104	5	5%
Total	2747	485	18%	2747	601	22%	2747	665	24%
400m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	1766	21	1%	814	79	10%	159	36	23%
Cluster 2	212	3	1%	346	3	1%	88	14	16%
Cluster 3	347	6	2%	159	36	23%	695	79	11%
Cluster 4	246	3	1%	88	14	16%	105	1	1%
Cluster 5	176	26	15%	334	6	2%	674	60	9%
Cluster 6	N/A	N/A	N/A	883	6	1%	123	21	17%
Cluster 7	N/A	N/A	N/A	123	21	17%	308	5	2%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	252	9	4%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	343	3	1%
Total	2747	59	2%	2747	165	6%	2747	228	8%
150m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	347	4	1%	334	4	1%	739	8	1%
Cluster 2	246	2	1%	814	2	0%	323	4	1%
Cluster 3	1766	11	1%	346	2	1%	714	2	0%
Cluster 4	176	2	1%	159	3	2%	139	1	1%
Cluster 5	212	3	1%	88	14	16%	159	3	2%
Cluster 6	N/A	N/A	N/A	883	1	0%	260	1	0%
Cluster 7	N/A	N/A	N/A	123	1	1%	87	14	16%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	121	1	1%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	205	29	14%
Total	2747	22	1%	2747	27	1%	2747	63	2%

Table 14 Results of clustering at arrival, K= 5, 7, 9

The outcome of cluster analysis for the arrivals in the case of a radius of 1000m is depicted in Figure 23, Figure 24, and Figure 25. The high resolution of the mentioned figures is presented in Appendix F (Figure 36, Figure 37, and Figure 38). Analysis of the hubs' geo-position shows an apparent difference only in the case of 9 clusters compared to the departure situation. The geo-position of cluster centers and the relationship between existing hubs and established clusters are identical in all other locations. This was not unexpected due to a similar distribution of the input data. The results of the five and seven cluster cases are shown in Figure 23 and Figure 24. In the 9 clusters example, the difference is that the hub Bouchain is not included, Figure 25. The next example is *Prouvy*, which is located more in Valenciennes' urban area, unlike *Bouchain*, which is in a rural area. The other difference is that the hub *Famars-Université* is within a 1,000 meters radius.

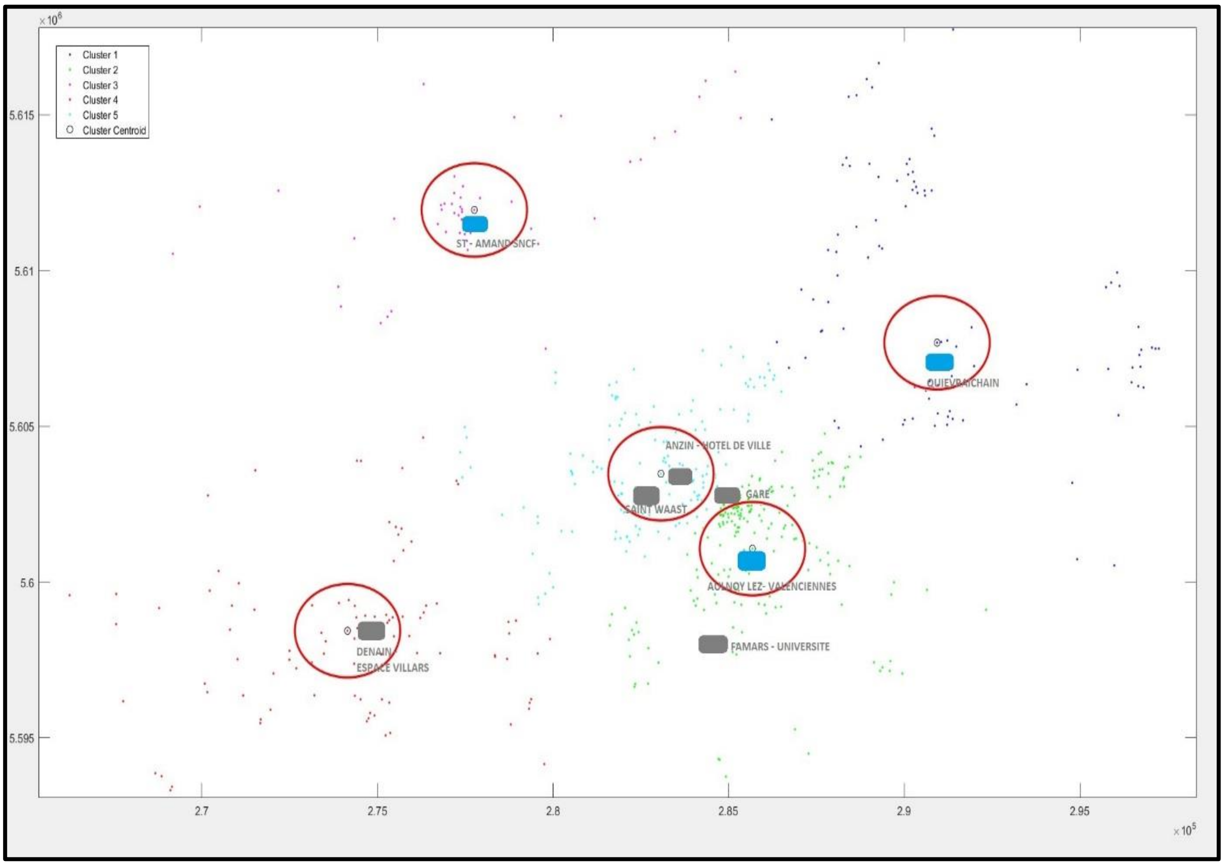

Figure 23 Geographical position at arrival: 5 clusters

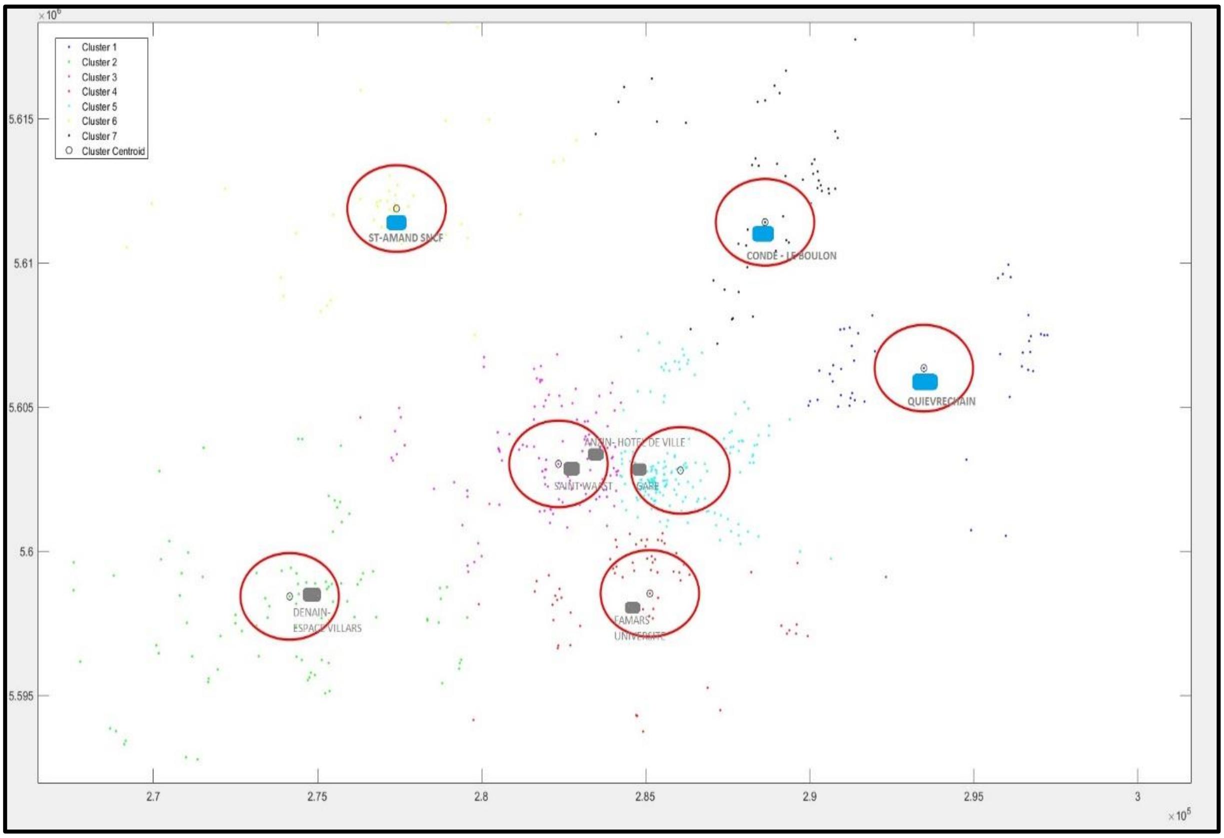

Figure 24 Geographical position at arrival: 7 clusters

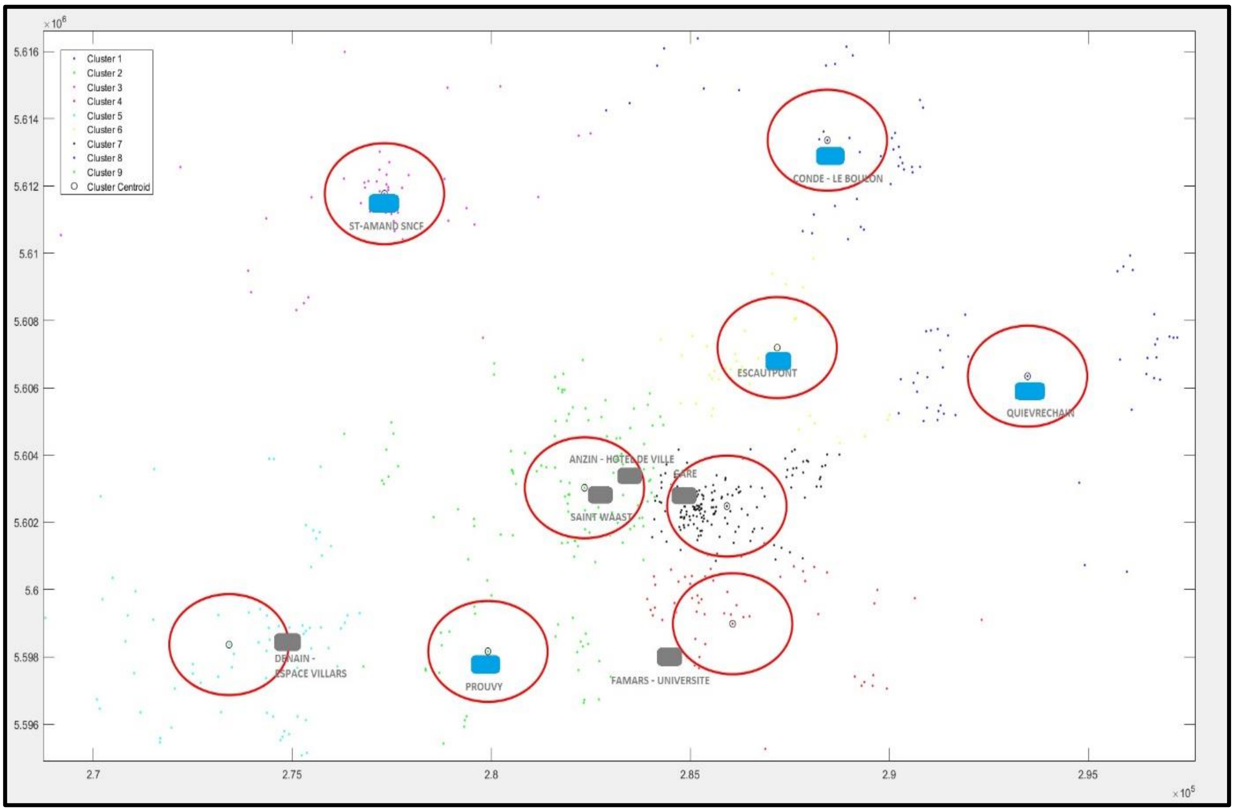

Figure 25 Geographical position at arrival: 9 clusters

4.5.3.3 Clustering of the geographical positions of PWD – all

The case of considering simultaneous departures and arrivals is analyzed only numerically because we were focused on the transport flow. The numerical analyses served to check the number of clusters and satisfied users.

The numerical presentation of the complete database is presented in Table 15. The graphic display is not part of this study, as it was more important to know the clusters in different transport flows. However, the numerical analysis has shown that 23% of satisfied users for 5 clusters, 25% for7 clusters, and 29% for 9 clusters if the radius is 1000m. As expected, this ratio is smaller for a radius of 400m and 150m.

ALL	5 Clusters			7 Clusters			9 Clusters		
1000m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	1734	364	21%	1608	364	23%	1501	674	45%
Cluster 2	668	168	25%	486	10	2%	210	44	21%
Cluster 3	356	166	47%	1870	622	33%	605	66	11%
Cluster 4	820	28	3%	340	174	51%	332	174	52%
Cluster 5	1932	524	27%	134	30	22%	210	4	2%
Cluster 6	N/A	N/A	N/A	404	12	3%	168	40	24%
Cluster 7	N/A	N/A	N/A	668	168	25%	540	44	8%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	1440	364	25%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	504	206	41%
Total	5510	1250	23%	5510	1380	25%	5510	1616	29%
400m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	3388	42	1%	634	12	2%	1188	36	3%
Cluster 2	694	12	2%	306	10	3%	158	6	4%
Cluster 3	246	42	17%	100	6	6%	1284	158	12%
Cluster 4	358	52	15%	1756	158	9%	246	42	17%
Cluster 5	824	32	4%	288	2	1%	504	18	4%
Cluster 6	N/A	N/A	N/A	480	2	0%	210	2	1%
Cluster 7	N/A	N/A	N/A	1946	232	12%	1180	48	4%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	332	72	22%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	408	32	8%
Total	5510	180	3%	5510	422	8%	5510	414	8%
150m	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%	Size of cluster	Satisfied	%
Cluster 1	3534	22	1%	356	10	3%	1390	4	0%
Cluster 2	694	8	1%	140	4	3%	246	2	1%
Cluster 3	366	4	1%	1834	24	1%	210	2	1%
Cluster 4	492	4	1%	1672	10	1%	617	8	1%
Cluster 5	424	6	1%	238	2	1%	332	6	2%
Cluster 6	N/A	N/A	N/A	496	10	2%	1349	14	1%
Cluster 7	N/A	N/A	N/A	774	4	1%	176	28	16%
Cluster 8	N/A	N/A	N/A	N/A	N/A	N/A	686	4	1%
Cluster 9	N/A	N/A	N/A	N/A	N/A	N/A	504	12	2%
Total	5510	44	1%	5510	64	1%	5510	80	1%

Table 15 Results of clustering all users, K= 5, 7, 9

4.6 Conclusion

This chapter proposed a clustering analysis to make the existing public transport network of Valenciennes more accessible to PWD. The primary goal was to develop a viable approach that enables PWD to use public transport freely, unlike the current arrangement where the transport of PWD is somewhat excluded. The transport of PWD in Valenciennes is achieved using a transport-on-demand service called *Sésame*, which is entirely independent of other parts of the public transport network.

