Évaluation et la représentation spatiotemporelle de l'accessibilité des réseaux piétonniers pour le déplacement des personnes à mobilité réduite

Thèse

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Résumé

La mobilité des personnes à mobilité réduite (PMR) joue un rôle important dans leur inclusion sociale. Les PMR ont besoin de se déplacer de manière autonome pour effectuer leurs routines quotidiennes comme aller à l'école, au travail, au centre de remise en forme ou faire du magasinage. Cependant, celles-ci ne sont pas entièrement exécutées en raison de la conception non-adaptée des villes pour ces personnes. En effet, la mobilité est une habitude de vie humaine qui est le résultat d'interactions entre les facteurs humains (par exemple, les capacités) et les facteurs environnementaux. Au cours des dernières années, la mise au point de technologies d'aide technique s'est développée progressivement pour permettre aux PMR d'améliorer leur qualité de vie. En particulier, ces technologies offrent une variété de caractéristiques qui permettent à ces personnes de surmonter divers obstacles qui réduisent leur mobilité et contribuent à leur exclusion sociale. Cependant, malgré la disponibilité des technologies d'aide à la navigation et à la mobilité, leur potentiel est mal exploité pour les PMR. En effet, ces technologies ne considèrent pas les interactions « humain-environnement » adéquatement pour ces utilisateurs.

L'objectif général de cette thèse est d'utiliser les potentiels des méthodes et des technologies de science de l'information géographique (SIG) afin d'aider à surmonter les problèmes de mobilité des PMR en créant un cadre d'évaluation de l'accessibilité et en développant une approche personnalisée de routage qui prend en compte les profils de ces personnes. Pour atteindre ce but, quatre objectifs spécifiques sont considérés: 1) développer une ontologie de mobilité pour les PMR qui considère les facteurs personnels et environnementaux, 2) proposer une méthode de l'évaluation de l'accessibilité du réseau piétonnier pour la mobilité des PMR en considérant spécifiquement les interactions entre les facteurs humains (la confiance) et les facteurs environnementaux, 3) étudier le rôle des facteurs sociaux dans l'accessibilité des zones urbaines et, finalement, 4) affiner les algorithmes existants pour calculer les itinéraires accessibles personnalisés pour les PMR en considérant leurs profils.

En effet, tout d'abord pour développer une ontologie pour la mobilité des PMR, la dimension sociale de l'environnement ainsi que la dimension physique sont intégrées et une nouvelle approche basée sur une perspective « nature-développement » est présentée.

Ensuite, une approche fondée sur la confiance des PMR est développée pour l'évaluation de l'accessibilité du réseau piétonnier, compte tenu de l'interaction entre les facteurs personnels et les facteurs environnementaux. De plus, dans une perspective de considération des facteurs sociaux, le rôle des actions politiques sur l'accessibilité du réseau piétonnier est étudié et l'influence de trois politiques potentielles est analysée. Enfin, une nouvelle approche pour calculer des itinéraires personnalisés pour les PMR en tenant compte de leurs perceptions, de leurs préférences et de leurs confidences est proposée. Les approches proposées sont développées et évaluées dans le quartier Saint-Roch à Québec, et ce, en utilisant une application d'assistance mobile et multimodale développée dans le cadre du projet MobiliSIG.

Abstract

Mobility of people with motor disabilities (PWMD) plays a significant role in their social inclusion. PWMD need to move around autonomously to perform their daily routines such as going to school, work, shopping, and going to fitness centers. However, mostly these needs are not accomplished because of either limitations concerning their capabilities or inadequate city design. Indeed, mobility is a human life habit, which is the result of interactions between people and their surrounded environments. In recent years, assistive technologies have been increasingly developed to enable PWMD to live independently and participate fully in all aspects of life. In particular, these technologies provide a variety of features that allow these individuals to overcome diverse obstacles that reduce their mobility and contribute to their social exclusion. However, despite increasing availability of assistive technologies for navigation and mobility, their potential is poorly exploited for PWMD. Indeed, these technologies do not fully consider the human-environment interactions.

The overall goal of this dissertation is to benefit from the potentials of methods and technologies of the Geographic Information Sciences (GIS) in order to overcome the mobility issues of PWMD by creating an accessibility-assessing framework and ultimately by developing a personalized routing approach, which better considers the human-environment interaction. To achieve this goal, four specific objectives were followed: 1) develop a mobility ontology for PWMD that considers personal factors as well as environmental factors, 2) propose a method to evaluate the accessibility of the pedestrian network for the mobility of PWMD considering the interactions between human factors (confidence) and the environmental factors, 3) study of the role of social factors in the accessibility of urban areas, and finally, 4) refine the existing algorithms to calculate accessible routes for PWMD considering their profile. First, to develop an adapted ontology for mobility of the PWMD, the social dimension of the environment with the physical dimension were integrated and a new approach based on a "*Nature-Development*" perspective was presented. This perspective led to the development of useful ontologies, especially for defining the relationships between the social and physical parts of the environment. Next, a confidence-based approach was developed for evaluation of the

accessibility of pedestrian network considering the interaction between personal factors and environmental factors for the mobility of PWMD. In addition, the role of policy actions on the accessibility of the pedestrian network was investigated and the influence of three potential policies was analyzed. Finally, a novel approach to compute personalized routes for PWMD considering their perception, preferences, and confidences was proposed. The approaches proposed were implemented in the Saint-Roch area of Quebec City and visualized within the multimodal mobile assistive technology (MobiliSIG) application.

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Je dédie ce travail:

À ma famille; Nastaran et Artin

À mes parents

Remerciements

Tout d'abord, je voudrais exprimer ma gratitude à mon directeur de recherche, le professeur Mir Abolfazl Mostafavi, pour m'avoir donné l'opportunité de travailler sur le projet MobiliSIG et pour s'être assuré que j'aie le soutien scientifique et financier nécessaire pour m'investir pleinement dans mes travaux de recherche durant mes études à l'Université Laval. Merci de m'avoir fourni la liberté et les ressources nécessaires pour compléter ce travail de recherche. J'aimerais également exprimer ma sincère reconnaissance aux membres de mon comité de supervision, soit le professeur Geoffrey Edwards et le professeur Patrick Fougeyrollas, pour leur soutien continu tout au long de mes travaux de recherche. Un gros merci au professeur Frédéric Hubert pour avoir effectué la pré-lecture de ma thèse. Je remercie également les évaluateurs externes de la thèse, le professeur Sean Doherty de l'Université Wilfrid Laurier et la professeure Pascale Marcotte du Département de géographie de l'Université Laval pour leurs commentaires et suggestions permettant l'amélioration de la thèse. Mes remerciements vont aussi aux membres du projet MobiliSIG, notamment au professeur Luc Noreau et au professeur François Routhier pour leur soutien scientifique et leur contribution à ce travail de recherche.

Merci aux nombreux amis que je me suis faits pendant mon doctorat au CRG et au CIRRIS, en particulier à Patrick Morales-Coayla, David Fiset, et Eveline Bernier.

Mes travaux de recherche étaient financés dans le cadre du projet MobiliSIG. Merci aux Instituts de recherche en santé du Canada (IRSC) et au Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG) pour leur soutien financier durant mes études.

Finalement, je remercie sincèrement ma famille, Nastaran et Artin, et mes chers parents, Mozaffar et Shokat. Cette thèse est autant la vôtre que la mienne. Votre soutien tout au long de ma vie m'a donné la confiance nécessaire pour terminer ce que j'ai commencé.

Avant-Propos

En plus des chapitres introductifs et la vue d'ensemble, cette thèse contient quatre articles qui sont publiés ou soumis pour publication dans des revues à comité de lecture. Le premier article a été publié en juillet 2017 dans la revue « Disability and Rehabilitation: Assistive Technology » et il constitue le troisième chapitre de cette thèse. Le deuxième article a été publié en juin 2017 comme un chapitre de livre dans « Advances in Cartography and GIScience, Lecture Notes in Geoinformation and Cartography » et est présenté comme le chapitre 4 de cette thèse. Le troisième article a été publié en mars 2018 dans le «ISPRS International Journal of Geo-Information» et est présenté comme le chapitre 5 de cette thèse. Le quatrième article a été soumis pour la revue «International Journal of Geographical Information Science» et est présenté comme le chapitre 6 de cette thèse. L'auteur de cette thèse, Amin Gharebaghi, est l'auteur principal de ces articles.

La contribution de l'auteur de cette thèse dans ces articles était d'effectuer tout le travail expérimental, la préparation et l'analyse des données, et d'écrire les premières versions. Le format final de chaque article est un résultat direct de la collaboration avec les coauteurs listés. Le chapitre 3 était un effort de collaboration entre Amin Gharebaghi et les coauteurs Mir-Abolfazl Mostafavi, Geoffrey Edwards, Patrick Fougeyrollas, Stéphanie Gamache et Yan Grenier. Le chapitre 4 était un effort de collaboration entre Amin Gharebaghi et les coauteurs Mir-Abolfaz Mostafavi, Geoffrey Edwards, Patrick Fougeyrollas, Patrick Morales-Coayla, François Routhier, Jean Leblond et Luc Noreau. Le chapitre 5 était un effort de collaboration entre Amin Gharebaghi et les coauteurs Mir-Abolfazl Mostafavi, Seyed-Hossein Chavoshi, Geoffrey Edwards et Patrick Fougeyrollas. Le chapitre 6 était un effort de collaboration entre Amin Gharebaghi et les coauteurs Mir-Abolfaz Mostafavi, Seyed-Hossein Chavoshi, Geoffrey Edwards et Patrick Fougeyrollas.