The proposed clustering approach suggests possibilities for the inclusion of PWD to the public network. One option is the re-direction of PWD to nearby hubs, from where they can access the public network in the same way as other users. Applying the clustering approach shows that at least 18% of PWD at departure/arrival could use the Valenciennes public transport network. Another option is to open up new hubs, which would result in improved satisfaction for PWD users. The next possibility would be to combine transport on-demand (*Sésame*) with other public transport network sections. This could happen by bringing PWD to hubs (by either Sésame, or independent PWD access to the closest hub), after which the public transport network is used in the same way as regular users. Finally, they arrive at a hub from where they go to the destination - either by *Sésame*, or independently if the distance is reasonable. For this option, the key issue is the appropriate dispatch of *Sésame* vehicles to hubs to bring PWD to corresponding hubs.

Final recommendations made to Transvilles are shown using the number of clusters K=5,7,9 with a radius of 1000m. This radius follows the situation on the ground, where they considered network station distances in the same manner. Although considered in this thesis, the radiuses of 400m and 150m are not used for the final recommendation because some preliminary questionnaires revealed that the distance of 1000m would be acceptable for PWD currently. However, the analysis outcomes for 400m and 150m presented in this thesis still provide significant insights for Transvilles on how to further optimize their network for PWD in the future.

The 5 clusters case. We will start with the recommendations for the situation of 5 clusters, which is the present case on the network. At this stage, we reported that 18% of users could use conventional transport instead of "*Sésame.*" What should be considered to change is the geo-location of current hubs. The recommendation is to introduce three new: *Aulnoy-lez-Valenciennes*, *Quiévrechain,* and *St-Amand SNCF.* The vehicles in charge of transport on demand can use some of this location as a depot, instead of having only one depot for all vehicles.

The 7 clusters case. The applied method indicates that up to 22% of PWD users could be brought to regular transport in the situation of 7 clusters. This percentage will be achieved if the new hubs are established in *Quiévrechain, St-Amand SNCF, and Conde – Le Boulon*. The centers *Quiévrechain and St-Amand SNCF* appeared in both situations, five and seven clusters. A similar recommendation at the operational level may be provided regarding vehicles: Consider the new hubs as possible depot locations.

The 9 clusters case. It was observed that in the case of 9 clusters, the percentages of PWD that could directly use public transport networks are 24% on arrival and 35% on departure. Enabling at least 24% of PWD users to become free users of the public transport network is a remarkable achievement. For this purpose, new hubs need to be located in *Quiévrechain, St-Amand SNCF, Conde – Le Boulon, Bouchain,* or *Prouvy.* Since we have a different graphic situation departure and arrival, we need to propose a unique geographic location. On arrival, we have a new hub *Prouvy,* and on departure, we have *Bouchain.* The proposition here is to develop the hub *Bouchain,* because *Prouvy* is located in the middle of two existing hubs *Denain and Famars.* Additionally, the *Prouvy* is closer to the center of Valenciennes.

These interpretations of the numerical and graphical results support our findings, but the recommendations for new hubs are in line with the map presented in Figure 26. This picture gives the establishments for disabled and/or elderly people in metropole Valenciennes. All of the specialized establishments are spread over the two Agglomeration communities.

A further recommendation is made in relation to facilities. The public transport of Valenciennes does not have the facilities to monitor the number of PWD users. Today, data on types of PWD, the mode of transportation they use is not available. In fact, this data does not exist at all. The available data set registers PWD users via an inscription for the appropriate travel subscription. After that, the current ticketing system cannot recognize different users. We strongly believe it is critical to accurately measure the use of public transport networks by diverse users. This could serve as an essential tool to help improve the service further.

This chapter proposes several potential research directions for the future. For example: optimizing further transport-on-demand by properly dispatching the existing fleet; determining the optimal number of transport-on-demand vehicles to ensure a certain level of user satisfaction; simultaneously address the dial-a-ride problem and clustering; create a user-friendly application that generates itineraries for PWD by combining dial-a-ride and the shortest path optimization problems, etc.

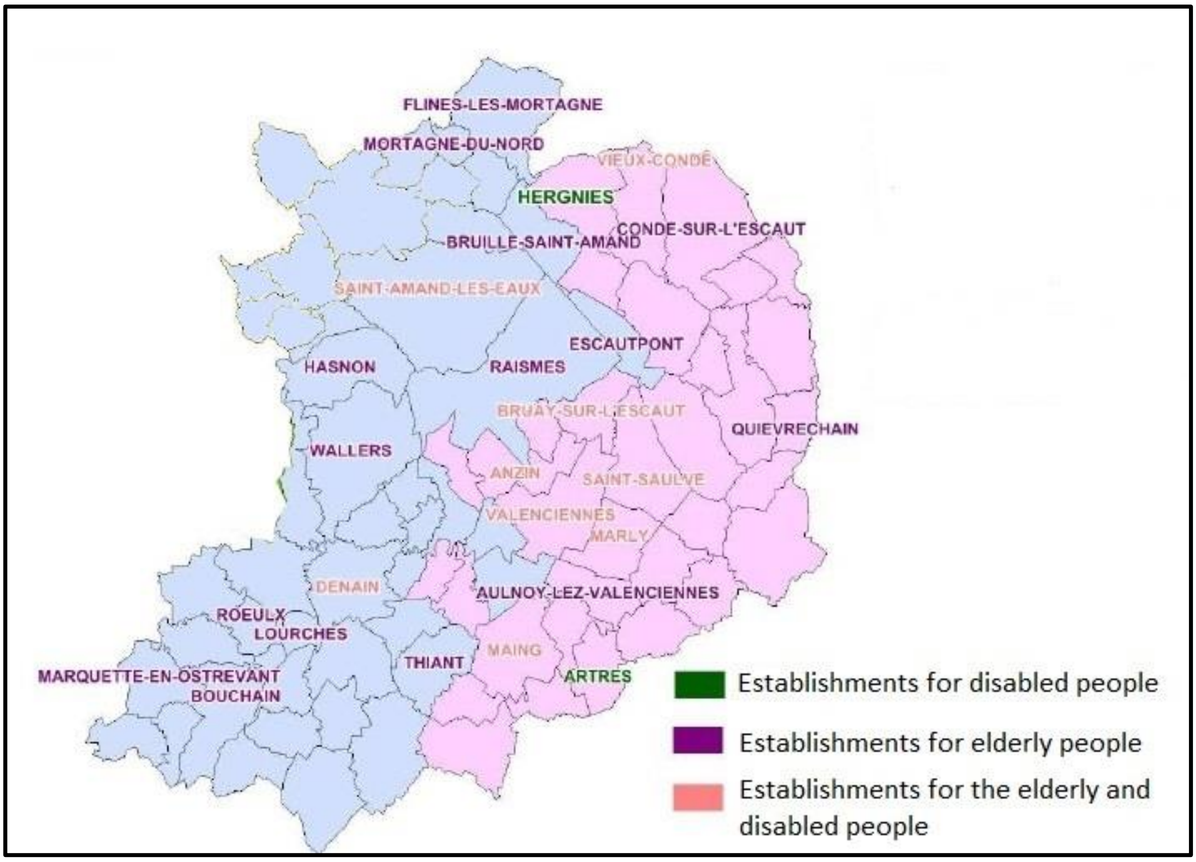

Figure 26 Establishments for disabled and/or elderly people in Valenciennes metropolitan region

(Egis France Villes & Transport, 2013b)

Chapter V

5 Closing statement

The same argument is applied in the closing statement as in the explanatory statement. Chapter V includes Section 5.1 Introduction, followed by Section 5.2 Main research findings, including the reframing and incomings elements. Section 5.3 is dedicated to the thesis contributions. Section 5.4 makes the recommendation for future work, and Section 5.5 concludes the chapter.

5.1 Introduction

As demonstrated throughout the chapters of this thesis, public transport systems are reaching out to serve more and more diverse users, particularly persons with disabilities. However, while PWD integration regulations have become increasingly demanding, the focus remains on the standard user, and transport system design has not fundamentally changed. The number of users and the diversity of their needs make transport planning incredibly complex. At the same time, we have seen this complexity increases to meet the specific needs of PWDs. On top of the number of participants, PWD transport is also limited by specific constraints, such as the types of journeys and vehicles. Optimization models such as transport-on-demand and the shortest path problem provide a starting point for one of the best-known approaches to help improve services for PWD. Still, these cannot deliver complete independence in PWD transport.

In the closing statement, we will summarize the main findings of this research and demonstrate why it was necessary to reframe the problem formulation. We found that the two basic optimization models do not fully satisfy the process. At this point, we demonstrated the decision analyst's central role in helping the client understand and formulate the problem correctly. The contributions of the thesis will be the topic of this chapter as well.

5.2 Summary of the main results and limitations

Notwithstanding this thesis's interdisciplinary approach, as discussed earlier, the decision-aiding process determines the development and research formalization of the thesis structure. The four stages of the decision-aiding process in this thesis are made up of the problem situation, the problem formulation, the evaluation model, and the final recommendation (Tsoukiàs, 2007) and each chapter's development. Consistent with the final recommendations, we need to consider the model's formality, the client's understanding of the model, and its legitimacy. Figure 27 shows the operational research models' steps and organizational legitimacy (Landry et al., 1996). Through the thirteen steps, the process of successful adoption of operational research inside the organization is explained. The third step, the change process through modeling, is reserved for an unforeseen element in the optimization models. This step prompted us to reframe the optimization model – clustering approach instead of transport on-demand or shortest path, which will be further explained in subsection 5.2.2 But, first,before the reframing, the main findings will be presented.

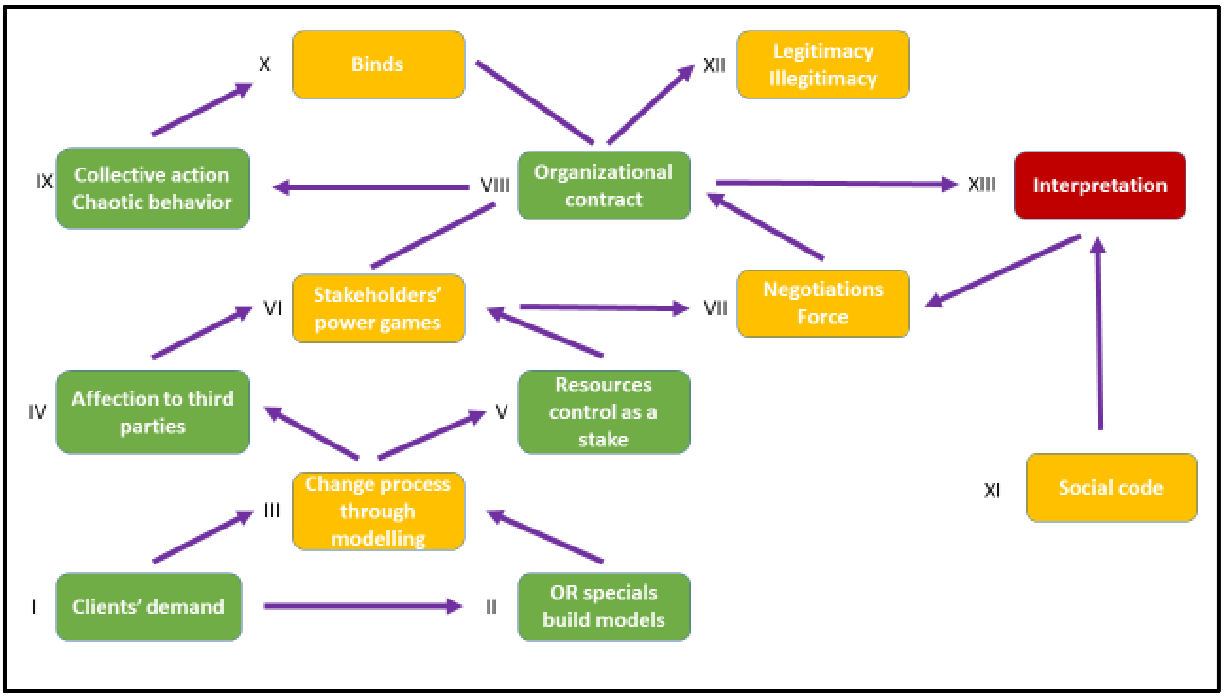

Figure 27 OR models and organizational legitimacy (Landry et al., 1996), adapted by the author

5.2.1 Findings

In this thesis, we have addressed the efficient integration of persons with disabilities into the public transport system, using the decision support process. This approach makes it possible to better align the required adaptations of a transport system while being aware of the challenges of players in the transport system, taking careful account of the needs of persons with disabilities.

Introducing decision models based on decision theory into organizations is a sensitive process that requires detailed knowledge, both of the computational foundations underlying the models and the decision-making factors involved in organizations. This challenge is usually avoided for two main reasons: i) practical problems associated with decision theory that typically relate to already formalized fields (John C. Henderson & Nutt, 1980; Landry et al., 1996; Landry et al., 1983). A transport system already responds to an established structure that significantly restricts decisions, which provides a prerequisite suitable for modeling; ii) the concept of a decision is intimately linked to human nature (H. A. Simon, 1973; H. A. Simon, 1997; H. A. Simon, 2000). The result is an interest in instrumental decision support that focuses its intervention on a result rather than a support aiming to improve the decision-making structure.

Approached in this way, modeling can be liberated from the mere construction of a representation faithful to the transport system to consider assumptions that change its nature. Thus, by approaching PWD as stakeholders in decisions, models become a factor of inclusion that will strengthen the validity of some decision-making processes and necessitate changing others. The management of transport networks then breaks down into a generic centralized part and a decentralized part that has better consideration for the particular needs of PWD.

Centralized management remains fundamentally based on the shortest path problem incorporating accessibility constraints. Decentralized governance is based on transport-on-demand, where external resources are mobilized. It is generally considered that transport-on-demand is helpful to many rural and urban communities, particularly with the development of telematics. In the case of PWD, on-demand transport also serves urban areas that are not covered by the network.

These areas, which do not present problems for non-disabled people, may be difficult to navigate for persons with disabilities. Transport on-demand then results in consideration of non-disabled people as a transport resource that can support PWD in rural areas adjacent to the network journey. Standard, non-disabled users can then become leverage for the inclusion of PWD in the transport system.

Accessibility plays one of the primary functions in bringing the transport system closer to PWD. To create such a system, it was necessary to develop the model with additional information (John C Henderson & Venkatraman, 1999). One part of this additional information relates to PWD needs. These needs have already been defined (U.S. Government Accountability Office (GAO), 2004) and presented as the 5As: Availability, Accessibility, Acceptability, Affordability and Adaptability. They represent PWDs requests, but they have not been considered in developing and evaluating optimizations models.

With this perspective of the problem, up-to-date information is needed on the service offering. Nevertheless, this offering must also be structured in a network to establish the vectors of inclusion. This network can be formed through strategic alliances (John C Henderson & Venkatraman, 1999) between the transport system management and new stakeholders that support PWD. Such stakeholders are usually part of the logic of non-governmental organizations, which strengthens the merits of decentralized governance. From their conception, models delimit organizational impact beyond their operational nature due to a strategic alignment logic.

Organizational arrangements, therefore, frame models. The robust analysis of solutions generates information on the means required for the model framework. The sensitivity analysis, for its part, appears more linked to the data and their acquisition chain.

5.2.2 Reframing

According to Herbert A. Simon, 1983), the problem is not resolved within the decision-aiding process, although the process of setting and fixing the issue is the same process. In fact, in the absence of a good problem position, a good solution cannot be found. As reported in the final recommendation (Tsoukiàs, 2007), and as stated at the beginning of this chapter (Landry et al., 1996), in order to have a successful model implementation, the model must be legitimate. One way of achieving legitimacy is to change the process through modeling, referred to as reframing.

Reframing the problem results from the comprehensive analysis of PWD needs and evaluating the corresponding models. The data set available for the actual examination required that the problem be reframed.

At the beginning of this thesis, it was proposed that the basic optimization models transport-on-demand and shortest path only partially satisfied PWD needs, as defined through 5As. Full independence for the inclusion of PWD in public transport cannot be provided. The interaction between the public transport network and basic optimization models was reviewed and evaluated through PWD needs. The results have shown that it would be more useful to demonstrate the model's legitimacy if the clustering approach is used. The available data for the Valenciennes public transport network relates to the geo-location of transport on-demand users. This data represents an important part of model development. However, the most important function is model implementation, which brings us back to the model's legitimacy. It also provides an example of problem reframing.

5.2.3 Incomings

Incomings is a general reflection on the model embedded in the organization. The issue of inclusion raises the question of what optimization means to users, which is the principle that underpins the transport-on-demand and shortest path approaches, and centralized management. In the modeling approach based on the decision-aiding process, optimization is approached in three ways:

1. Identification of an issue or a sub-set of topics that legitimately resembles an optimization logic that will provide a basis of stability by centralized management models.

2. Change management according to the position of the problem in the hierarchy of issues:
   - Strategic - to address mobility issues in order to restore capacities that organizational alliances and networks have reduced.
   - Tactical - to create information systems that mobilize the network of non-disabled people assisting PWD.
   - Operational - to implement a support network for each request received from a PWD.

3. Monitoring the organizational dynamics of disseminating data produced within the reconfigured organization to adjust the models and identify new model needs.

It should be noted that this modeling approach, taking organizational factors into account, highlights the value of reflecting on the challenges of improving the quality of service beyond the normative approach provided by models alone. Thus, by coordinating non-disabled people with PWD, a combination of centralized and decentralized transport management modes reveals two different aspects of mobility. For persons with disabilities, mobility challenges are unique to the individual. Alternately, for the non-disabled person, movement becomes an organizational issue. More general and shared common factors are needed to develop the transport system on a lasting basis. Subject to an individual's particular circumstances, the issue of mobility does not have the same status. This issue, therefore, concerns the organization responsible for the transport system. For an individual, disabled or not, the issue is proximity, the use of the transport system being a resource to get to a preferred destination.

The concept of non-disabled people supporting PWD is essentially a social cohesion issue.

5.3 Scientific contributions

To explain scientific contributions, we will first restate the research objectives of the thesis. One of the thesis's main goals is to improve the quality of life for persons with disabilities. A key component of PWD quality of life is the extent of their inclusion in a public transport network. Another goal was to assist in the decision-making process of our client: Communauté d'agglomération Valenciennes Métropole. The third goal was to develop an optimization model to ensure the inclusion of PWD in public transport without changing the network itself.

To address the first goal, we focused on understanding the needs and obstacles for PWD in the daily use of public transport. This was summarized by the literature review from various disciplines, including legislation from different countries, studies, and the analysis of international organizations, medical examinations, etc. As it was the project input to some optimization models, a systematic review was carried out to identify the appropriate models.

For the second goal, the process of decision aiding has been comprehensively explained to clearly demonstrate the methodology's useful tools to the client and reader. Also, through the process of applying the methodology, each phase provides examples and clarification of the process related to the appropriate transportation optimization model. Ultimately, the proposed model facilitates the provision of a transport service that gives full autonomy to PDW.

The third goal was achieved through the clustering approach. Since that decision-aiding process reveals the results that analyzed optimization models transport on-demand and the shortest path satisfied only one part of the solution, the clustering approach is proposed as the Analytic tool. The clustering approach is analyzed the transportation flow of PWD and proposes the new exchange hubs with a higher number of satisfied PWD users.

The scientific contribution is presented through three themes of the thesis: theoretical, methodological, and application.

5.3.1 Theoretical

The review of the relevant literature within a single discipline is a challenging task. When a multidisciplinary review is carried out, the challenge is amplified. The organization of this research and the identification of relevant data is the most demanding job. The resulting output is our contribution.

The 5As, as defined by the U.S. Government Accountability Office (U.S. Government Accountability Office (GAO), 2004), identified the primary needs of persons with disabilities and formed a key reference for our study. The 5As are: Availability, Accessibility, Acceptability, Affordability and Adaptability, and form the foundation for the theoretical research of this thesis. As far as we are aware, this is the first time that an analysis of the optimization models has been carried out through a systematic review.

The systematic review was implemented in two parts: transport on-demand and shortest path. The six models in transport-on-demand optimization models include: Dial A Ride Problem – DARP, Demand Adaptive System – DAS; Flexible Transport System – FTS; Scheduled Paratransit Transport System – SPTS; Mobility Allowance Shuttle Transit – MAST, and Integrated Dial-a-Ride – IDAR. These were analyzed in relation to PWD needs in accordance with the 5As. The second part considered the shortest path models, which were classified into four models: Multimodal Shortest Path Problem – MSPP; Time Dependent Shortest Path Problem – TDSPP; Resource Constrained Shortest Path Problem – RCSPP; and Multi Objective Shortest Path Problem – MOSPP. For the first time, in addition to the classification contribution, all the models were defined and evaluated relative to the 5A attributes. A ranking table including detailed studies of each model component has been provided.

In addition, the framework of transport legislation relating to PWD transport rights has been provided at three levels: globally, across Europe, and nationally (France and Canada). The most significant contribution is that almost all the literature relating to the transport of persons with disabilities has been summarised in a single place.

5.3.2 Methodological

The methodological contribution spans several segments. The first methodological contribution comes from combining three different approaches: management, the decision-aiding process, and optimization. This interdisciplinary approach enabled the resulting high quality of research.

Management emerged as the second methodological contribution by examining numerous sources of literature. The provision of references such as numerical data, regulations, and the bibliography required a precise and systematic approach.

For the decision-aiding methodology component, we can report four contributions: - 1) Practical application of the decision-aiding process within the thesis as shown in the thesis structure; 2) The structure is maintained through each chapter; 3) In Chapter III all steps of DAP are implemented and the matrix is developed.

The matrix presents the structure of the relationships between existing optimization models, subject to public network information, particularly the actual accessibility of the public network. The decision-aiding process proposes a comprehensive analysis, enabling selecting a suitable model at any time for the inclusion of disabled persons.

As already observed, the decision-aiding process includes four approaches: normative, descriptive, prescriptive, and constructive (D. Bouyssou, 2000, 2006). Different decision-aiding approaches are dependent on different disciplinary concerns, and in this case, we were applying interdisciplinary thesis research, so all four approaches were implemented. Normative was used for the investigation on regulations regulative investigation in Chapter II. Descriptive was used for the analysis of optimization models, also included in Chapter II. Prescriptive is provided in Chapter IV, where we proposed a clustering approach, and constructive in Chapter III.

5.3.3 Application

The clustering approach was used to improve actual accessibility to the public network. This contribution has demonstrated for the first time that the clustering approach can be used to bring the existing public transport network closer to PWD based on a real data set. Additionally, a case study on the network of Valenciennes has been provided.

The aim was to propose a method that helps PWDs to use the public network independently. The data used was obtained from transport-on-demand users, as this was the only transport mode provided in Valenciennes for persons with disabilities. The clustering approach helped avoid a hard requirement imposed at the beginning of research - that the network infrastructure could not be changed. Having complied with to guarantee to meet the PWD needs h this requirement, our approach improves the transport network's use just by reorganizing the hubs. Moreover, the proposed clustering approach suggests further possibilities for the inclusion of PWD into the public network.

The first contribution is based on directing PWDs to the nearest hub where they can access the public network alongside other users. The clustering approach shows that at least 18% of PWD in departure/arrival could use to use the public transport network of Valenciennes as freely as regular users.

Another contribution is the recommendation to open up new hubs by simply designating some of the existing stations to serve as hubs. In this way, a significant increase in the number of satisfied PWD users is achieved.

5.4 Recommendation for future work

Future work includes the development of organizational levers that serve the mobility of persons with disabilities. This is broken down into five components: i) organizational levers for strategic alignment; ii) social networks; iii) levers of strategic alliances and corporate networks; iv) definition of sectoral and public policy guidelines; v) data.

i. **Organizational levers for strategic alignment:**

   a. Decision-making hierarchy of stakeholders that are strategically involved in disability; the definition of objectives and the transportation means of urban mobility; the tactics for an arrangement of the transportation means; the operation of the implementation of the transportation means, and activities of production of the effects of transportation means;
   b. Decline of mobility issues from the point of view of the individual, organizations and society;
   c. Analysis of the potential for the service to be offered directly by existing means of mobility, for particular citizens, or achieved by the transfer of means devoted to issues other than mobility;
   d. Inventory of stakeholders in mobility services applicable to people with disabilities;
   e. Information and communication vectors, social networks on the internet, and mobile applications that can make the offer and demand tangible and to guarantee to meet the PWD needs

ii. **Social networks**

   a. Additions to mobile technologies in order to identify needs in WEB technologies and services;
   b. Structuring of data flows to establish information continuity between strategy, tactics, operation and action, both within and outside the value chain;
   c. Centralized and decentralized information systems that guarantee organizational continuity between stakeholders.

iii. **Levers of strategic alliances and organizational network:**

   a. Structuring of the organizational network around shared and specific issues;
   b. Contractual bases for commercial relations, partnerships and framework agreements;
   c. Definition of online communities to support the productivity of agreements.

iv. **Definition of sectoral and public policy guidelines:**

   a. Social cohesion in order to guarantee the continuity of digital technology in social connection;
   b. Societal and economic value for joint development of markets, economic value, non-market value, intangible capital, and amenities;
   c. Protection of vulnerable groups in order to avoid prejudicial bias, polarization, discrimination and exclusion;
   d. Digital and technology education to enable stakeholders to be aware of their rights and responsibilities;
   e. Safe society that protects against acts of unlawful interference, to guarantee the meeting of basic needs, and the rule of law;

f. Roles and missions of sectoral and territorial governance bodies to put in place organizational levers that guarantee respect for political boundaries.

v. **Data:**

a. Urban analytics to build elements of knowledge that can inform the consolidation of political boundaries and the enhancement of territories and users of urban space;
b. Protection and integrity of personal data;
c. Open data and clarification of internal public data that can be disseminated, both proprietary data and external data.

5.5 Conclusion

The closing statement is provided as a summary of the main findings and scientific contributions. As required, in this section, we have demonstrated the necessity of using an interdisciplinary approach, as well as acknowledging the steps of the decision-aiding process.

Conclusion

The earlier chapters demonstrated and clarified the multiple elements of the accumulation process in the execution of interdisciplinary research. The main factor in the accumulation process is the continuous gathering of information, which generates a high level of complexity. Multidisciplinary research is not welcome everywhere. It is unusual for it to be acknowledged even within science or in the views of administrators, technicians, and support staff. This will remain the case until problems are encountered, then there will be a general consensus that insists on the need to implement knowledge from different domains in a single place (Palmer, 2013).

In our case, we encountered complex problems. The first complexity was in the definition of the needs of persons with disabilities. Before addressing these requirements, it was necessary to analyze the definition of various categories of disability. The high number of categories led us to the first decision: - to consider only the needs of the persons with disabilities that were wheelchair users. The next complexity arose in the literature review in determining where and how we could find information on PWD needs. In order to make progress, we applied a management discipline through the methodology of the systematic review, with a special review of regulations relating to PWD needs. The optimization models for PWD transport obtained from the systematic review are analyzed and observed to 5As (Availability, Accessibility, Acceptability, Affordability and Adaptability) and present the scientific contribution in this part of the thesis. Again, the integration of disciplinary research generated a result.

The second complexity comes from the problem formulation, which requires a further disciplinary domain: that of the decision-aiding process. The systematic review revealed that basic optimization models do not meet all PWD needs. With this information, we could not arrive at a solution providing independence for PWD in public transport, so it was necessary to reframe the project problem formulation. Given the inadequacy of these optimization models, this time, we wanted to highlight PWD needs, but this would have involved numerous participants in the transportation chain.

The steps of the decision-aiding process yielded many contributions, such as: - i) the matrix of the possible interactions between the needs and obstacles of PWD; and ii) structure of the relationships within existing optimization models, subject to the public network information, particularly on the current accessibility to the public network. Moreover, the decision-aiding process suggests a comprehensive analysis, enabling the ability to choose at any time an appropriate model for the inclusion of disabled persons.

The problem formulation confirmed that optimization models (transport-on-demand and SPP) are the primary tools to obtain an efficient solution for a part of the problem. However, the problem of accessing the network is not resolved. The lack of connectivity between the start point (International Conference on Smart et al.) and the public network (sidewalks) results in the need to define the cluster centers (hubs or exchange poles). Now we need a new discipline to solve the problem - optimization. Using the available real data set from the transport operator in Valenciennes "*Transvilles*," for the first time, a clustering approach is proposed to include PWD in public transport, where we succeeded in improving current accessibility to the public network.

This thesis demonstrates that an interdisciplinary approach is necessary to solve a complex problem efficiently, particularly when different information types are involved.