1 Introduction général

1.1 Contexte de la recherche

Assurer la pleine participation sociale des personnes ayant des incapacités dans les sociétés d'aujourd'hui est un grand défi à relever dans la plupart des régions du monde. Ceci est dû au fait que les besoins spéciaux de ces gens ne sont pas souvent pris en compte dans le développement des villes, y compris des lieux publics ainsi que des nouvelles technologies et services. Les personnes ayant des incapacités qui ne peuvent se déplacer de façon autonome sont limitées dans l'accomplissement de leurs activités quotidiennes telles que d'aller au travail ou à l'école, de faire du magasinage ou de participer aux activités de la communauté et de la vie familiale. Marston et Golledge (2002) appellent les demandes d'améliorer la participation des personnes ayant des incapacités à des activités sociales des « demandes cachées ». Les demandes cachées réfèrent à des activités que les personnes ayant des incapacités désirent accomplir, mais qu'elles ne peuvent faire. Pour permettre aux personnes ayant des incapacités de vivre de façon indépendante et de participer pleinement à tous les aspects de la vie, les considérations appropriées devraient être prises en compte. Par exemple, nous devrions nous assurer que ces personnes ont accès, sur un pied d'égalité avec les autres, à des environnements physiques et des services publics tels que les moyens de transport.

La ratification de la Convention relative aux droits des personnes handicapées par plus de 160 pays a représenté un tournant pour le mouvement des droits des personnes handicapées. Elle informe les acteurs des secteurs publics et privés de leurs responsabilités en matière de politiques, de services et de produits qui doivent garantir l'égalité d'accès pour tous les citoyens, indépendamment de toute limitation fonctionnelle. Cependant, dans un même temps, cela pose des défis majeurs en termes de mise en œuvre et mise en vigueur. La Convention est fondée sur le modèle social du handicap (Fougeyrollas, 2010; Oliver, 1996; Shakespeare and Watson, 1997) qui affirme que le handicap est un produit social, pas une condition médicale.

Dans la formulation originale du modèle, la déficience peut être considérée comme une limitation biologique, mais dans le modèle social, un handicap survient lorsque la société ne parvient pas à fournir les moyens de surmonter les limites rencontrées de manière adéquate. En effet, la société est responsable de l'imposition du handicap chez les personnes ayant des incapacités (Oliver, 1996). Contrairement au modèle médical du handicap, l'environnement est considéré comme l'un des éléments les plus centraux des modèles de handicap contemporains (qui reposent tous sur le modèle social). Par exemple, le modèle Processus de production du handicap (PPH - Fougeyrollas et al., 1998), le modèle Classification Internationale du Fonctionnement, du handicap et de la santé (CIF-Organisation, 2001) et le modèle Institut de Médecine (IOM - Brandt Jr et Pope, 1997), tous des modèles de handicap bien connus, affirment que l'environnement joue un rôle fondamental dans le processus de création d'un handicap et « le handicap ne peut être entièrement compris sans tenir compte du contexte environnemental » (Whiteneck et al., 2004). Cependant, le modèle social est à bien des égards plus une position politique qu'un modèle complètement élaboré.

L'Enquête canadienne sur l'incapacité montre que parmi les autres types de handicaps, l'ouïe, la mobilité, la flexibilité, la dextérité, la douleur, l'apprentissage, le développement, le mental/psychologique, la mémoire et le manque de mobilité sont les sources d'incapacité les plus courantes chez les adultes canadiens (ECI, 2012). Les problèmes de mobilité représentent 7 % des problèmes d'invalidité susmentionnés où, dans la province de Québec, le nombre d'utilisateurs de fauteuils roulants est supérieur à 52 000, dont 86 % utilisent des fauteuils roulants manuels (EQLAV, 2011). La Figure 1.1 montre la prévalence de la mobilité et de l'incapacité totale des personnes âgées de 15 ans et plus au Canada (Enquête canadienne sur l'incapacité, 2012).

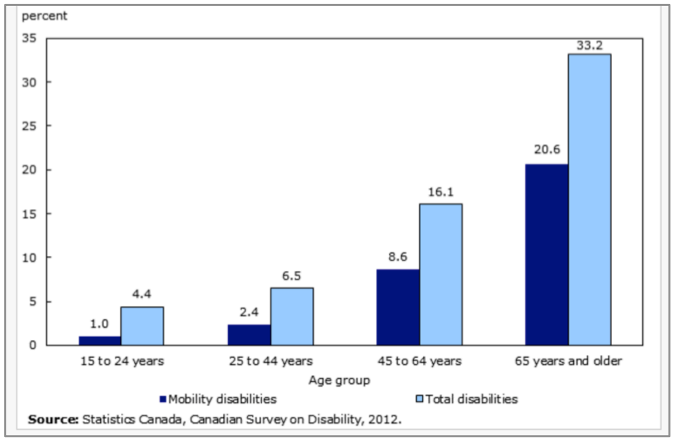

Figure 1.1. Prévalence des incapacités motrices et des incapacités totales, Canada, 2012 (Enquête canadienne sur l'incapacité, 2012)

Un moyen évident d'aider les PMR dans leurs efforts pour se déplacer dans les zones urbaines est de leur fournir des informations sur les chemins accessibles, en tenant compte de leurs limitations de mobilité. En effet, assurer une navigation sûre, utilisable et accessible dans les zones urbaines pour les PMR peut considérablement améliorer leurs possibilités de pleine participation sociale et l'exercice de leurs droits humains fondamentaux. Afin de résoudre ce problème, un projet a été lancé dans le but de développer une technologie d'assistance pour la navigation des PMR à Québec. Ce projet s'appelle MobiliSIG et est un projet multidisciplinaire mené au sein d'une équipe multidisciplinaire regroupant le Centre de recherche en géomatique (CRG) et le Centre interdisciplinaire de recherche en réadaptation et intégration sociale (CIRRIS). L'objectif principal de MobiliSIG est de développer une technologie d'assistance multimodale mobile pour la navigation des PMR à Québec en tant que pilote d'accessibilité ameliorée pour effectuer des tests initiaux. La ville de Québec a des caractéristiques propres à une vieille ville; par exemple, il y a de nombreuses collines et différents types de trottoirs qui rendent la navigation difficile.

Le projet a débuté en 2013 et dans un an, un travail de thèse de recherche encadré dans le programme de recherche plus large de MobiliSIG pour aborder les questions spécifiques de l'évaluation de l'accessibilité des trajectoires urbaines et la cartographie de ces trajectoires sur la base du profil fonctionnel des PMR. Cette recherche, effectuée dans le cadre du projet MobiliSIG, visera à faire des ponts entre les différents membres de travail de l'équipe ayant des origines en géomatique, en informatique, en santé et en sciences de la réadaptation. Cet assemblage sera effectué en identifiant les modèles fondamentaux appropriés, en développant les algorithmes pertinents et en affinant les méthodologies nécessaires pour concevoir l'interface d'assistance multimodale mobile. En conclusion, l'objectif principal de cette recherche a été développé une approche pour le routage personnalisé pour les PMR en ce qui concerne leurs besoins essentiels et leurs perceptions des routes souhaitables. Parmi les divers besoins vitaux, dont l'accessibilité, la sécurité, le confort et le plaisir, l'accessibilité est utilisée pour calculer les itinéraires optimaux pour les PMR.

1.2 Problèmes de recherche, défis et signification

1.2.1 Problème général

Le problème général de cette étude est de modéliser les interactions entre les facteurs humains et les environnements physiques et sociaux dans lesquels les PMR vivent. Selon le « Processus de production du handicap » (PPH - Fougeyrollas et al., 1998), la qualité de la participation sociale des personnes handicapées est le résultat de telles interactions qui sont très complexes à modéliser. La raison en est que, premièrement, les profils d'utilisateurs des PMR sont très hétérogènes (caractéristiques physiques, nature du handicap, expérience, etc.). Deuxièmement, les activités quotidiennes des PMR sont effectuées dans un environnement rempli de barrières telles que les escaliers, les trottoirs, les portes étroites et les barrières architecturales qui contraignent fortement leur mobilité.

1.2.2 Problèmes spécifiques

Considérant le problème général, les problèmes spécifiques de cette recherche sont présentés comme suit.