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APPENDIX A. European legislative framework for transport of PWD

No	Reference	Title	Transport mode	Accessibility requirements
1	European Union Charter 2012/C 326/02	Charter of Fundamental Rights of the European Union	MULTIMODAL	General
2	Commission communication 2010/0636	European disability strategy 2010-2020	MULTIMODAL	General
3	Commission proposal for a directive 2015/0278 (COD)	Approximation of the laws, regulations and administrative provisions of the Member States as regards the accessibility requirements for products and services European Accessibility Act	MULTIMODAL	General
4	Commission Regulation (EC) No 1107/2006	Rights of disabled persons and persons with reduced mobility when traveling by air	AIR	Specific
5	Commission Regulation (EC) No 1371/2007	Rail passengers' rights and obligations	RAIL	Specific
6	Commission Regulation (EC) No 454/2011	The technical specification for interoperability relating to the subsystem “telematics applications for passengers’ services” of the trans-European rail system (TAP-TSI)	RAIL	Detailed
7	Commission Regulation (EC) No 1300/2014	Technical specifications for interoperability relating to the accessibility of the Union's rail system for persons with disabilities and persons with reduced mobility (TSI-PRM)	RAIL	Detailed
8	Commission Directive (EU) No 2016/797	Interoperability of the rail system within the European Union (recast)	RAIL	Specific
9	Commission Directive (EU) No 2010/40	Framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport	MULTIMODAL	Specific
10	Commission implementing decision (EU) 2016/209	Standardization request to the European standardization organizations as regards Intelligent Transport Systems (ITS) in urban areas in support of Directive 2010/40/EU	INTELLIGENT - ROAD	Specific
11	Commission Regulation (EC) No 181/2011	Concerning the rights of passengers in bus and coach transport	ROAD	Specific
12	Commission directive (EC) No 2001/85	Special provisions for vehicles used for the carriage of passengers comprising more than eight seats in addition to the driver's seat	ROAD	Specific
13	Commission Directive (EU) NO 2016/2102	Accessibility of the websites and mobile applications of public sector bodies	INTELLIGENT - COMMUNICATION	Specific
14	Commission Regulation (EU) 1177/2010	Rights of passengers when traveling by sea and inland waterway	MARITIME	Specific
15	Council Directive 98/18/EC	Safety rules and standards for passenger ships	MARITIME	Specific
16	European Standard EN 16584	Infrastructure and rolling stock - Railway applications - Design for PRM Users	RAIL	Detailed
17	European Standard EN 16585	Rolling Stock-Railway Applications - Design for PRM Use - Equipment and Components On Board Rolling Stock	RAIL	Detailed
18	European Standard EN 16586	Railway applications - Design for PRM Use - Accessibility of persons with reduced mobility rolling stock	RAIL	Detailed
19	European Standard EN 16587	Railway applications - Design for PRM Use - Requirements for obstacle-free routes for infrastructure	RAIL	Detailed
20	European Standard EN 12896	TRANSMODEL - Reference Data Model For Public Transport	MULTIMODAL	Detailed

APPENDIX B. Matrix of relation

Table 16 Matrix of relation

			Strategic level		Operational level	Tactical level	
Levels / Needs			Institutional framework - Legislation - Conceptual outlook - Policy	Economic issues - Finance - Budget - Funding	Operational issues	Operator and community attitudes - Stakeholders approaches	Information and education - Human and Social resources
Availability		Time	Improve the legislation - Develop implementation plan - Assessment of the legislation changing	Financing the creation or modification of the legal framework - Financial plan for the action implementation	Fleet capacities - Scheduling - Minimizing the total vehicle travel time; the total tour time; the fleet size; the number of vehicles; the maximum flow time; vehicle timeout; travel time of each user - Maximize the number of requests served; the number of requests served on time	Assignment to the operators - Assignment to the demanding time - Reliable intervals between the vehicles - Prompt provision of compensation possibilities in case of failure of the vehicles - Real-time ride-matching	Staff capacities - Information systems (booklets, leaflets, timetables, journey planner) - Advance traffic control system
		Place	Evaluation of network - Assessment of the developing the new network or extending existing one - Provide connection place with the hospitals and the places demand by PWD- Implementation plan	Financing the developing the new network or extending an existing one - Investment plan	Network capacities - Involved additional service through door-to-door service - Minimizing the total distance travel; the total routing costs - Maximize the number of requests served; the number of requests served on time	Assignment to the operators - Assignment to the demanding places - Flexible route transit	Information systems (booklets, leaflets, timetables, journey planner) - Corridor management
Accessibility	Information and travel training	Pre-journey planning information	Legislation obligation - Interconnection among transport, education and system information legislation	Developing the information system (mobile applications, websites) - Findings for the new information systems - Providing funds among the participants in this chain - Developing a comprehensive citywide journey planner and information system	Distribution and organization of system information to reach the exciting group	Providing information on the website of the operators, municipalities, associations	Maintaining information system - Real-time information - Date base
		Information at transport stops and stations	Legislation obligations for three types of information: visual, audible and tactile	Budget assessment for all types of information (visual, audible and tactile) - Providing funds among the participants in this chain - Finds for real-time information displays, Terminal and kiosks	Distribution and organization of system information to reach the exciting group	Provide a responsible participant (operators, municipality, etc) for managing and updating information	Provide static visual information, real-time information displays, real-time and pre-recorded audible information in stations, Terminals and kiosks (for information and the purchasing of tickets)

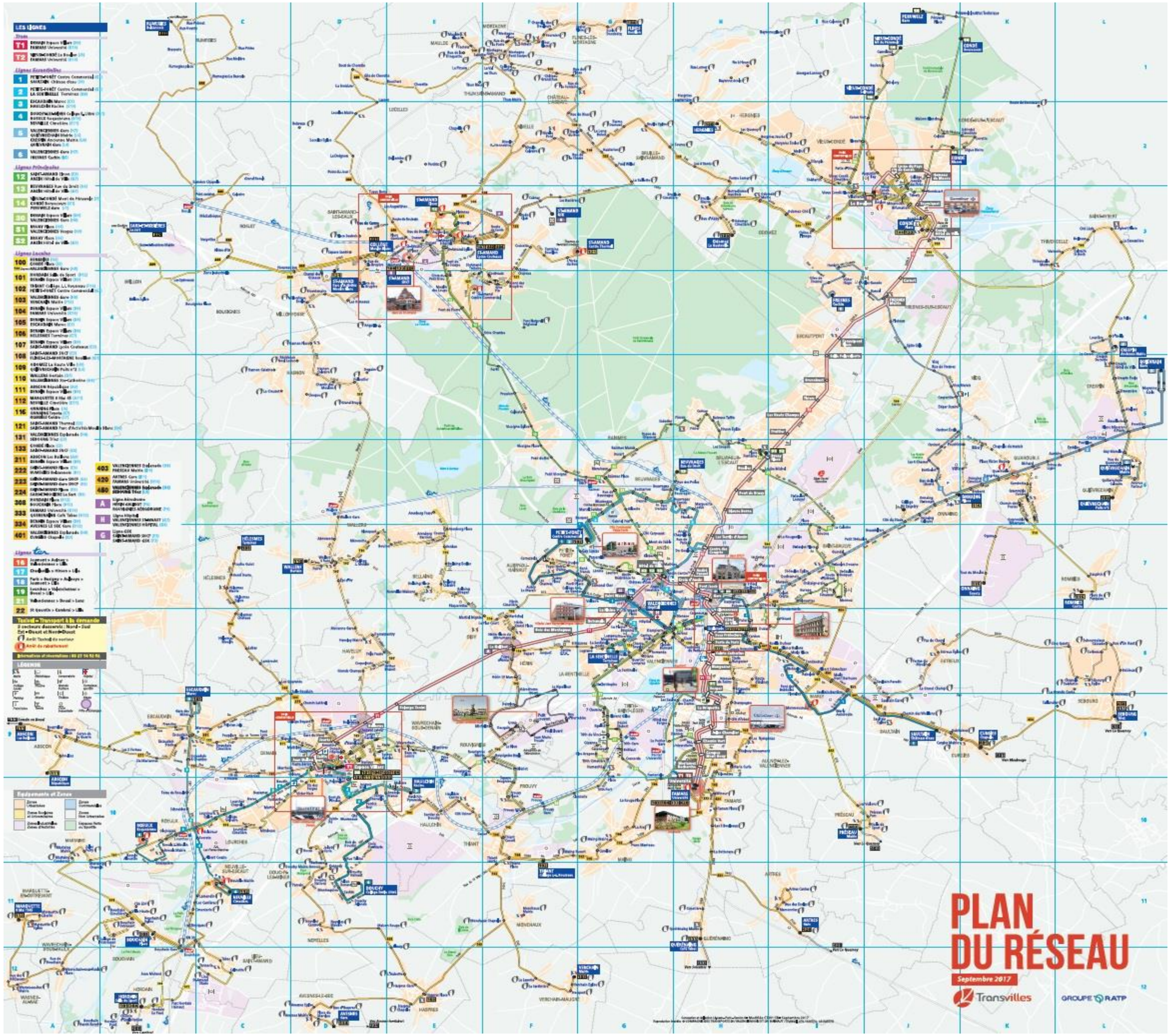
Accessibility		**On-board information**	Legislation obligation - Display information on vehicles concerning the vehicle route, timetable, current location, and exit routes	Budget planning for implementation of the system information in every vehicle	Adapt vehicles for the necessary information system	Provide a responsible participant (operators, municipality, etc) for managing and updating information	Operating staff and PWD training for the new information system - usage; readings and understanding information
		Travel training	Legislation obligation - defining the responsibilities among local government, local transport operator, a charity, and define where will be provided (classroom, school, etc.)	Budget planning for providing travel training to the staff	Scheduling of staff travel training	Provide the training in all organization who are involved in this type of transport, design the programs that will meet a needs and takes into account culture issues	Community educations through the events, consultations, information and guidance, travel support and assistance, and vocational or academic training programs
		Disability awareness training	Legislation obligation - defining who is responsible for this type of training	Budget planning - provide financial support through the subventions, private partners or voluntary work	Providing disability awareness training events, disability awareness video, disability awareness posters and leaflets	Building cooperation between operators and associations, as well as with the hospitals, etc	Community educations through the events, consultations, information and guidance, travel support and assistance, and vocational or academic training programs
	Pedestrian footways and street crossing	**Footways and sidewalks**	Legislation obligations for the new construction, and reconstructions of footways and sidewalks	Budget planning - analyzing the costs of local labor and materials - defining the priorities for the future works	Survey on footways and sidewalks accessibility, especially to a transportation network; Works on the - Monitoring and providing data related to the mobility	Selection of materials appropriate to the climate, as maintenance of new surfaces; Consultation and planning	Training and education of local citizens and PWD of using tactile pavement and signage
		Dropped curbs and street crossings	Legislation obligations for the new construction, and reconstructions of dropped curbs and street crossings	Budget assessment depends on the costs of local labor and materials	Implementing street accessibility in public transport through: Dropped curb, footway buildouts, zebra crossing, island refuge, raised table, footbridge/subway	Assure the environment about a street crossing is accessible to provide the PWD journey without interruption	Traffic enforcement and driver education programs for drivers to become more aware of pedestrians crossing the road

Accessibility	**Public transport stops and station infrastructure**	**Bus Stops**	Legislation obligations for providing the accessibility to the bus stops such as: Step-free accessibility; Step-free maneuvering space; Footways, storage places, toilets and service areas are required to have sufficient maneuvering and clear space; All operating controls and communication systems should be within reach of sitting persons; Step-free accessibility of the shelter; Sufficient parking space	For the reconstruction of the existing bus stop make a budget assessment through the costs of surfacing material, labor costs, location of the shelter, gradient, drainage, etc. - Building a new bus stations	Bus stop surfacing, bus shelters, folding or fixed seats, raised boarding structures	The space limitation, available access during construction: passengers should be prevented from standing in the roadway	Providing a survey of existing accessibility on the bus stops
		BRT (Bus Rapid transit) and light rail stops	Legislation obligations for providing the accessibility to the BRT and light rail stops	Budget is enormous for this type of works - planning, construction, etc. - should be planed in significant transport project	Accessible BRT Station, bus mounted boarding bridges, elevator or stairlift, folding seats within stop/station	Cooperation between national and regional government - a joint project	Provide the appropriate information system, which data will be in a real-time update and use in optimization transport model.
		Major bus/train/metro interchanges and terminals	Global strategic plans - providing the legislation obligations for intermodal passenger transport: connection points (platforms) - client assistance, accessible entrances and exit, ticketing facilities, waiting space, toilet facilities, service information	Budget is enormous for this type of works - planning, construction, etc. - should be planed in significant transport project	Ramps to provide a level, step-free environments, passenger elevator to the platform, accessible toilets, available automatic ticket barriers, accessible information and ticket desks, access terminals and kiosks	Cooperation between national and regional government - Regional transportation management system	Provide the appropriate information system, which data will be in a real-time update and use in optimization transport model.

Accessibility	**Public vehicles**	**Buses and Mass Transit Vehicles**	Legislation obligations for providing the accessibility to this type of vehicles: Step-free entrance and exit; Step-free corridors and maneuvering space; Corridors, storage places, seats, toilets and service areas are required to have sufficient maneuvering and clear space; All operating controls and communication systems should be within reach of sitting persons; Doors should be operated fully automatically - Travel patterns	Costs vary significantly between manufacturers - depend on what strategy will be used. Some potential: buy new vehicles, repair an existing one	Fleet efficiency - Flexible route - Vehicle routing problem - Demand adaptive system - Mobile allowance shuttle transit - Demand Responsive Bus Routing Problem	Cooperation between national and regional government to have the same strategy concerning the purchase of new vehicles or repairing existing - Regional transportation management system - Vehicle condition monitoring	Driver training for a safe trip with avoiding sudden braking and acceleration, assisting in boarding and alighting safely
		Trains	Implementing Technical Specification for Interoperability (Papanikolaou, Basbas, Mintsis, & Taxiltaris) - Wholly accessible rolling stock, portable manual train lifts, wheelchair ramps, automatic doors on trains, Handrails on stairs	The investment program for the new rolling stock with full accessibility - Financial budget for reconstruction of existing rolling stock to meet the needs of PWD	Line planning (max the service towards the passengers, min the operational costs of the railway system) - Timetabling - Platforming - Rolling stock circulation -Shunting - Real-time traffic control - Number of direct connections, frequencies, and reliability	European Rail Traffic Management System (ERTMS), GSM–R (communication), European Train Control System (ETCS, signaling), European Train Management Layer (ETML)	Railway staff training with the object how to use equipment (ramps and platforms) safely with an awareness of the PWD issues
	Private modes of transportation	**Adapted vehicles**	Improve legislation framework for public-private partnership - technical documentation regarding the conditions about the vehicles	Restructure public transport - Subsides of transportation modes - Independent projects investments	Integrate transit and feeder services - Real-time response to changing demand - New personalized public transit - Define the hub center to bring PWD to the public network	Providing the infrastructure, friendly-user parking spaces to enable PWD to use adapted vehicles - Cooperation among several institutions - Regional transportation management system - Vehicle condition monitoring	Information about the aid getting in and out of the vehicle, transfer board, wheelchair ramps, button-operated clutch on the gearshift, handbrake adaptations, simple car control adaptations (steering spinners/knobs and brake/accelerator hand controls), horizontal steering wheel, wheelchair-accessible motorcycle, wheelchair accessible vehicle

Accessibility		**Parking facilities and associated concessions**	Improve legislation framework for public-private partnership - Urban planning - Parking design incorporates footways, ramps, and doorways establishing the whole journey accessible	Restructure public transport - Ticketing policy	Disabled parking permits - Enlarging parking spaces - Accommodating parking spaces closer to the public transport network	Cooperation between national and regional government - Regional transportation management system	Disability awareness training for staff members on the parking
		Taxis and minivans	Improve legislation framework for public-private partnership - technical documentation regarding the conditions about the vehicles	Restructure public transport - Subsides of transportation modes - Independent projects investments	Integrate transit and feeder services - Real-time response to changing demand - New personalized public transit - Define hub center to bring PWD to a public network - Dial-a-ride problem - Transport on demand	Cooperation between national and regional government - Regional transportation management system - Vehicle condition monitoring	Drivers education/training to be able to provide adequate assistance to PWD - Service as board and alight the vehicle; being patient while PWD board; driving carefully
Acceptability			The conditions described in the scope of the service of public transport. Particular focus on safe transport	Establish the budget for the friendly users	Clean, safe, and user-friendly transport. How often should be cleaning, do they need special treatment (after some patients)	Provide user-friendly access to quality transportation services	Medical treatment education - Driver condition monitoring
Affordability			Financial assistance - legal base; contract, PSO (Public Service Obligation)	Restructure public transport - Subsides of transportation modes	Enhanced fare card	Cooperation between national and regional government - a joint project	Education of PWD how they can use it financial assistance - Transportation pricing
Adaptability			Develop the legislation to have one act for all transportation modes	Restructure public transport - Subsides of transportation modes	Quality service - Always provide a seat - Service assistance by a person, with special support if required - PWD can book by phone, by SMS, or on-line - Transport chain without interruption	Flexible route transit - Regional transportation management system - Regional transportation information clearinghouse	Driver training - Multimodal pre-trip and en-route travel information

APPENDIX C. Transport network map in metropole Valenciennes (High resolution)


PLAN
DU RÉSEAU
Septembre 2017
Transvilles
GROUPE RATP

APPENDIX D. Exchanges poles in Valenciennes

Source of all figures in this appendix: https://www.transvilles.com/poles-echanges