1.2.2.1 Manque d’une définition formelle des facteurs environnementaux et sociaux affectant le déplacement des personnes à mobilité réduite dans une zone urbaine

Afin d'évaluer l'accessibilité d'une trajectoire et de calculer en fin de compte les voies optimales pour les PMR, un nombre significatif de facteurs environnementaux en interaction avec des facteurs personnels devrait être pris en compte. Dans divers modèles conçus pour évaluer l'accessibilité, de nombreux obstacles et facilitateurs environnementaux sont identifiés (Kirschbaum et al., 2001; Kirby et al., 2002; Sobek et Miller, 2006; Beale et al., 2006; Karimanzira et al., 2006; Kasemsuppakorn et Karimi, 2009; Rushton et al., 2011; CEREMH, 2011; Neis et Zielstra, 2014; Neis, 2015 et Hashemi et Karimi, 2016). Cependant, l'hétérogénéité dans la détermination des concepts et de leurs sémantiques complique l'évaluation efficace de l'accessibilité d'un itinéraire. Une ontologie de la mobilité dans une zone urbaine fournit un vocabulaire convenu et évite d'utiliser des sémantiques différentes qui intègrent plusieurs ontologies. Des recherches significatives ont été menées pour définir de telles ontologies dans les zones urbaines (Berdier, 2011 et Métral et Cutting-Decelle, 2011). L'une des limitations des projets de recherche mentionnés ci-dessus est qu'ils se sont concentrés uniquement sur les concepts généraux de mobilité et n'ont pas pris en compte les exigences particulières des PMR. De plus, ils sont presque entièrement concentrés sur les aspects physiques de leurs caractéristiques alors que les aspects sociaux de l'environnement sont rarement pris en compte. En effet, une ontologie efficace devrait aborder la conception et la mise en œuvre des infrastructures de mobilité ainsi que leur utilisation et leur sémantique diverse, y compris celles qui décrivent le domaine social, et les deux doivent être intégrées dans une approche globale. De plus, dans le modèle PPH (Fougeyrollas et al. 1998), les interactions entre les facteurs environnementaux et humains sont représentées en termes généraux et les relations entre les facteurs spécifiques n'ont pas été déterminées exactement. Par conséquent, il semble y avoir pénurie d'ontologies détaillées pour les problèmes de mobilité des PMR.

1.2.2.2 Faibles prise en compte de la capacité des personnes à mobilité réduite par les modèles d'évaluation de l'accessibilité et par les outils de navigation existants

Bien que l'accessibilité du réseau piétonnier dépende de facteurs environnementaux tels que la pente et la largeur du trottoir, l'accessibilité des segments d'itinéraires sont également liées aux capacités humaines. Bien qu'une voie puisse être accessible à une personne, elle peut être inaccessible pour d'autres; par conséquent, les interactions entre les capacités humaines et les facteurs environnementaux devraient être prises en compte pour élaborer un modèle d'accessibilité adéquat. Les facteurs environnementaux ne constituent pas des obstacles absolus par eux-mêmes; ce n'est que par leur relation avec les facteurs humains qu'ils peuvent permettre, entraver ou rendre impossible la réalisation d'une habitude de vie. En raison des différents niveaux de capacités, des types de handicaps et de la diversité des environnements, la modélisation de ces interactions est très complexe.

1.2.2.3 Absence des facteurs sociaux dans l'étude de l'accessibilité du réseau piétonnier pour les personnes à mobilité réduite

La plupart des modèles d'accessibilité existants considèrent que les facteurs physiques de l'environnement. Ces modèles sont généralement définis en fonction de la facilité d'atteindre chaque destination en fonction de la distance, du temps et du coût (Church et Marston, 2003). Les entités affectant l'accessibilité ont deux dimensions, soit physique et sociale, où la dimension sociale fait partie intégrante de l'environnement, qui doit être compris comme incluant des facteurs politiques, économiques et culturels ainsi que des préoccupations strictement sociales. Par conséquent, l'impact des facteurs sociaux sur l'accessibilité des PMR devrait également être étudié en lien avec l'accessibilité du réseau piétonnier. Ainsi, nous devons également tenir compte de l'influence des facteurs sociaux sur le processus d'évaluation de l'accessibilité.

1.2.2.4 Limites des méthodes et outils existantes dans le calcul des routages adaptés et accessibles pour les personnes à mobilité réduite

Pour trouver la route optimale en utilisant les algorithmes de routage disponibles, une fonction de coût doit être calculée. Dans un cas simple, la fonction de coût est définie comme la longueur de tous les segments dans une certaine procédure de chemin, et la procédure de minimisation est ensuite appliquée pour trouver le chemin le plus court en recherchant des sections de chemins localement adjacentes. Pour appliquer l'algorithme de routage pour les PMR des contraintes supplémentaires doivent être imposées pour le calcul des routes optimales. Cependant, des exigences supplémentaires peuvent ne pas être compatibles avec la longueur des segments. Par exemple, la longueur et l'adéquation d'un itinéraire (par exemple, la qualité des surfaces ou la sécurité d'un itinéraire) peuvent entrer en conflit les uns avec les autres. La recherche de l'itinéraire optimal avec des paramètres supplémentaires nécessite de considérer l'effet de compensation parmi les paramètres, ce qui complique la méthode.

1.3 Objectifs de la recherche

1.3.1 Objectif général

Des recherches intensives ont été menées pour fournir un cadre permettant d'évaluer l'accessibilité des réseaux piétoniers et de proposer des itinéraires accessibles pour les PMR (Beale et al., 2006 et Kasemsuppakorn et Karimi, 2009). Cependant, ces efforts ne répondent pas entièrement aux besoins de ces personnes et il y a place à beaucoup d'améliorations. Dans cette étude, l'objectif général est de proposer et d'implémenter un cadre d'évaluation de l'accessibilité pour les PMR considérant les facteurs environnementaux ainsi que les capacités et la confiance des PMR. En fin de compte, nous proposons de développer une approche pour le routage personnalisé pour les PMR en considérant leurs besoins et leurs perceptions des routes accessibles.

1.3.2 Objectifs spécifiques

Afin d'atteindre l'objectif général de cette recherche, les objectifs spécifiques suivants sont considérés dans cette étude.

1.3.2.1 Développer une ontologie de mobilité pour les personnes à mobilité réduite

Le premier objectif de cette dissertation est de développer une ontologie adaptée à la mobilité des PMR. Cette ontologie devrait prendre en compte les obstacles et les facilitateurs rencontrés par les usagers ayant des handicaps moteurs dans les zones urbaines pendant leur navigation. Elle doit generer une formalisation explicite de l'environnement social d'une manière compatible avec les exigences d'une ontologie de la mobilité pour les PMR. De plus, cette ontologie devrait étudier comment les propriétés sociales de l'environnement seraient intégrées aux propriétés physiques.

1.3.2.2 Développer une approche pour l'évaluation de l'accessibilité du réseau piétonnier pour les personnes à mobilité réduite

Le deuxième objectif consiste à aider les PMR dans leur planification de déplacement en élaborant un cadre d'évaluation de l'accessibilité dans les zones urbaines. Ce cadre considérera les barrières environnementales tout en tenant compte des capacités des PMR. Notre objectif est de proposer un tel cadre pour évaluer le niveau d'accessibilité d'un réseau piétonnier pour les PMR. Cette approche tiendra compte des perceptions, des préférences et des capacités des utilisateurs de fauteuils roulants manuels.

1.3.2.3 Ètude du rôle des facteurs sociaux dans l'accessibilité des zones urbaines

Dans le troisième objectif, nous mettons davantage l'accent sur la manière dont les facteurs sociaux influencent l'accessibilité des infrastructures urbaines. Nous aimerions montrer comment l'accessibilité du réseau dépend non seulement des capacités des personnes handicapées, mais aussi de facteurs environnementaux et sociaux. Alors, cette application peut être utilisée non seulement comme un outil de décision pour un individu pour sa navigation dans une ville, mais aussi comme un outil de prise de décision pour les autorités de la ville.

1.3.2.4 Affiner les algorithmes existants pour calculer les itinéraires accessibles personnalisés pour les personnes à mobilité réduite en considérant leur profile

Enfin, nous cherchons à proposer une approche de routage pour les PMR qui prend en compte exclusivement leurs perceptions, leurs préférences et leurs capacités. Parmi les divers besoins vitaux, y compris l'accessibilité, la sécurité, le confort et le plaisir, le critère d'accessibilité est utilisé pour calculer les itinéraires optimaux pour les PMR. Les critères requis seraient optimisés grâce à cette approche tout en permettant la compensation d'un critère par un autre. En d'autres termes, nous sommes intéressés à trouver des routes qui offrent des compromis entre l'accessibilité et la distance.

1.4 Méthodologie

Le but de cette section est d'exposer la méthodologie pour atteindre les objectifs de notre travail de recherche. Notre méthodologie est présentée en cinq phases. La première phase est une revue de la littérature sur la recherche connexe. La deuxième phase est le développement de l'ontologie de la mobilité pour les PMR. La troisième phase offre une approche basée sur la confiance pour l'évaluation de l'accessibilité des réseaux piétonniers pour des PMR. Dans la quatrième phase, nous explorons le rôle des facteurs sociaux dans l'accessibilité du réseau piétonnier pour les PMR. Enfin, dans la cinquième phase, nous proposons une approche multi critères pour calculer les itinéraires personnalisés pour les PMR. La Figure 1.3 montre le diagramme d'activités détaillé de la méthodologie de recherche.

Afin de mieux présenter le contexte et les problèmes étudiées dans le cadre de cette recherche, une analyse documentaire approfondie est effectuée au chapitre 2. Les sujets abordés par cette revue sont: les ontologies, les modèles d'incapacité, les approches de mesure des compétences en fauteuil roulant, les approches d'évaluation de l'accessibilité, l'analyse de critères et des algorithmes de routage. Cette phase nous permet d'identifier les problèmes qui doivent être résolus, de réaliser les objectifs du projet et de déterminer les méthodologies appropriées pour notre étude. De plus, cette phase fournit les fondements théoriques de la recherche. Trouver un ensemble de données approprié, puis collecter et adapter les données à notre objectif est un autre but de cette étape. L'ensemble de données utilisé dans cette recherche est collecté dans le quartier Saint-Roch à Québec (identifié comme le laboratoire d'accessibilité). La méthodologie et les algorithmes proposés sont appliqués et testés en utilisant cet ensemble de données. Les données de Saint-Roch sont recueillies à partir de plusieurs sources de données existantes, notamment les collections de données de la Ville de Québec de 2015 et du portail Web de la Ville de Québec ainsi qu'une enquête complémentaire sur le terrain. La Figure 1.2 illustre la carte de base de la zone d'étude et la distribution spatiale des barrières potentielles.

Figure 1.2. Carte du réseau piétonnier de Saint-Roch et répartition spatiale des barrières identifiés pour la mobilité de PMR

La deuxième phase de cette thèse est de développer une ontologie pour identifier les concepts les plus pertinents dans la mobilité des PMR et leurs relations intégrant les environnements sociaux et physiques. Nous proposons d'initier en formalisant explicitement l'environnement social de manière comparable aux exigences d'une ontologie de la mobilité pour les PMR. Ensuite, nous intégrons les dimensions humaines, sociales et physiques de l'environnement au sein de l'ontologie de la mobilité. Cette intégration nécessite de modéliser les objectifs possibles de l'activité de mobilité, qui est entreprise par les utilisateurs en fonction de leurs habitudes de vie et de leurs activités. Le cadre d'ontologie proposé pourrait inclure plusieurs domaines, y compris le handicap, la réadaptation, les sciences sociales et l'informatique, en réconciliant les nomenclatures entre ces domaines et en réduisant l'hétérogénéité des terminologies entre eux. Cette approche sera utile dans la conception d'outils visant à évaluer les assemblages « humain-environnement ». En conclusion, cela permettra aux spécialistes du handicap de cartographier la complexité d'une situation donnée en identifiant directement les relations entre les aspects physiques et sociaux d'une entité.

La troisième phase consiste à élaborer une approche pour évaluer l'accessibilité des segments du réseau piétonnier pour les personnes qui utilisent un fauteuil roulant manuel dans leurs activités quotidiennes. Nous étudions les capacités réelles et perçues de ce groupe de personnes. La confiance de l'utilisateur est utilisée comme critère pour mesurer les capacités perçues de l'utilisateur, et le processus d'évaluation de l'accessibilité est réalisé en sept étapes : 1) capture des données du réseau piéton, 2) partition des réseaux piétons en segments, 3) collecte des informations du profil utilisateur, 4) liaison des paramètres de segments avec les confidences d'utilisateurs correspondantes, 5) agrégation des niveaux de confiance pour chaque segment, 6) évaluation du niveau d'accessibilité de chaque segment basé sur la confiance totale et 7) visualisation du niveau d'accessibilité de chaque segment sur la carte du réseau piétonnier. Afin d'effectuer l'étape d'agrégation, une approche basée sur la logique floue (Zadeh et al., 1965) est utilisée.

Lors de la quatrième phase, nous mettons davantage l'accent sur la manière dont les facteurs sociaux influencent l'accessibilité des infrastructures urbaines telles que les réseaux piétonniers. Parmi les divers facteurs sociaux, l'impact des règles et des politiques de la municipalité est exploré. Nous visons à étudier l'influence de la mise en œuvre de tests de politiques sur l'accessibilité des intersections et des trottoirs. Parmi les différentes politiques, nous testons l'impact de trois politiques, soit l'amélioration de la qualité des bateaux pavés, l'amélioration de déneigement dans les intersections et la relocalisation des poteaux électriques sur les trottoirs. L'influence de ces politiques est quantifiée et visualisée sur la carte d'accessibilité générée pour le secteur Saint-Roch à Québec.

La cinquième phase consiste à proposer une approche pour le processus de routage personnalisé des PMR par 1) la quantification des préférences de route et 2) le calcul de l'itinéraire (Kasemsuppakorn et Karimi, 2009). La quantification des préférences d'itinéraire détermine un poids pour chaque segment de trottoir en fonction des préférences individuelles indiquant à quel point chaque segment est favorable au déplacement des PMR. Des segments pondérés sont ensuite utilisés pour l'étape de calcul de l'itinéraire optimal. Généralement, la route optimale est calculée en résolvant le problème de minimisation correspondant. Dans cette étude, le niveau d'accessibilité est considéré comme la valeur de coût des segments, qui est calculée en agrégeant les capacités des utilisateurs par rapport aux multipropriétés de ce segment. Ce processus est réalisé sur la base de l'approche multi critères (Fuzzy-TOPSIS).

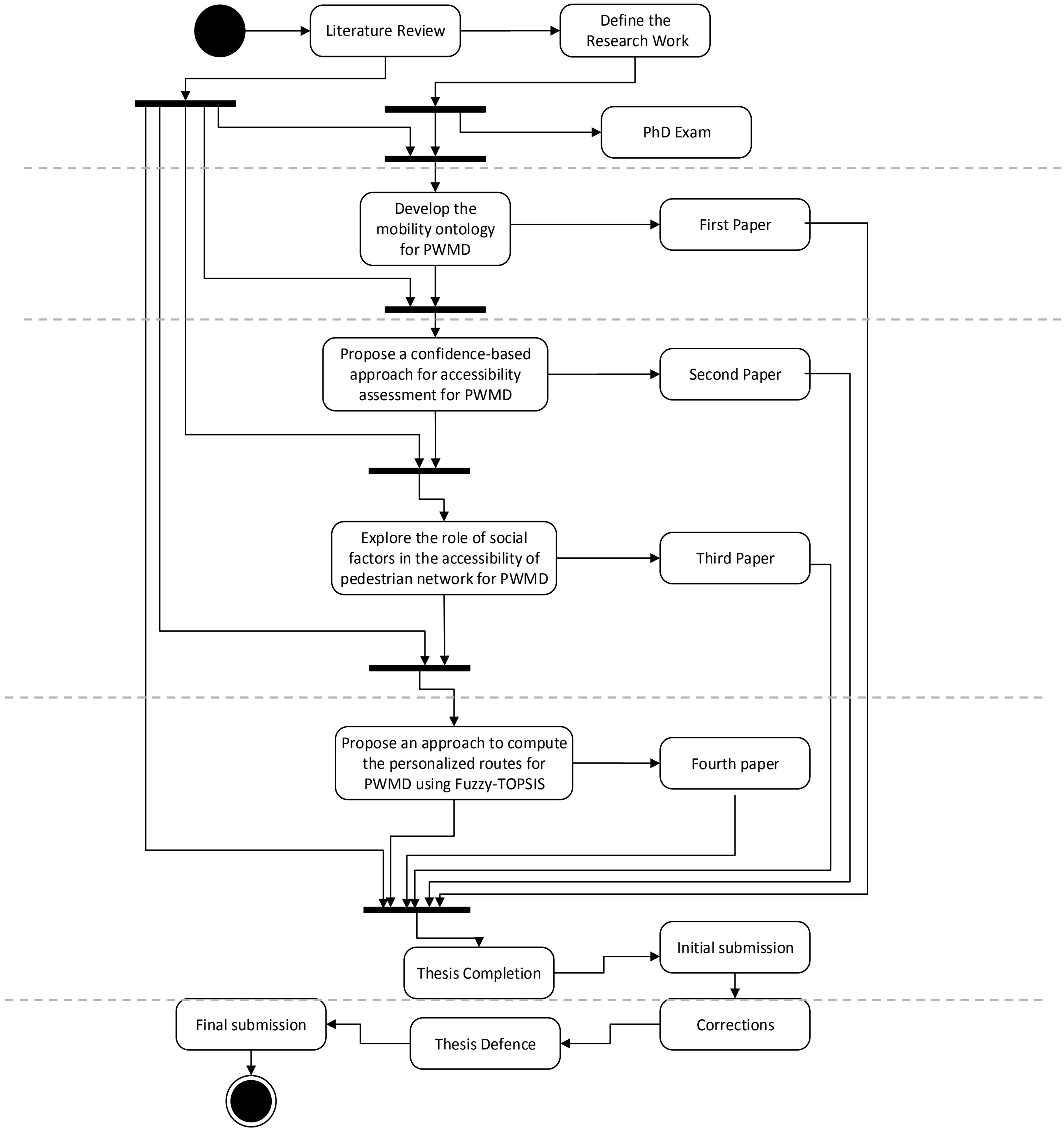

Figure 1.3. Diagramme d'activités de la méthodologie de recherche

1.5 Organisation de la thèse

Cette dissertation est organisée comme suit. Le chapitre 1 élabore le contexte, les problèmes, les objectifs et présente un aperçu de la méthodologie proposée pour cette thèse. La vue d'ensemble des concepts, des défis et des problèmes relatifs à la mobilité des PMR sera expliquée dans le deuxième chapitre. Ce chapitre traite des problèmes et des défis de la mobilité des PMR, des modèles d'incapacité, de la mobilité comme habitude de vie, de la segmentation du réseau piétonnier, des approches d'évaluation de l'accessibilité et des algorithmes de routage. Le chapitre 3, publié comme un article dans la revue « *Disability and Rehabilitation: Assistive Technology* », présente une ontologie de la mobilité pour les PMR et étudie l'intégration de l'environnement social dans cette ontologie. Le chapitre 4, publié comme un chapitre de livre dans « Advances in Cartography and GIScience, Lecture Notes in Geoinformation and Cartography », propose une approche basée sur la confiance pour évaluer l'accessibilité des réseaux piétonniers en développant des Fuzzy Rules. Dans ce travail, seuls les facteurs physiques de l'environnement tels que la pente et la largeur des segments et les facteurs humains aussi sont pris en compte. Le chapitre 5, également publié comme un article dans la revue « ISPRS International Journal of Geo-Information », traite de la façon dont les facteurs sociaux mettent particulièrement l'accent sur les normes et les politiques municipales, qui peuvent être influencées par l'évaluation de l'accessibilité du réseau piétonnier pour les PMR. Le chapitre 6, aussi présenté comme un article dans une revue scientifique, développe une approche pour planifier des itinéraires personnalisés pour les PMR en tenant compte de leurs perceptions, de leurs préférences et de leurs confidences. Un résumé, une conclusion et des perspectives de recherche sont fournis dans le dernier chapitre. Les articles publiés dans la thèse ont conservé leur contenu original.