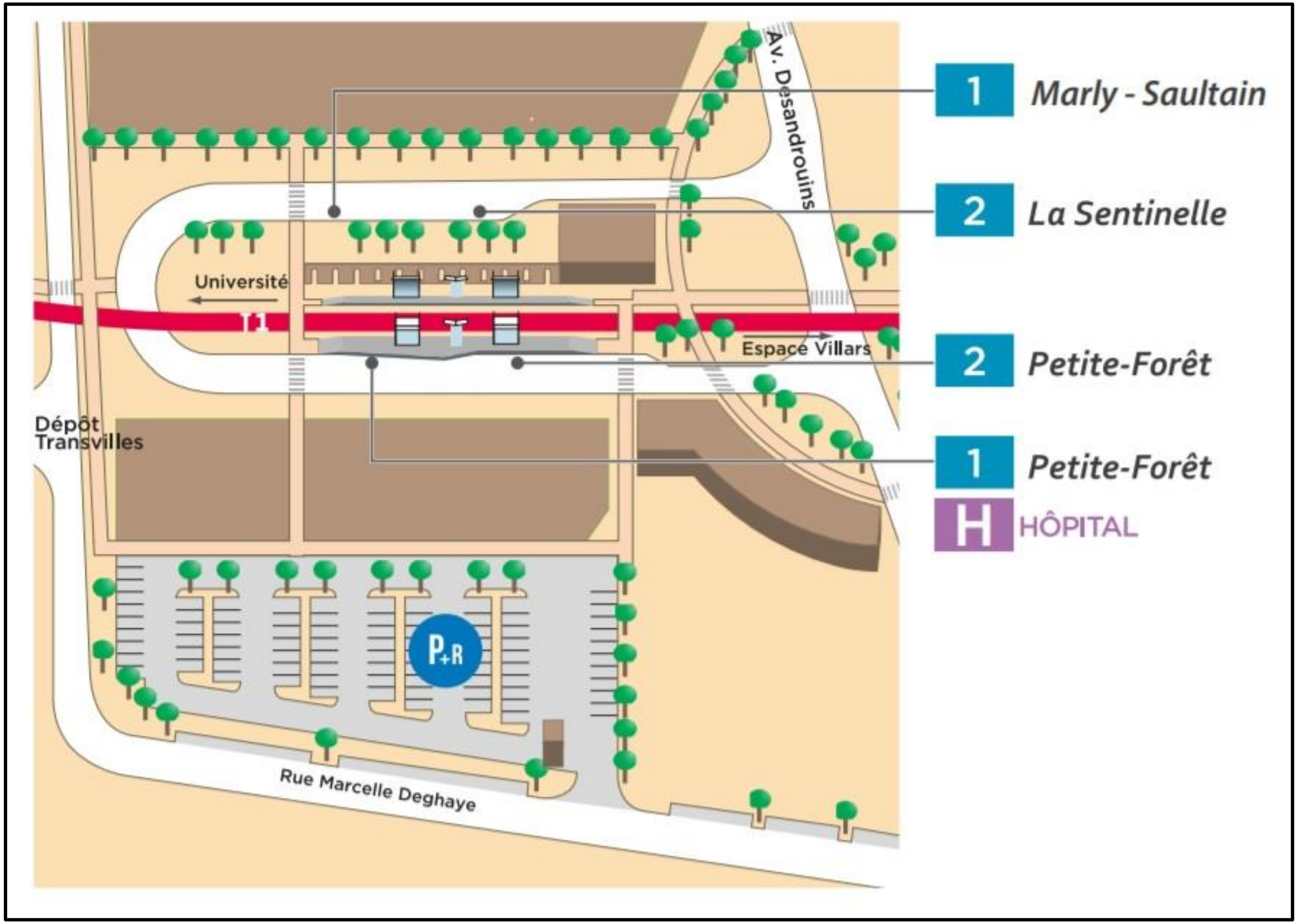


Figure 28 Exchange pole: Station Saint-Waast

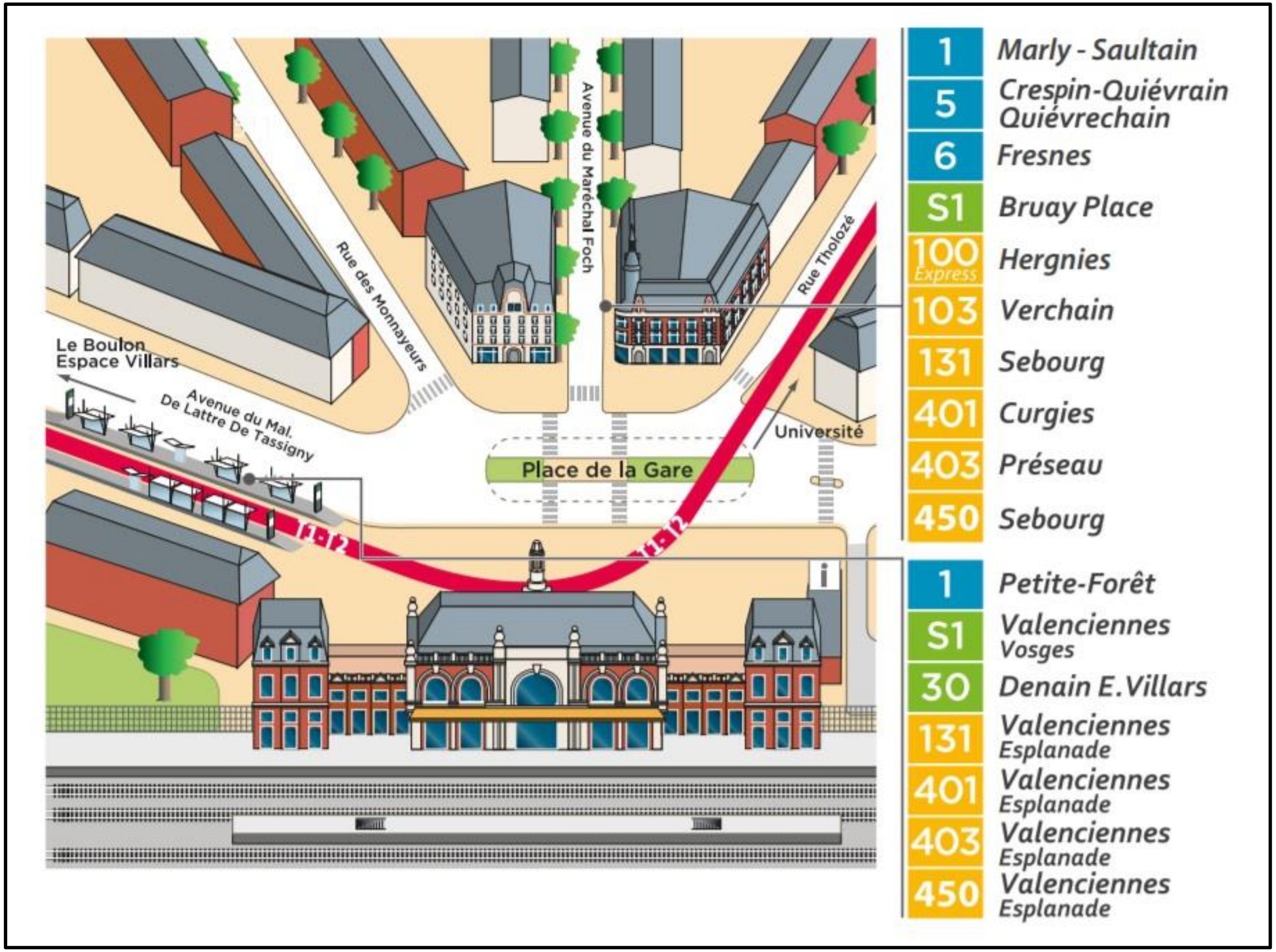


Figure 29 Exchange pole: Station Gare

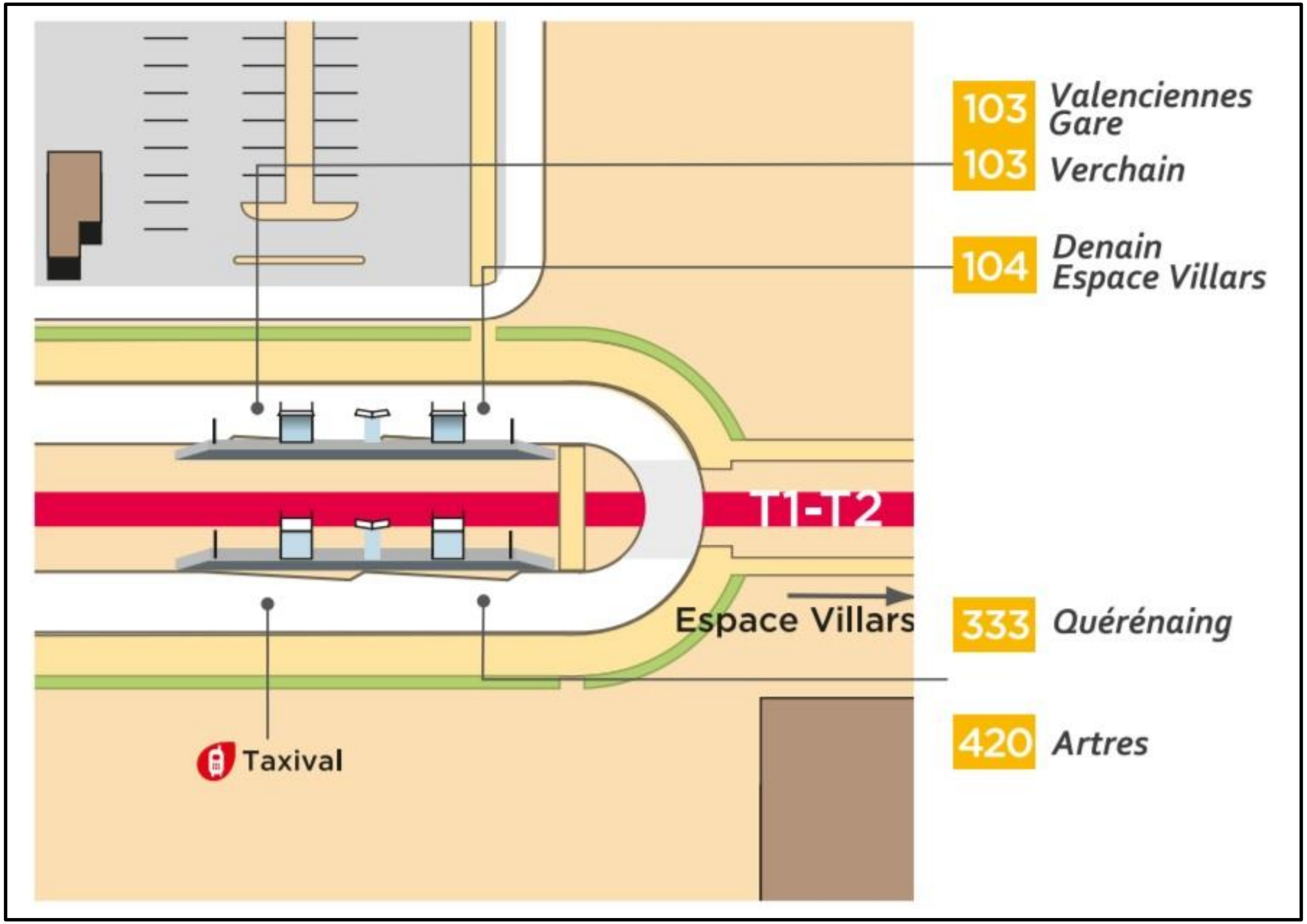


Figure 30 Exchange pole: Station Famars Université

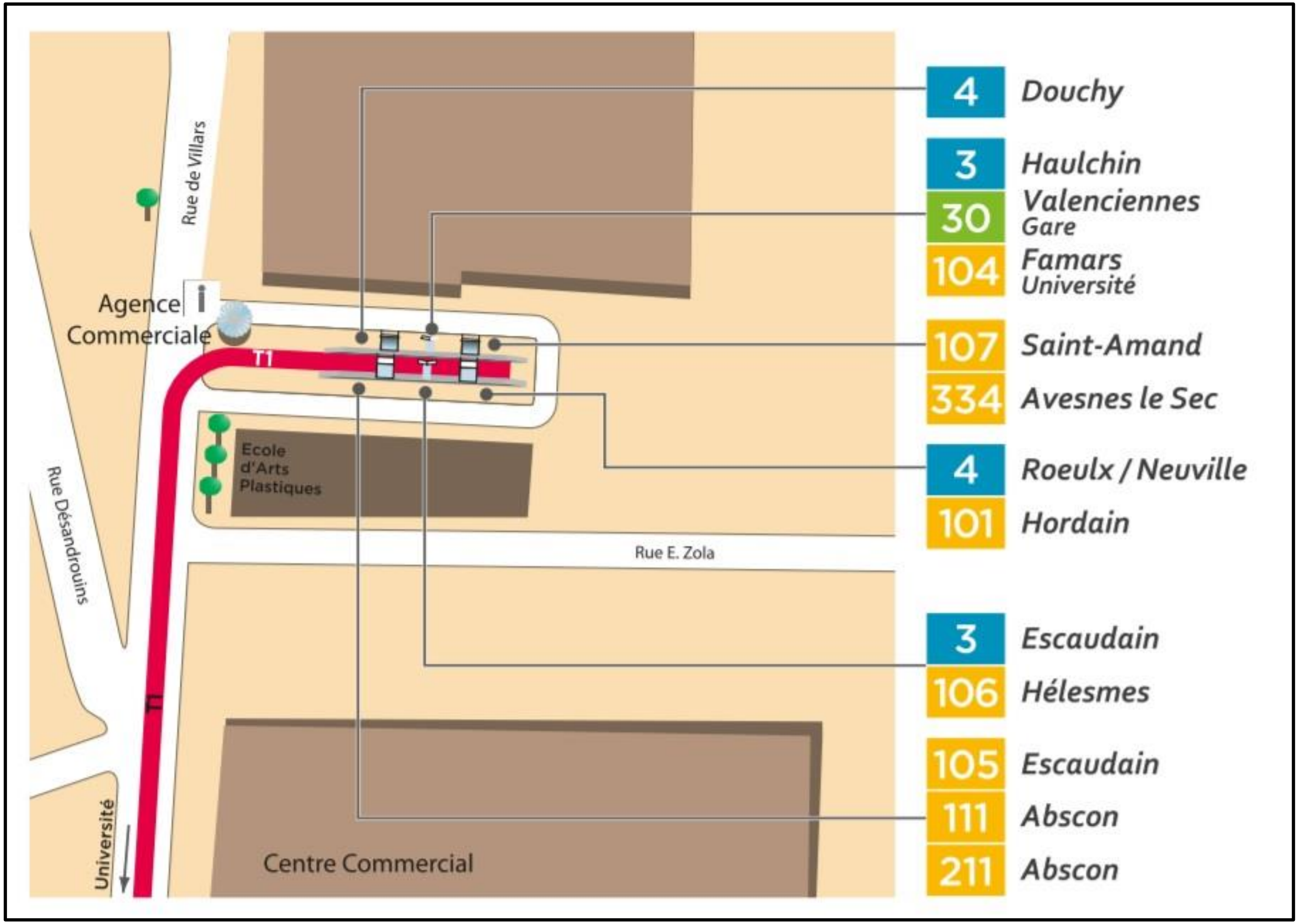


Figure 31 Exchange pole: Station Denain Espace Villars

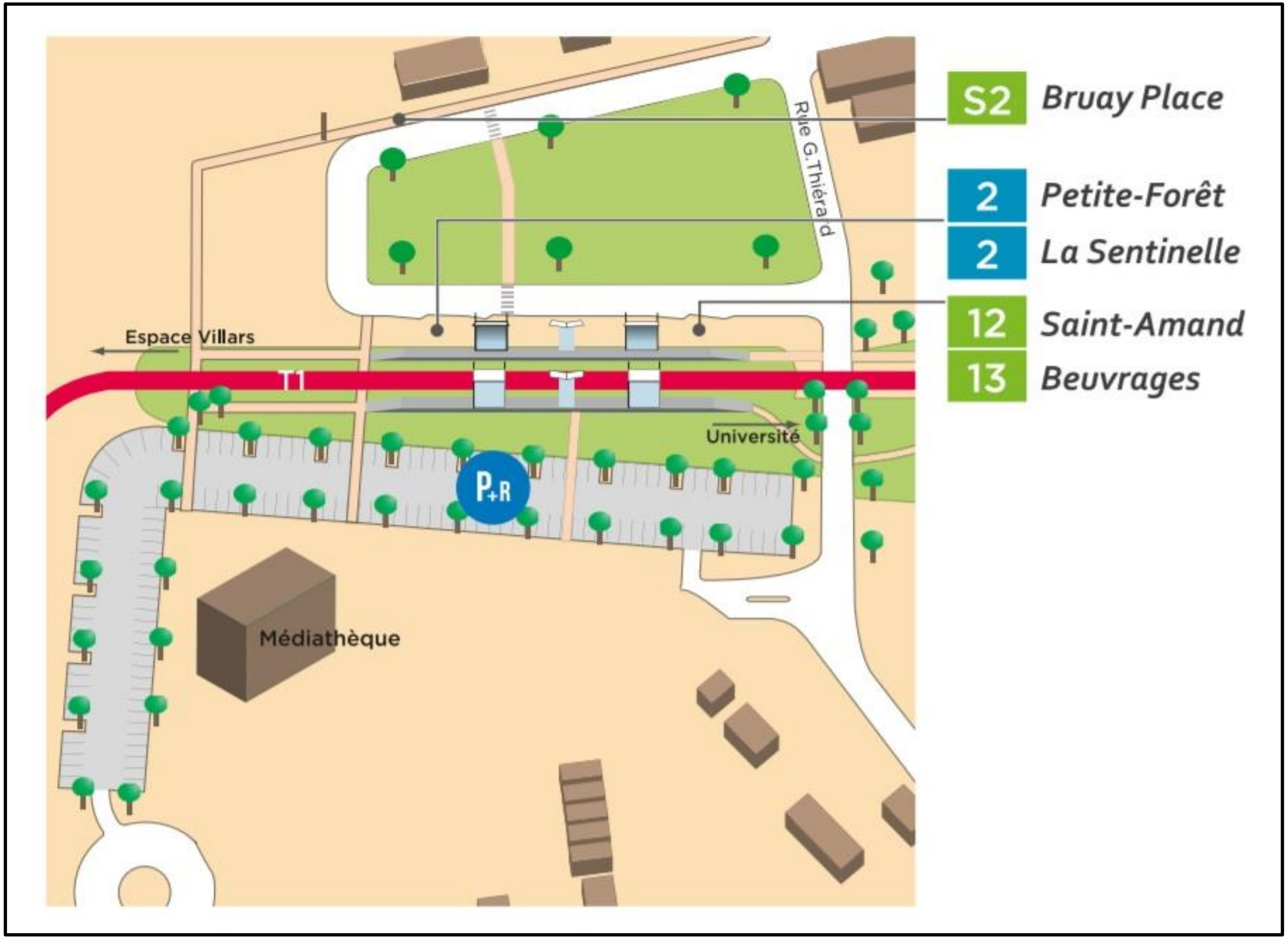


Figure 32 Exchange pole: Station Anzin Hôtel de Ville

APPENDIX E. Optimal number of clusters

ALL	MaxIteration	Replicates	No of stations= Max no of cluster	1	2	3	4	5	6	7	8	9	10	Avg
1	10 000	1	420	415	420	416	417	418	409	417	416	420	420	**417**
			210	209	207	205	209	206	204	199	210	205	210	**206**
			105	99	102	104	92	100	99	100	101	103	97	**100**
			50	39	47	50	50	48	44	49	48	42	48	**47**
			25	23	24	24	22	23	16	25	25	23	22	**23**
			12	9	12	8	9	8	8	11	11	11	12	**10**
			9	9	4	6	8	8	4	9	8	8	6	**7**
			7	4	4	6	4	4	6	4	6	4	7	**5**
			5	4	4	4	4	4	4	4	4	4	4	**4**
2	100 000	1	420	419	420	420	419	418	413	420	417	416	420	**418**
			210	209	209	210	210	205	210	205	209	209	209	**209**
			105	99	104	101	105	105	102	98	97	105	96	**101**
			50	50	48	47	50	50	50	49	48	50	50	**49**
			25	24	25	24	25	25	23	25	21	18	25	**24**
			12	9	11	12	11	12	11	7	9	9	12	**10**
			9	7	8	8	8	4	9	9	4	9	7	**7**
			7	4	7	6	7	4	4	7	6	4	4	**5**
			5	4	4	4	4	4	4	4	4	4	5	**4**
3	100 000	10	420	419	418	415	420	419	413	412	420	416	417	**417**
			210	205	210	207	210	207	210	204	202	205	210	**207**
			105	105	105	104	105	102	101	105	100	105	91	**102**
			50	45	44	50	50	50	50	50	44	49	50	**48**
			25	25	25	25	25	23	25	22	24	24	21	**24**
			12	8	9	7	12	8	9	8	4	7	8	**8**
			9	4	6	8	8	8	7	7	9	8	8	**7**
			7	4	7	4	7	4	4	6	7	4	7	**5**
			5	4	4	4	4	4	4	4	4	4	4	**4**
4	100 000	100	420	415	419	414	420	419	418	419	416	417	418	**418**
			210	208	204	210	208	203	210	210	206	209	203	**207**
			105	104	101	104	103	103	103	105	105	103	100	**103**
			50	49	49	50	50	44	45	47	47	49	49	**48**
			25	20	19	25	25	22	22	24	22	21	23	**22**
			12	9	9	9	11	11	8	12	10	12	10	**10**
			9	9	8	4	8	8	8	9	4	9	7	**7**
			7	7	7	7	4	4	6	4	4	7	7	**6**
			5	4	5	4	4	4	4	4	4	4	4	**4**
5	1 000 000	100	420	419	414	419	419	416	420	414	416	419	411	**417**
			210	207	208	209	209	210	207	207	208	210	206	**208**
			105	93	103	104	104	100	104	105	104	105	104	**103**
			50	50	50	47	50	47	50	50	48	49	47	**49**
			25	25	18	25	18	18	22	24	24	25	25	**22**
			12	9	10	11	7	10	7	11	10	10	11	**10**
			9	6	7	9	4	8	8	7	8	4	4	**7**
			7	7	7	4	6	7	7	6	4	4	7	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
6	1 000 000	1 000	420	416	417	420	416	416	419	418	410	419	419	**417**
			210	207	208	201	210	207	208	209	210	207	205	**207**
			105	103	104	105	99	103	102	105	105	103	101	**103**
			50	50	50	45	45	37	50	48	50	50	50	**48**
			25	25	21	23	24	25	25	24	23	23	25	**24**
			12	12	4	12	10	9	7	9	11	10	9	**9**
			9	9	7	9	7	9	8	9	8	8	7	**8**
			7	6	7	4	4	7	7	6	4	7	7	**6**
			5	5	4	4	4	4	4	4	4	4	4	**4**
7	1 000 000	10 000	420	416	419	417	416	415	420	417	420	417	419	**418**
			210	210	208	208	210	210	210	210	210	207	204	**209**
			105	96	99	103	103	101	100	105	101	94	101	**100**
			50	45	50	50	50	50	46	50	48	48	50	**49**
			25	20	20	25	22	19	25	24	23	25	22	**23**
			12	12	10	12	8	9	11	12	10	12	7	**10**
			9	9	4	7	6	4	9	4	8	9		**7**
			7	4	4	4	6	6	6	4	7	4	6	**5**
			5	4	4	4	4	4	4	4	4	4	4	**4**

Table 17 Optimal number of clusters: PWDs in arrival and departure

DEPARTURE	MaxIteration	Replicates	No of stations= Max no of cluster	1	2	3	4	5	6	7	8	9	10	Avg
			420	418	419	417	415	419	420	418	417	415	418	**418**
			210	210	209	207	209	207	209	210	208	197	207	**207**
			105	105	101	100	103	105	96	102	102	104	96	**101**
			50	50	48	49	42	50	50	50	49	50	50	**49**
1	10 000	1	25	24	22	23	18	24	24	25	25	24	24	**23**
			12	12	7	10	12	6	8	12	12	7	10	**10**
			9	8	7	6	6	8	6	7	8	8	9	**7**
			7	4	7	6	5	7	4	4	4	6	4	**5**
			5	5	4	5	5	4	4	4	5	4	4	**4**
			420	417	419	412	407	420	419	420	418	417	414	**416**
			210	209	206	202	200	209	207	207	201	209	210	**206**
			105	104	104	104	104	100	105	102	103	105	102	**103**
			50	50	46	50	48	49	48	48	50	49	50	**49**
2	100 000	1	25	22	21	22	23	25	21	16	22	21	24	**22**
			12	8	11	7	12	11	8	12	9	8	9	**10**
			9	6	7	7	4	4	8	8	8	8	9	**7**
			7	7	7	4	4	4	4	4	4	7	6	**5**
			5	4	4	4	4	4	4	4	4	5	4	**4**
			420	419	420	419	420	414	419	416	418	419	419	**418**
			210	210	204	209	206	209	208	203	208	208	205	**207**
			105	102	99	104	100	96	105	99	105	102	104	**102**
			50	50	47	47	45	50	50	48	49	50	50	**49**
3	100 000	10	25	23	22	19	25	25	25	24	18	23	21	**23**
			12	8	7	10	11	9	7	10	11	11	11	**10**
			9	8	4	8	8	9	8	9	4	8	7	**7**
			7	7	4	4	5	4	6	7	7	7	7	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
			420	418	414	414	420	419	409	417	420	420	416	**417**
			210	208	209	208	201	206	205	208	204	210	210	**207**
			105	101	103	98	104	102	97	104	101	98	99	**101**
			50	49	46	50	43	47	49	49	50	49	44	**48**
4	100 000	100	25	25	20	25	25	23	24	23	17	25	24	**23**
			12	9	11	11	9	6	6	10	12	7	10	**9**
			9	9	4	6	8	4	9	8	7	9	9	**7**
			7	4	4	7	7	7	7	4	6	7	4	**6**
			5	4	4	4	4	4	4	4	4	4	5	**4**
			420	419	414	417	420	417	418	416	419	418	415	**417**
			210	206	208	195	198	207	206	205	204	207	202	**204**
			105	101	101	101	103	102	98	101	102	100	103	**101**
			50	50	49	49	45	49	50	46	48	44	42	**47**
5	1 000 000	100	25	21	21	25	24	18	25	24	24	23	23	**23**
			12	4	9	9	11	10	8	10	11	10	12	**9**
			9	7	7	8	9	8	8	7	8	7	9	**8**
			7	7	7	4	6	7	7	4	4	4	4	**5**
			5	5	4	5	4	4	4	4	4	4	4	**4**
			420	419	419	419	420	420	419	419	420	416	419	**419**
			210	208	209	210	204	209	210	208	209	205	204	**208**
			105	97	102	105	99	97	102	97	105	102	105	**101**
			50	50	47	50	45	50	46	44	49	46	47	**47**
6	1 000 000	1 000	25	18	25	25	20	24	18	21	25	21	22	**22**
			12	10	9	12	12	9	10	9	9	10	10	**10**
			9	7	9	8	4	8	7	6	7	8	7	**7**
			7	6	4	4	7	7	4	7	7	7	4	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
			420	420	418	420	411	415	412	418	417	419	419	**417**
			210	194	203	210	210	206	207	206	210	210	204	**206**
			105	104	104	100	104	102	102	105	104	102	104	**103**
			50	49	44	50	40	49	50	50	45	50	50	**48**
7	1 000 000	10 000	25	23	21	24	25	21	22	21	22	20	25	**22**
			12	10	12	12	11	8	9	12	10	9	12	**11**
			9	8	9	7	9	9	7	9	7	7	9	**8**
			7	6	6	6	4	7	6	7	4	4	6	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**

Table 18 Optimal number of clusters, users in a departure

ARRIVAL	MaxIteration	Replicates	No of stations = Max no of cluster	1	2	3	4	5	6	7	8	9	10	Avg
			420	416	419	418	417	404	404	412	417	418	419	**414**
			210	205	210	209	209	207	208	202	207	202	210	**207**
			105	98	103	105	103	101	96	103	100	103	103	**102**
			50	50	48	49	45	48	46	50	50	49	50	**49**
1	**10 000**	**1**	25	20	23	20	24	25	24	25	15	23	23	**22**
			12	10	10	12	7	10	8	11	9	8	8	**9**
			9	6	9	7	7	8	7	9	9	7	4	**7**
			7	6	7	6	4	4	7	4	4	7	7	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
			420	420	420	411	417	417	417	420	420	416	420	**418**
			210	196	204	205	206	208	207	205	201	207	208	**205**
			105	105	103	100	97	103	102	104	96	105	102	**102**
			50	49	49	45	49	50	49	50	48	44	50	**48**
2	**100 000**	**1**	25	25	24	18	23	23	25	24	21	22	25	**23**
			12	8	9	12	9	10	12	11	9	12	12	**10**
			9	7	9	8	4	7	9	7	7	4	6	**7**
			7	4	7	4	4	6	4	4	7	7	7	**5**
			5	4	4	4	4	5	4	4	4	4	4	**4**
			420	420	419	418	419	416	420	418	420	418	419	**419**
			210	207	209	209	202	209	209	210	210	210	203	**208**
			105	105	98	98	102	98	101	101	104	103	104	**101**
			50	49	49	46	47	47	49	49	50	49	49	**48**
3	**100 000**	**10**	25	25	23	25	22	25	19	17	25	25	21	**23**
			12	11	12	10	8	9	12	8	11	9	9	**10**
			9	9	7	7	8	7	8	7	4	8	8	**7**
			7	4	7	4	7	6	4	4	7	7	4	**5**
			5	4	4	4	4	4	4	4	4	4	4	**4**
			420	420	415	414	416	415	420	420	417	419	419	**418**
			210	210	210	209	208	210	204	209	204	209	208	**208**
			105	105	104	102	101	103	105	105	105	105	105	**104**
			50	48	50	50	44	49	48	44	49	50	50	**48**
4	**100 000**	**100**	25	20	22	20	23	21	24	25	24	22	23	**22**
			12	9	12	9	9	11	11	9	10	12	11	**10**
			9	9	6	9	9	8	6	9	4	9	7	**8**
			7	4	6	7	4	4	7	6	6	6	7	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
			420	418	415	420	420	420	417	419	420	420	420	**419**
			210	204	208	206	206	208	207	207	204	207	210	**207**
			105	103	102	105	102	102	105	105	99	104	99	**103**
			50	49	49	49	49	47	50	45	50	50	50	**49**
5	**1 000 000**	**100**	25	22	24	22	23	21	25	25	25	25	21	**23**
			12	11	10	10	12	9	12	11	11	8	12	**11**
			9	4	8	6	7	7	9	4	8	8	7	**7**
			7	4	4	7	7	7	7	6	7	4	7	**6**
			5	5	4	5	4	4	4	4	4	4	4	**4**
			420	412	419	420	419	420	415	420	420	417	418	**418**
			210	210	209	210	209	210	191	208	204	203	210	**206**
			105	104	102	97	91	97	101	105	101	101	105	**100**
			50	46	49	44	50	50	50	47	48	48	50	**48**
6	**1 000 000**	**1 000**	25	24	25	20	20	24	23	21	23	25	21	**23**
			12	11	7	7	9	11	9	12	8	10	10	**9**
			9	9	9	7	9	8	4	8	9	9	7	**8**
			7	7	7	4	7	4	7	7	4	7	7	**6**
			5	4	4	4	4	4	4	4	4	4	4	**4**
			420	416	419	418	420	419	419	419	415	420	417	**418**
			210	207	209	208	204	209	209	197	210	210	200	**206**
			105	104	96	94	104	104	102	100	99	105	104	**101**
			50	49	46	50	47	46	49	48	48	48	45	**48**
7	**1 000 000**	**10 000**	25	22	20	25	22	20	18	17	23	24	22	**21**
			12	9	11	8	12	12	8	7	7	8	8	**9**
			9	7	8	9	7	4	4	9	4	9	7	**7**
			7	6	4	4	4	6	6	4	4	4	7	**5**
			5	5	4	4	4	4	4	4	4	4	4	**4**

Table 19 Optimal number of clusters, users in an arrival

.

APPENDIX F. Figures of clustering analysis - High resolution

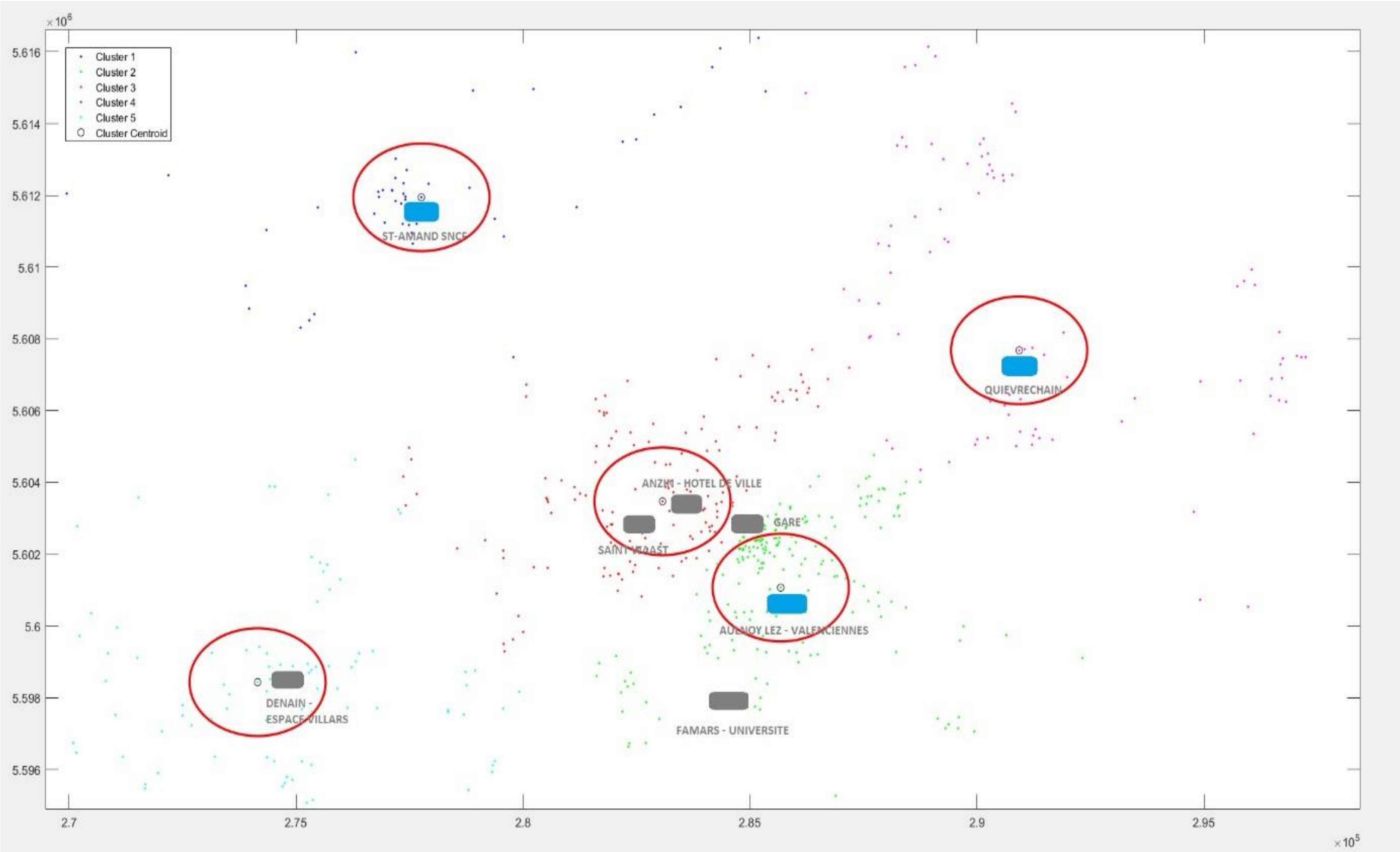


Figure 33 Geographical position in departure: 5 clusters (High resolution)

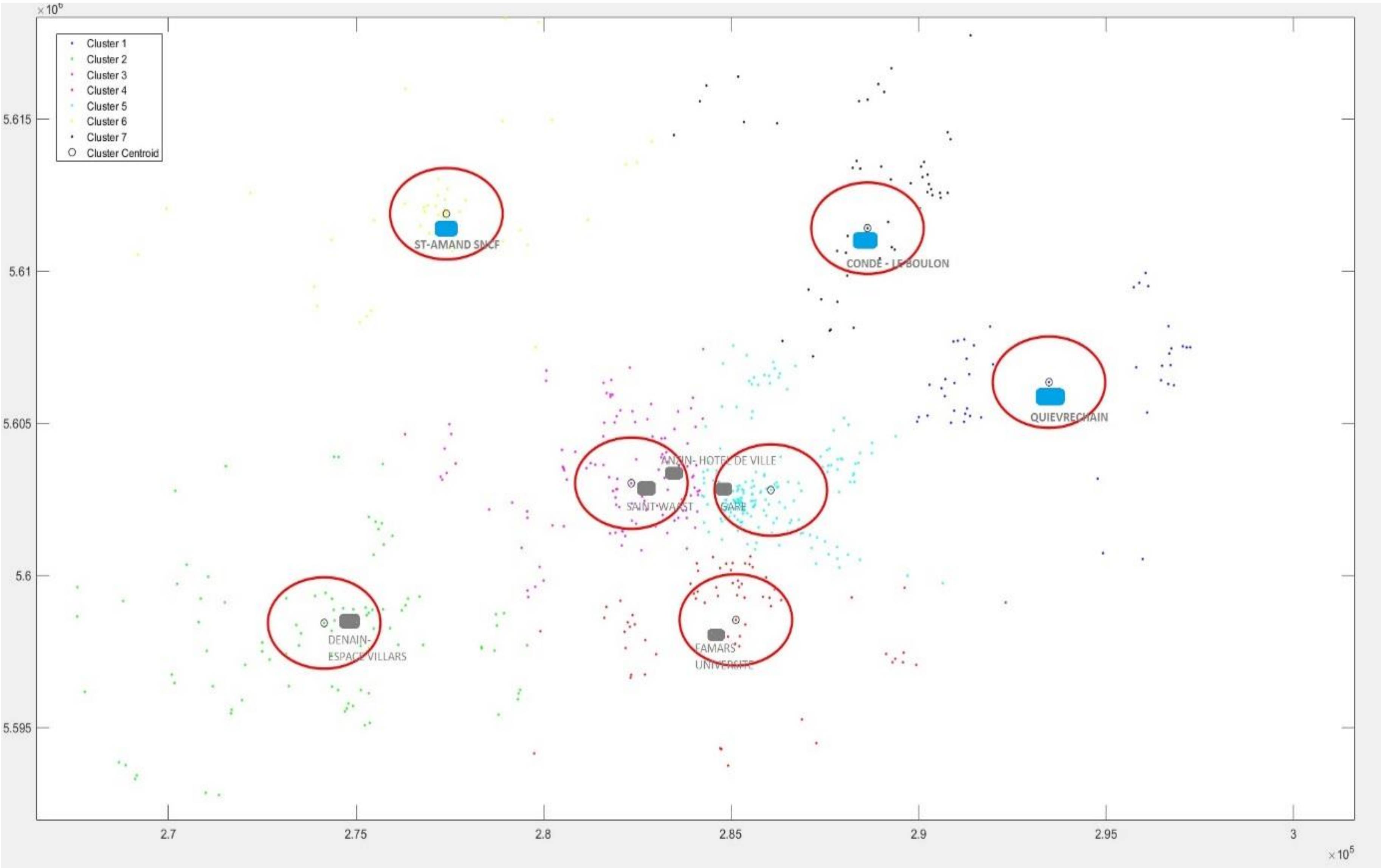


Figure 34 Geographical position in departure: 7 clusters (High resolution)