Telle que mentionnée, cette thèse est présentée avec l'insertions de plusieurs articles scientifiques issues de la recherche effectué dans le cadre de ce projet de doctorat. De ce fait, certaines sections de la thèse peuvent contenir des informations redondantes et non évitables. Ceci a pour but de rassurer que chaque article inclue les informations requises pour les lecteurs en tant que document de recherche indépendant.

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2 Vue d'ensemble de la mobilité des personnes à mobilité réduite

Résumé: La mobilité des PMR est considérablement limitée par leurs déficiences et la présence de différents obstacles dans l'environnement, ce qui affecte leurs activités quotidiennes. Les technologies d'assistance visent à fournir diverses fonctionnalités pour aider à surmonter divers obstacles. Malgré la disponibilité croissante des technologies d'assistance à la navigation et à la mobilité, leur potentiel est mal exploité pour les PMR. En effet, ces technologies ne considèrent pas completement les interactions « humain-environnement », ce qui est considéré comme une base pour développer une telle application. Dans ce chapitre, des modèles fondamentaux et des applications existantes développées pour la mobilité des PMR sont passés en revue. Premièrement, nous élaborons les composantes de l'acteur (c'est-à-dire les caractéristiques environnementales et les capacités personnelles) dans la mobilité humaine en développant spécifiquement le modèle du *Processus de production du handicap* (PPH) comme cadre fondamental dans le processus du handicap. Ensuite, nous étudions les modèles existants et les applications de l'évaluation de l'accessibilité pour les PMR. Dans cette section, trois principales étapes de l'évaluation de l'accessibilité et leurs défis, y compris la segmentation du réseau piétonnier, la pondération des propriétés des segments, et le calcul de la valeur de coût sont passés en revue. En outre, nous étudions aussi le processus de calcul de route pour les PMR utilisé dans différentes recherches.

An overview of the mobility of people with motor disabilities; from a socio-spatial perspective

2.1 Context

Social exclusion of people with disabilities is a challenging issue for international societies, and Canada is not an exception. The Canadian Survey on Disability (CSD, 2014) shows that among distinct types of disabilities including sensory (seeing, hearing), physical (mobility, flexibility, dexterity, pain), cognitive (learning, developmental, mental/psychological, and memory) and mental health, pain, lack of flexibility, and lack of mobility are the most common sources of disabilities in Canadian adults. To improve health and security and facilitate social participation of PWD, disability models must be developed. In contemporary approaches, the environment is one of the most central elements. Current disability models are based on social models, where the impairment term is used for the physical condition of body and the disability is connected to the environment as a significant factor in causing disability. The social participation of people with disabilities is viewed as the result of interactions between personal and environmental factors as well as life habits in the disability models including the International Classification of Functioning (ICF) model (Organization, 2001), and the Institute of Medicine (IOM) model (Brandt Jr and Pope, 1997), and the Disability Creation Process (DCP) model (Fougeyrollas, 2010, 1998). In the DCP, for example, environmental factors have been divided into social and physical factors that can be either obstacles or facilitators for the realization of life habits understood as social activities.

For people with disabilities, the ability to move independently is crucial to perform their daily activities and their effective engagements in social roles (Noreau and Fougeyrollas, 2000). Mobility problems reported comprise 7% of the disabilities considered in the Canadian Survey of Disability report (CSD, 2014). The mobility of people with motor disabilities (PWMD) is significantly constrained by their impairments as well as the presence of different obstacles in the environment, which affects their activities throughout their daily routines. According to the DCP model by (Fougeyrollas, 2010), the quality of social participation of people with disabilities is a result of interactions between their personal factors (identity, and physical and mental abilities) and factors of the environment in which they live. Such interactions are complex because, first of all, profiles of PWD (physical characteristics, the nature of the disability, and experiences) are very heterogeneous, and secondly, the barriers of the environment, where PWD perform their daily activities (e.g. stairs, steep slopes, narrow sidewalks, architectural barriers), are extremely variable.

Recent advances in geospatial technologies offer techniques and tools that bring solutions to assist people with disabilities (Kasemsuppakorn and Karimi, 2009; H Matthews et al., 2003; Adam D. Sobek and Miller, 2006; Voelkel and Weber, 2007; Völkel and Weber, 2008). Assistive solutions implemented based on these technologies, target improving health and security and facilitating social participation by means of providing easier navigation. Despite the advances made in recent decades to assist in the navigation of people with disabilities, current tools are not adapted for the needs of PWD and require more investigations in order to better help these people. Indeed, the existing solutions do not effectively consider the interactions between the personal factors of people with disabilities (e.g. their capabilities) and the environmental factors in the estimation of accessibility information and the computation of optimal routes. These issues may occur due to the lack of geospatial resolution (level of details), poor geographical data, and missing the adaptation of the developed algorithms to the user profile (e.g. for route computation) (Völkel and Weber, 2008). For example, one of the drawbacks of existing navigation systems is related to their databases, which are not often usable for navigation by pedestrians with disabilities. Pedestrian network databases require information about the environment in much greater details (e.g. obstacles on the sidewalks). In addition, to employ such databases for navigation of people with different capabilities, these databases should be adapted to their needs; containing user profile information, including their capabilities, as well as information about the environmental factors in relation to the mobility of people with disabilities.

This chapter presents an overview of the current models and methodologies developed for improving the mobility of PWMD and describe the challenges and problems of the existing applications. The structure of the chapter is as follows: In Section 2.2 the disability models, specifically the DCP model, are reviewed. In section 2.3, we describe mobility as one of the most important life habits in the daily activities of PWMD. In addition, we describe the impact of the perceived environmental factors and user capabilities in the mobility of PWMD. Section 2.4 reviews the existing models and applications of accessibility assessment for PWMD. In this section, three main steps of accessibility assessment, including pedestrian network segmentation, weighting of the segments' properties, and cost value computation and the challenges associated with each of these are reviewed. In addition, we investigate the process of route computation for PWMD employed in several different research studies in section 2.5 followed by a summary in section 2.6.

2.2 Disability Creation Process (DCP) model

The DCP model, as stated by Fougeyrollas et al. (1998), is an explanatory model of the cause and consequences of disease, trauma and other disruptions to a person's integrity and development. For a better understanding of the DCP model, how the DCP model is constructed, and its main components, this model is explained next.

2.2.1 Foundations of the DCP model

The Quebec Committee on the International Classification of Impairments, Disabilities and Handicaps (QCICDH) was established in 1986 to improve the International Classification of Impairments, Disabilities and Handicaps (ICIDH) model (Fougeyrollas et al., 1998). In the ICIDH model, developed by the world health organization (WHO, 1980), environmental factors were not recognized as a part of its disability model. This observation led to highlighting the importance of exploring and introducing environmental factors by the Quebec Committee. The Human Development Model (HDM) which resulted from this effort was published by Fougeyrollas et al., (1998), and explored the relation between personal factors (internal) and environmental factors (external) in social interactions. Figure. 2.1 presents the relation between the super-classes of personal factors, environmental factors, and life habits explicitly. This framework provides a generalized form of the DCP model that can be used for broader applications. In order to provide the broadest possible basis for a model of disability, the DCP model was improved gradually to adapt to different applications. The first significant modification of the DCP model was an anthropological adaptation, which facilitated understanding and modeling relations between human biology and society. The second substantial development of the model was the integration of time-changing human abilities and disabilities. This evolutionary perspective considers disability as a dynamic state, which is an intrinsic part of human development and aids in understanding how people with disabilities function as socio-environmental beings in a diachronic context.

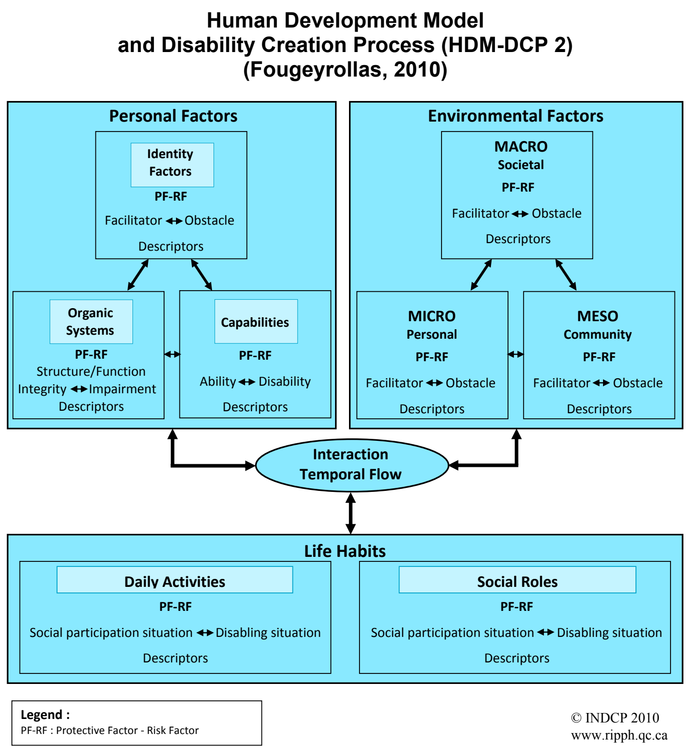


Figure. 2.1. The Disability Creation Process Model (Fougeyrollas, 2010)

2.2.2 Components of the DCP model

2.2.2.1 Personal factors

In the original DCP model, personal factors were subdivided into two categories including capabilities (abilities or disabilities) and the organic system. Capabilities refer to the potential of a person to perform mental or physical activities while the organic system refers to a group of bodily components, all sharing a common function. Therefore, impairment and disability are related to organic system and capabilities, respectively. The refinement of the DCP model made in 1998 introduced a third subcomponent of personal factors called the Identity Factors component. Identity factors include age, gender, sociocultural identity, sexual orientation, etc.

2.2.2.2 Environmental Factors

One of the most important components of the DCP model is defined with respect to the environmental factors. These factors have been divided into two categories: social factors and physical factors (Fougeyrollas et al., 1998). Physical factors are subdivided into two main sub-classes of nature and development, referring to the natural and artificial elements of reality, respectively.

Social factors are the second subclass of environmental factors in the DCP model. Social factors are elements that are related to political, economic, social and cultural systems of an environment. These factors are subdivided into political-economic and sociocultural factors. For assessing the environmental factors, a formal method called the Measure of the Quality of the Environment (MQE) was developed in the DCP framework. MQE maps major facilitators and major obstacles in seven levels from *major, moderate, and minor* obstacle through *no influence* to *minor, moderate, or major* facilitator. MQE offers a comprehensive method for assessing environmental factors including over one hundred elements that may act as either obstacles or facilitators. Note that this measurement scale only makes sense in relation to the life habits (social activities) and relevant personal variables (impairments, disabilities, abilities and identities).

2.2.2.3 Life Habits

Within the DCP model, life habits are defined as the results of the interactions between human and environment and refer to daily activities or social roles valued by persons or the socio-cultural context according to their characteristics such as identity, ability, etc. It is also worth noting that the inclusion of a life habits component in the DCP model is a way of focusing on the specific issues in relation to the disability. The concept of life habits situates elements from both personal factors and environmental factors - it is a bridging concept, and one of the significant features of the DCP model. Within the DCP model, life habits are categorized into 12 categories including nutrition, fitness, personal care, communication, housing, mobility, responsibility, interpersonal relationships, community life, education, employment, and recreation. Life habits determine the quality of social life. As for the other primary categories within the DCP model, a measurement scale is established to evaluate the quality of social life. The measurement tool presented by the DCP is called *the Quality Assessment Scale (QAS)*. The QAS measures the quality of a life habit from full social participation to a total disabling situation.

2.3 Mobility as a life habit

According to the DCP model, mobility is a life habit, which is categorized into short and long distance mobility with or without means of transportation. Mobility is one of the most important life habits that everyone performs in daily life and it is considered as a basis for other life habits (Fougeyrollas et al., 1998; Imrie, 2004; Whiteneck et al., 2004; Badley, 2008). For example, in order to take part in education (school) or employment (work), a person should be mobile (go to school/work). In addition, mobility might be a goal for other life habits in some cases. For example, the goal of mobility, instead of going from one point to another, can be to enable nutrition, community life, education, employment, and so on. Whether these goals are practical, aesthetic, or linked to entertainments, they vary from one individual to another and they also may vary for the same life habit. For example, mobility can enable one to “reach a place”, “get a sandwich” or “have fun”. Also, “walking to work” or “taking a walk” set different goals for the same life habit. These goals can affect mobility applications (e.g. route choice).

Mobility is the result of human-environment interactions (Brandt Jr and Pope, 1997; Fougeyrollas et al., 1998, 2002; Organization, 2001; Noreau et al., 2002). These interactions should be defined and characterized by considering not only environmental factors but also human factors that affect mobility. Hence, in order to model this interaction, environmental factors must be considered in relation to human factors. Modeling such interactions to characterize the mobility of PWMD is complex because user profiles are heterogeneous and environmental factors are extremely varied. In the following sections, the pertinent environmental factors related to the mobility of PWMD are investigated.

2.3.1 Environmental factors which affect the mobility of PWMD in urban areas

A pedestrian network is one of the most important facilitators in an urban area where PWMD perform their mobility activities. A pedestrian network can be represented by a geometric graph which incorporates the geometry of a pedestrian path, its segments, and the relationships (topology) among these segments (Karimi and Kasemsuppakorn, 2013). A pedestrian network is typically classified into sidewalks, crosswalks, footpaths, building entrances, trails, pedestrian bridges, and tunnels, where each of these may be composed of several segments. A segment is defined by two points, starting from one point and ending at another. Each segment has properties that can be either permanent or temporal. For example, while the slope, width, and length of a segment are considered as permanent properties, properties such as "is covered by snow" or "is under construction" are considered as temporal properties of that segment. These properties make the segment different in terms of passability (e.g. difficult to pass and easy to pass) as a function of the user's capabilities. The overall framework of a pedestrian network database (Ambler, 2005) is illustrated in **Figure 2.2**.

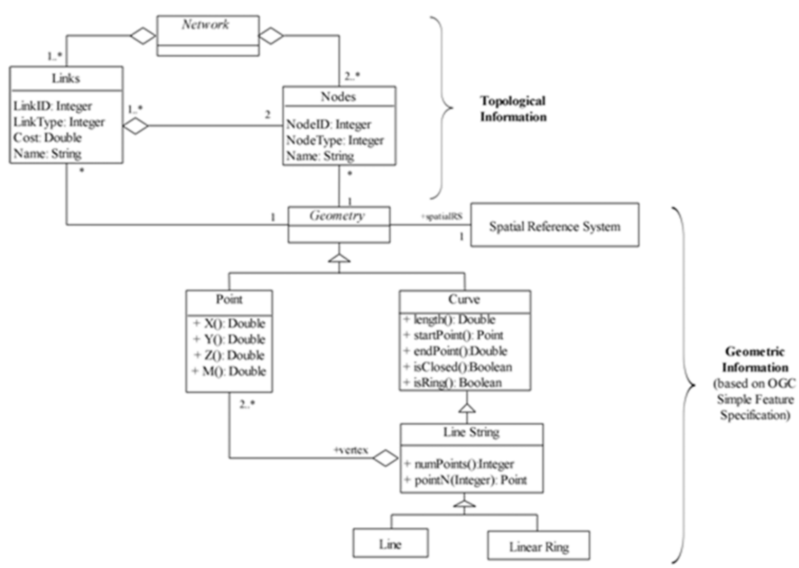


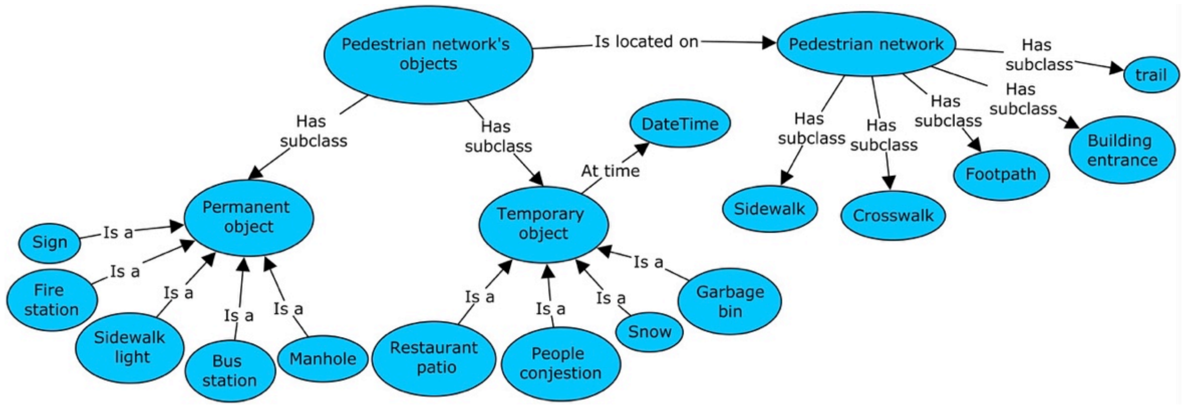
Figure 2.2 The overall framework of the pedestrian network database (Kasemsuppakorn, 2011)

Some of the properties presented in **Figure 2.2** are inherently spatial such as the slope and the width. Other properties emerge from the relationships between the components of a pedestrian network and different barriers in the environment. For example, once there is a presence of snow on a sidewalk, this may act as a barrier to certain persons. Hence, properties such as "is covered by snow" should be added to a sidewalk's properties. This property is a temporary property that will disappear after a period of time. All movable objects located on the pedestrian network belong to this temporal category. These objects might be either obstacles or facilitators based on the person's capacities.