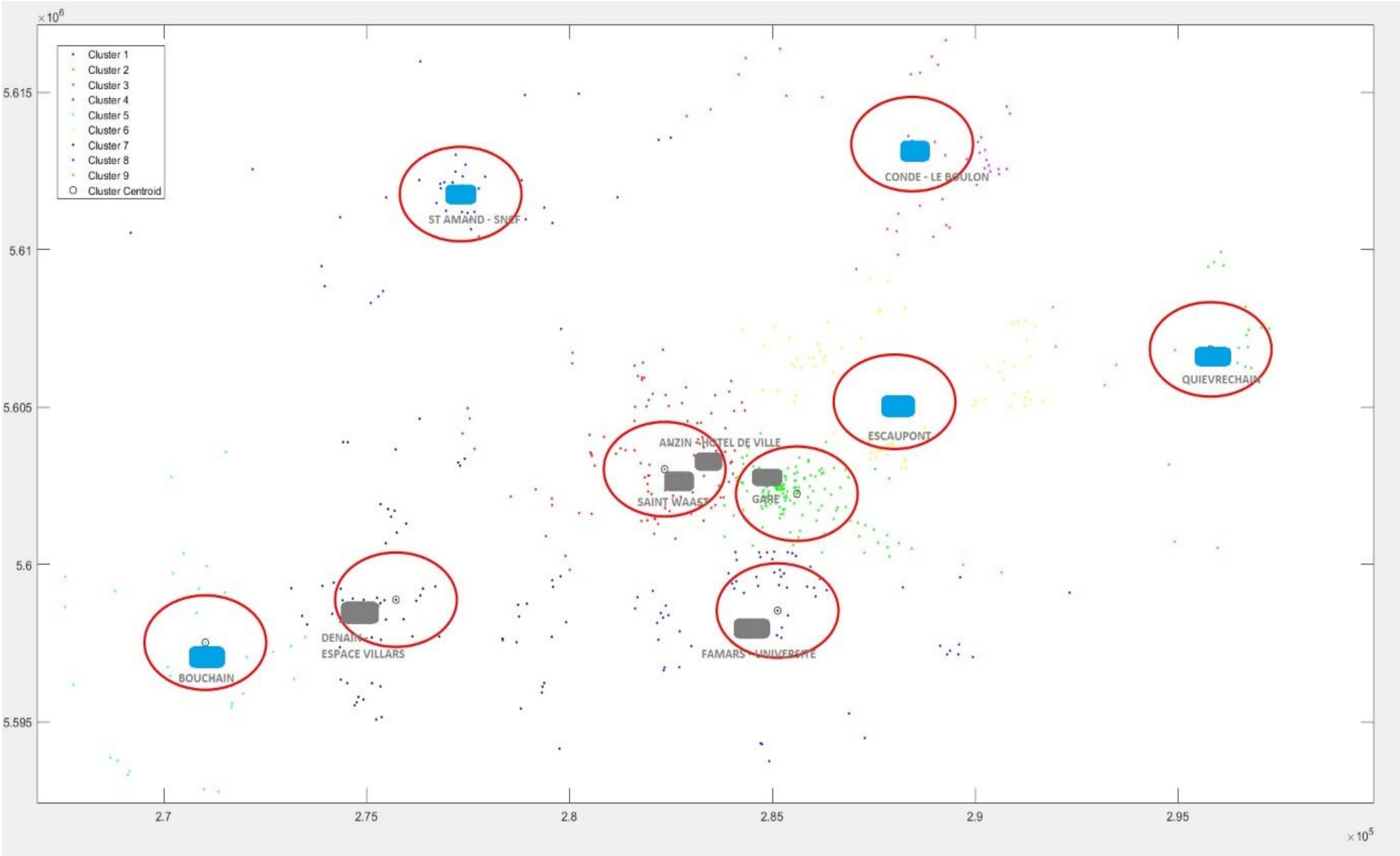


Figure 35 Geographical position in departure: 9 clusters (High resolution)

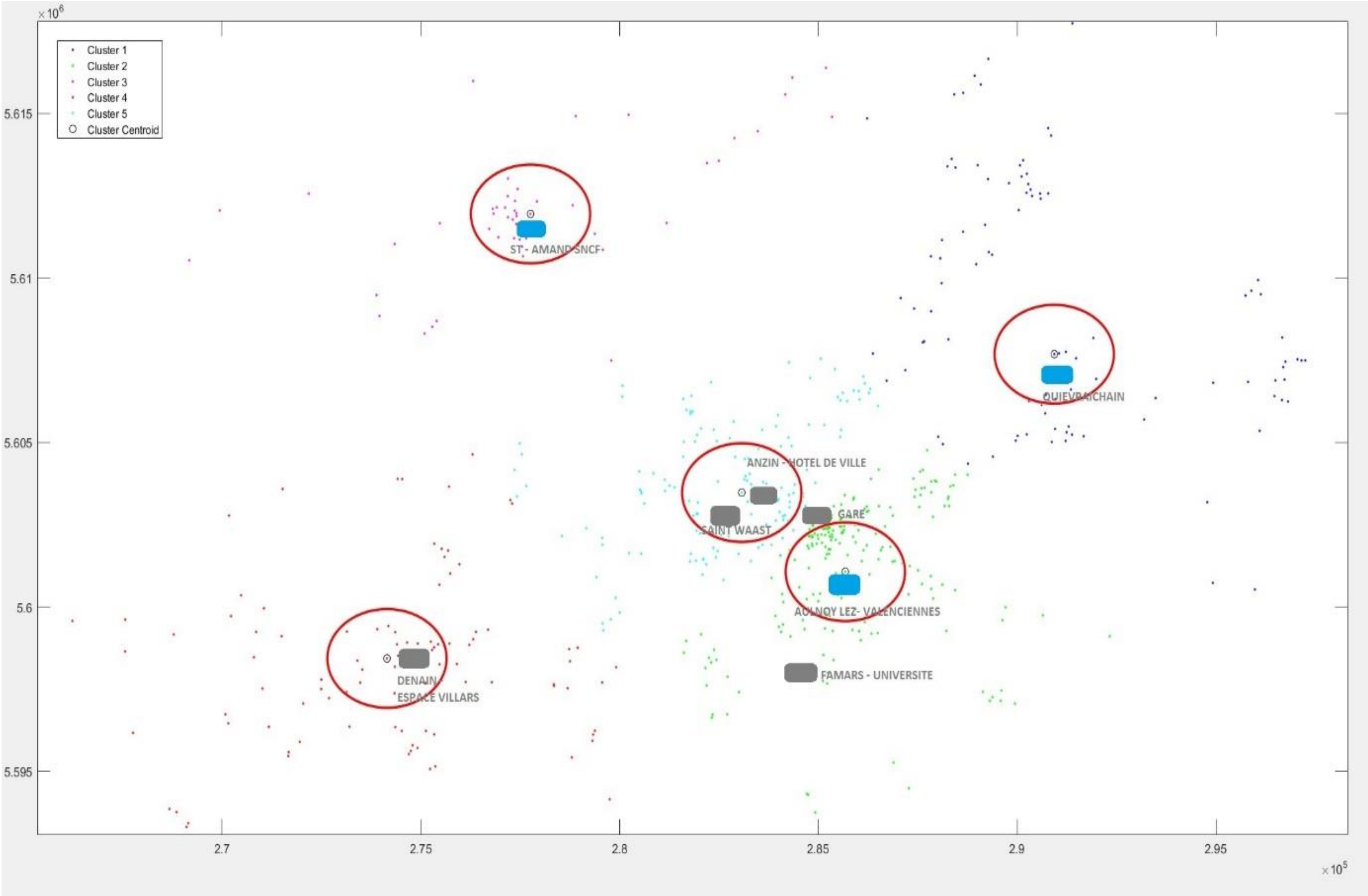


Figure 36 Geographical position in arrival: 5 clusters (High resolution)

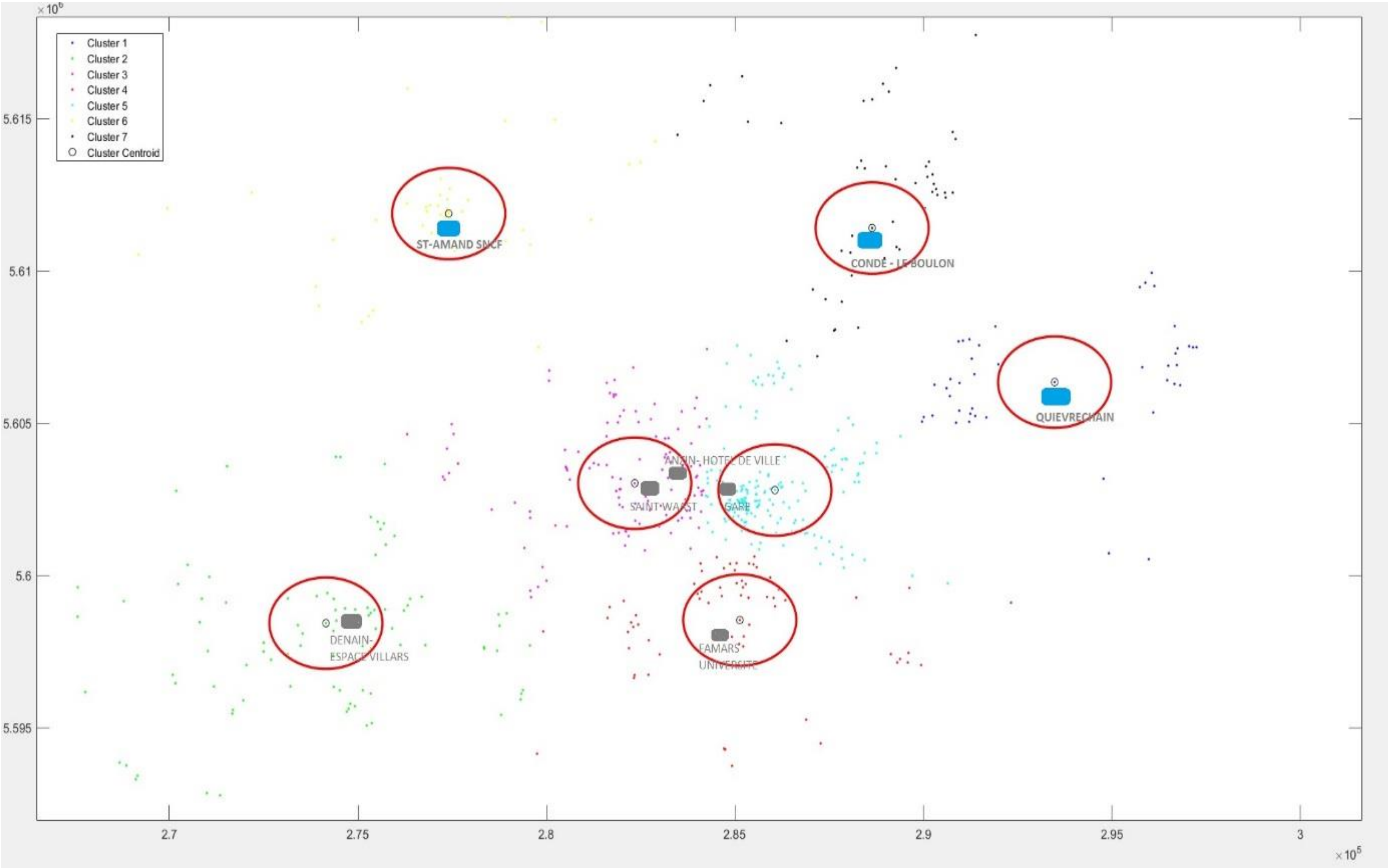


Figure 37 Geographical position in arrival: 7 clusters (High resolution)

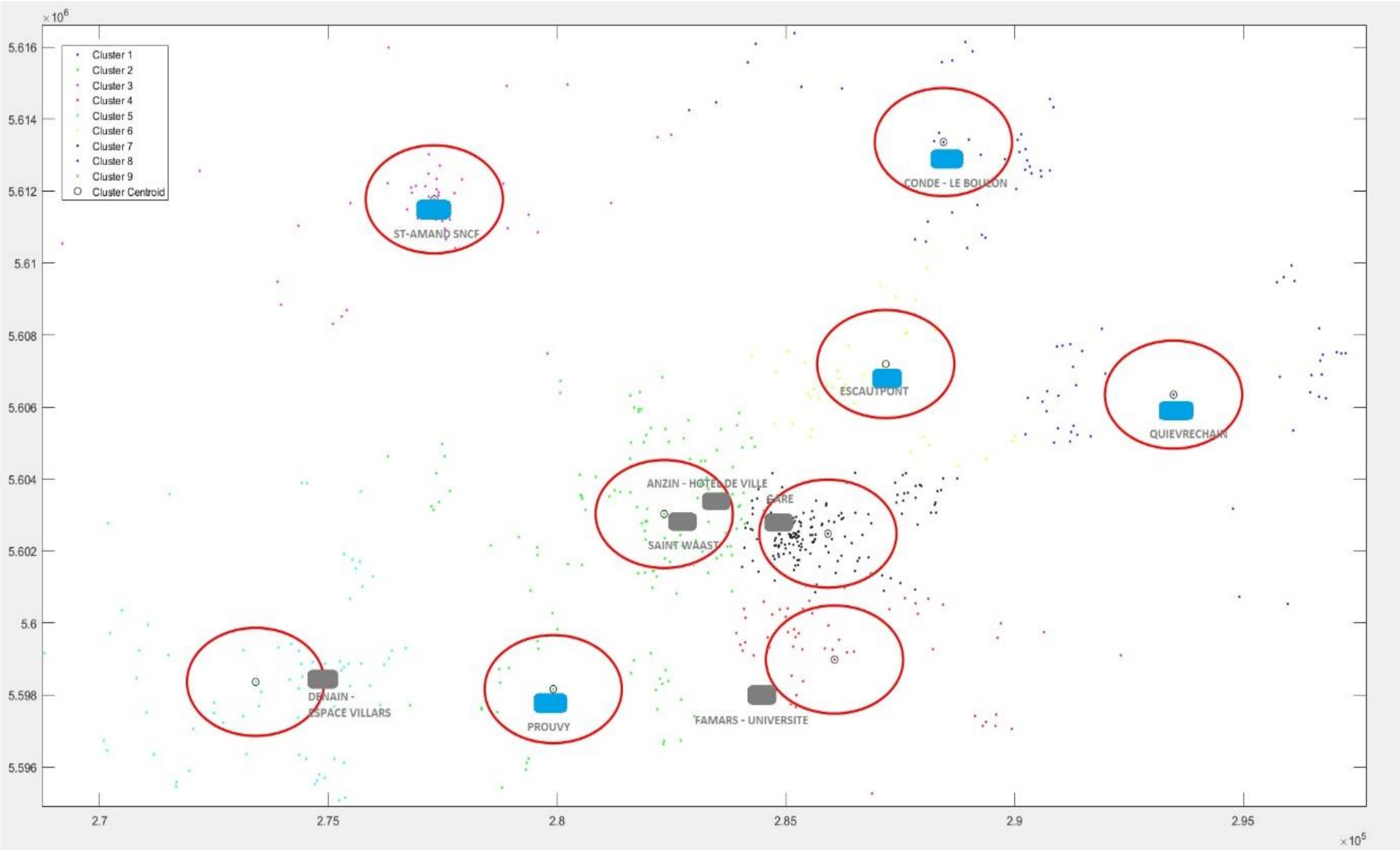


Figure 38 Geographical position in arrival: 9 clusters (High resolution)