The DCP model specifies a range from optimal facilitators to total obstacles, which define the quality of environmental factors. A facilitator refers to an environmental factor that contributes to the accomplishment of life habits when interacting with personal factors (impairments, disabilities and other characteristics of a person). An obstacle refers to an environmental factor that hinders the accomplishment of life habits when interacting with personal factors (Fougeyrollas, 1998). Each of these properties is required to be identified, quantified, and incorporated into a model for a specific application. **Figure 2.3** shows a few instances of permanent and temporal obstacles in relation with the pedestrian network.

a. Static obstacles on the sidewalk

a. Temporal obstacles on the sidewalk



c. *Pedestrian network* in relation with its temporary and permanent obstacles (Gharebaghi et al., 2017b)

Figure 2.3. Examples of obstacles and their relation with the pedestrian network

A number of studies have investigated parameters to identify significant barriers, including Kirschbaum et al. (2001), Kirby et al. (2002), Sobek and Miller (2006), Beale et al. (2006), Karimanzira et al. (2006), Kasemsuppakorn and Karimi (2009), Rushton et al. (2011), CEREMH (2011), Neis and Zielstra (2014), and Neis (2015). Investigated barriers are summarized in Table 2-1. Although pertinent, there is no evidence that most of these barriers are determined according a rigorous study involving the perception of people with disabilities or the experience of expert groups. In addition, all of them emphasize the physical properties of the environment and the social aspect is not studied. To cope with these issues, developing a mobility ontology, which formally identifies and specifies concepts from the real world that impact the mobility of PWMD, is needed. This ontology can provide an appropriate solution to specify the semantics of the concepts and their relations and provide a common of reference for the representation of the perceived barriers and their relations for PWMD.

Table 2-1. The most cited barriers in the related studies

Criterion	Sobek and Miller (2006)	Kasemsuppakorn and Karimi (2009)	Beale et al. (2006)	Kirschbaum et al. (2001)	Karimanzira et al. (2006)	Kirby et al. (2002)	Rushton et al. (2011)	Neis and Zielstra (2014)	Neis (2015)	CEREMH
Slope	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Surface quality		✓	✓	✓	✓	✓	✓	✓	✓	✓
Height changes		✓	✓	✓	✓	✓	✓	✓		✓
Width	✓	✓	✓	✓	✓				✓	✓
Surface type		✓	✓	✓		✓	✓	✓	✓	
Segment Length	✓	✓	✓		✓	✓			✓	✓
Segment type			✓				✓	✓		✓

Significant efforts have been made to define mobility ontologies of urban areas. For example, a wayfinding ontology developed by Timpf (2002) proposed multiple transportation modalities from two distinct perspectives of a traveler and a public transportation system designer. Urban ontologies proposed by Berdier and Roussey (2007) included those devoted to road systems, to urban mobility, and to issues of urban renewal. Berdier (2011) continued the research work by developing an ontology for urban mobility by integrating a road system ontology and an urban mobility ontology (**Figure 2.4**).

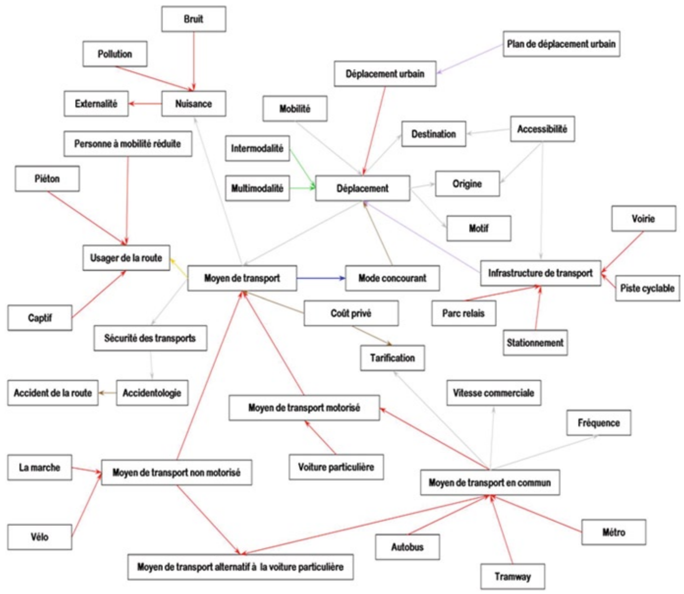


Figure 2.4. Mobility ontology in urban area; concepts and relations (Berdier, 2011)

All these aforementioned efforts focused on the identification of environmental factors in the context of mobility. One of the weaknesses, however, in many of these ontologies is that they rarely take the social aspects of the environment into account. They focus almost entirely on the physical elements and their characteristics. An effective ontology for the mobility of PWMD should address both the physical and social dimensions. In addition, in the existing mobility ontologies described above (e.g. ontologies for pedestrian networks) none of the personal factors and limitations experienced by persons with disabilities are taken into account (Berdier, 2011; Berdier and Roussey, 2007; Sen, 2008; Timpf, 2002).

Furthermore, none of the disability models effectively allows for the creation of an ontology adequate for handling the mobility of persons with disabilities, primarily because they lack depth - they do not address the environment at a fine enough level of detail. For example, in the DCP model, the interactions between environmental and personal factors as well as life habits is fairly comprehensive, however, environmental factors and their relations are presented in general terms only - it lacks the specific elements that participate in the disabling process from an operational perspective. However, it can be argued that the DCP is the most complete model among all the three models as it ensures a mutually exclusive conceptualization concerning what belongs to the individual, to the environment, and to social participation or life habits (Badley, 2008; Imrie, 2004; Whiteneck and Dijkers, 2009). Therefore, there is a need to develop a mobility ontology for PWMD that identifies the entities from the real world, which are relevant to the mobility task.

2.3.2 Challenges with definitions and evaluation of users' profiles

Environmental factors do not constitute absolute obstacles by themselves; it is only through their relationship with human factors that they can allow, hamper, or render impossible the realization of a life habit. For example, a sidewalk segment can be accessible for some people while inaccessible for others, as a result of each user's capabilities. According to the DCP, capability is a person's potential to accomplish a mental or physical activity, defined in a manner to be measured on a scale ranging from optimal ability to total disability. Indeed, capability is an intrinsic property of a person while performing activities without considering the environment. In order to evaluate the capability of wheelchair users, several approaches such as the Wheelchair Skill Test (WST) (Kirby *et al.*, 2002), the Wheelchair Circuit (Kilkens *et al.*, 2004), the Wheelchair Outcome Measure (WhOM) (Mortenson *et al.*, 2007), and WheelCon (Rushton *et al.,* 2013) have been developed. WheelCon and WST were developed specifically for studying the mobility of wheelchair users and are briefly explained below.

2.3.2.1 The Wheelchair Mobility Confidence Scale (WheelCon)

WheelCon is one of the most reliable approaches for evaluating capabilities of wheelchair users. In this approach, the user's confidence level for a mobility task is evaluated and expressed using a value between 0 (low confidence) to 100 (high confidence). The purpose of this approach is to assess users' confidence levels using wheelchairs while performing various tasks and activities (Rushton *et al*., 2011). The questionnaire covers both manual and motorized wheelchair users. The questionnaire includes 65 items, which were identified by a three-round Delphi survey among a panel of experts (43 experts), of which 30 percent were wheelchair users. The items identified in this survey include both indoor and outdoor factors affecting the mobility of people with disabilities.

2.3.2.2 Wheelchair Skill Test (WST)

The WST is a standardized evaluation method that is intended to assess a specific person in a specific wheelchair in a standardized manner. The WST is " a 32-item objective evaluation of an individual's ability to perform various wheelchair skills. Spanning the spectrum from those as basic as rolling the wheelchair forward to those as difficult as ascending/descending stairs" (Kirby et al., 2002). The tester scores the success in accomplishing each skill ranging from 0 to 2, meaning fail, pass with difficulty, and pass easily, respectively.

In the following section, we aim to investigate existing applications, which compute optimal routes for moving PWMD along a path from origin to destination, which also take into account the human-environment interactions. However, effective routing requires first and foremost an understanding of the needs of PWMD in determining their desired routes.

2.3.3 Accessibility as the basic criterion in the mobility of PWMD

Computing optimum routes depends on the profile of the users. People with disabilities are often classified into diverse groups such as people with motor disabilities (PWMD) and people with visual disabilities. Each group of users has navigation preferences. For instance, PWMD may prefer a route with less slope or specific surface types. Although several navigation systems exist for pedestrians, most of them are not usable for people with disabilities. One of the major issues of available navigation systems is that most of them use a single optimization criterion only (such as travel time or shortest distance). People with disabilities have very heterogeneous profiles and their needs, capabilities, and preferences are different. Hence it is important to consider this heterogeneity in the computation of optimal routes. In other words, whether a certain route is better than another one depends on the user capabilities and user preferences. Among these preferences, a few are more essential and fundamental than others. Inspired from the walkability hierarchy developed by Alfonzo (2005), these needs and preferences are determined for route computation (Figure 2.5). In the hierarchy of a walking needs model, the walking decision-making process is categorized into five levels of needs. These needs progress from the most fundamental need, feasibility (i.e. related to personal limits) to higher-order needs (i.e.

related to urban form) that include accessibility, safety, comfort, and pleasure, in sequence.

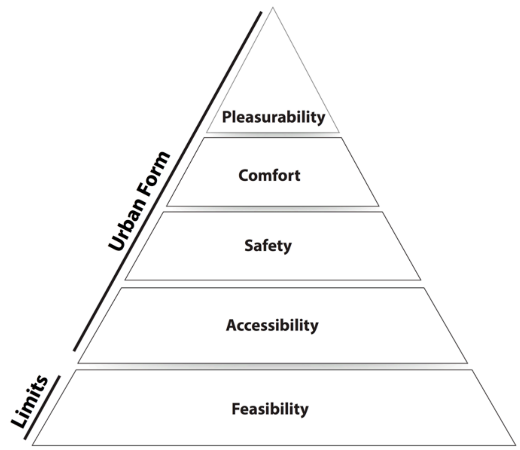


Figure 2.5. Walkability Hierarchy (Alfonzo, 2005)

The same hierarchical structure can be used and justified to prioritize the needs of PWMD in the procedure of routing for them. In this hierarchical structure, a higher-order need is not considered if the most basic need (e.g. accessibility) is not already met. For example, the landscape and scenery of a route as a need for pleasure is not taken into account while the accessibility of that route is not satisfied. In the hierarchy of walking needs model, feasibility is considered as a criterion that is mostly affected by the individual's physical condition, age, and weight. In our research, we assume that PWMD are capable by using mobility assistive technologies, such as wheelchairs, for mobility. Thus, the accessibility would be considered as the basic criterion in the routing computation for PWMD.

The aforementioned issue might be adjustable by most PWMD; however, compensation of the insufficient information is impossible. Employing additional requirements imposed by PWMD in the navigation systems would facilitate navigation for this group of people. In order to compute an optimal accessible route for PWMD, the following steps need to be conducted: 1) the evaluation of the accessibility level for each segment based on capabilities and preferences, and 2) computation of the optimal routes for an origin-destination pair. Thus far, a number of studies have been published investigating these steps. Although pertinent, no single study exists which carries out this process completely and significant weaknesses are still present. In the following section, we elaborate this workflow and investigate the challenges and drawbacks of existing studies.

2.4 Evaluation of network accessibility

In order to evaluate the accessibility level of network segments, we need to determine a weight for each segment based on individuals' preferences and capabilities that indicate how favourable each segment is for a travel. This weight is considered as the cost value of each segment and varies in different contexts. It could be related to distance, time, accessibility and so on. Weighted segments are then used in the route calculation step where an algorithm considers each segment's weight in order to determine an optimal route. The cost value evaluation is carried out in two steps. First, we should quantify the weight for each parameter of the segment, and then the aggregation of the weights should be carried out. Over the past two decades, several studies have investigated the accessibility of urban areas for people with disabilities using various methods. In the following paragraphs, relevant studies, challenges, and limitations are presented.

Matthews et al. (2003) and Beale et al. (2006) used a Geographical Information System (GIS) to generate accessibility maps for wheelchair users within a project called *Modelling Access with GIS in Urban Systems (MAGUS)*. MAGUS employed the feedback of wheelchair users to identify the most important barriers, quantify the barriers, and consequently incorporate them into the GIS model. They identified and then quantified 10 key barriers that impede access and mobility in urban environments including steps, deep gutters, narrow pavement, ramps/local slope, cambers, poor pathway maintenance, raised manhole covers, fixed street furniture, and (un)supervised crossings. In MAGUS, the impedance value of each segment was calculated using mathematical models and then the optimal routes were calculated. These calculations took six routing criteria into account, namely, shortest distance, minimum barriers, fewest slopes, avoiding bad surfaces, using only controlled crossings, and limited road crossings. This model is a sophisticated one that necessitates using information about sidewalk parameters from user perceptions.

Sobek and Miller (2006) developed and implemented a web-based routing system called *U-Access*. This tool facilitates the navigation of pedestrians with different capabilities. *U-*

Access provides a pre-planning tool for a trip using shortest feasible route as a criterion. In this model pedestrians were categorized into three levels of capability, unaided mobility, aided mobility, and wheelchair users. The pedestrian network in *U-Access* included sidewalk features (minimum width, minimum step height), qualities of entranceways (door handles, minimum step height, width), parking (width), ramps (slope, width, turn radius), and curb cuts (minimum step height, width). Sobek and Miller (2006) showed that the total distance of routes adopted by wheelchair users was longer than the total distance of routes used by unassisted users. In addition, this study showed that removing three obstacles in the wheelchair route led to a significant decrease in the total distance traversed.

Jonietz et al. (2013) and Jonietz and Timpf (2013) proposed a framework for modeling spatial-suitability of pedestrian networks based on affordance theory. Proposed frameworks assessed suitability determined by characteristics of users, their environment, and interactions between these. The suitability value obtained by combining pairs of environmental properties and human capabilities was calculated by these models. Environmental properties such as trip distance and sidewalk slope were used to rate the suitability of paths. This model was implemented in a navigation scenario for five persons with different abilities with respect to segment slopes and presence of stairs.

Tajgardoon and Karimi (2015) proposed an approach based on a weighted linear model for different characteristics of sidewalk segments to evaluate the accessibility of sidewalks for PWMD. These characteristics included segment distance, slope, width, surface quality, and different sidewalk traffic zones. They developed this approach to simulate and visualize accessibility for two groups of PWMD as well as blind users.

Kasemsuppakorn and Karimi (2009) developed a model to personalize routing for wheelchair users focusing on user priorities and sidewalk parameters. Three weighting methods were used in this research: the Absolute Restriction Method (ARM), the Relative Restriction Method (RRM) and the Path Reduction Method (PRM). Each method was carried out in four steps: (1) weighting the sidewalk parameters, (2) quantifying the impedance value of each segment, (3) modeling the routes for wheelchair users, and (4) choosing the optimal route. They employed an Analytical Hierarchy Process (AHP) and a fuzzy logic approach to weigh and quantify the impedance of each segment, respectively. This method was further evaluated via participation of five wheelchair users (Kasemsuppakorn et al., 2014).

Continuing Kasemsuppakorn and Karimi (2009)'s work, Hashemi and Karimi (2016) employed the AHP approach instead of the fuzzy logic method to assign an impedance value for each segment. They applied a Z-test to statistically compare the accessibility of computed routes for the routes offered by Kasemsuppakorn and Karimi's (2009) approach. This research showed that the AHP approach provided more accessible routes compared to applying the fuzzy logic approach employed in the previous research work. In addition, a collaborative wayfinding approach was presented to update and augment the sidewalk database. In this approach, the feedback from the users was captured and reflected in the future optimal routes. In order to enhance the satisfaction of the users regarding the computed routes, they assigned the feedback of diverse wheelchair groups only to the routes of that given group. The quality of the suggested routes was assessed by users and then employed to adjust the database. They stated that the proposed routes were more viable as user's feedbacks were incorporated.

In another attempt, Neis (2015) introduced a novel approach to assess and evaluate a personalized routing algorithm for PWMD influenced by wheelchair users' restrictions and needs. The routing approach was embedded on a network, which was based upon the Volunteered Geographic Information (VGI) derived from the Open Street Map (OSM). Since the VGI dataset quality is not completely consistent, the author proposed a reliability factor for the computed routes, by which wheelchair users could obtain extra information on the quality of the generated routes. The reliability factor was calculated based on dividing the length of segments that contain available value for the potential barriers by the total length of that route multiplied by the individual weights. This algorithm was evaluated and tested for an area in Bonn, Germany.

All of the above studies have considered human-environment interactions in the evaluation of accessibility of a pedestrian network. However, they have only evaluated the physical aspect of the environment and ignored the impact of the social aspect on accessibility for

PWMD. To address this issue and in order to quantify the accessibility level of network segments, three steps were carried out, including: 1) segmentation of the network, 2) weighting of the different properties of each segment, and 3) calculating the cost value for each segment by aggregating the different weights which should be conducted. The following section explains each step in detail.

2.4.1 Pedestrian network segmentation

Generally, in databases for urban areas, the path segments are defined within road networks between two intersections and contain more than one attribute such as slope, surface quality, and width. These attributes often are not constant and change along the segment. In such databases, it is necessary to employ an appropriate algorithm to subdivide these segments into the segments for which the attributes are constant. Hence, the segmentation of the pedestrian network is the first step for measuring and mapping accessibility. The segmentation process includes three steps: 1) extracting the center lines of the network, 2) ensuring their connectivity and consistence, and 3) segmentation based on their static (permanent) and temporal parameters. The centre lines of the pedestrian network could be extracted (if not already available in the city database) employing existing algorithms such as the Straight Skeleton algorithm, which was developed by Aichholzer et al. (1995). In this method, each path polygon is used to generate the topological skeleton, including a large number of small straight-line segments. The small segments could be then simplified by employing another algorithm such as the Douglas Peucker algorithm (Douglas and Peucker, 1973). The center lines are then segmented by breaking these whenever a change happens in each static property along the segment. For example, once the slope value, the width value, and the surface quality of the segment is significantly changed, a new segment is generated.

The segmentation process is extended to generate new segments based on the temporal parameters such as segments under construction or segments that are covered by snow. Employing a dynamic segmentation approach is an appropriate approach to carry out this process (Weigang and Guiyan, 2009). In dynamic segmentation, segments are located dynamically by changing attribute values without splitting linear features (Jennifer Cadkin, 2002). In this process, attribute information is combined with linear objects located on the ground. Dynamic segmentation of a linear feature requires a unique identifier for each event (linear/point) as well as the event position along the linear feature. This position is used to assign attributes to the corresponding linear feature using a linear referencing measurement system.

In the linear referencing method, the geographic locations are stored by using relative positions along a measured linear feature. This method facilitates employing urban databases for various applications such as transportation planning, traffic modeling, traffic accident modeling as well as pedestrian navigation.

Figure 2.7 and Table 2-3 show how the network's attribute table is modified in dynamic segmentation without adding new nodes or changing the topology of arc-node structure. To add the dynamic segment, a linkage as a new data type should be inserted to the primary database. Thus, the relative positions of start and end points are stored by the linkage. In addition, the geometric data of generated arc can be calculated using relative positions of dynamic nodes in the start and end of the linkage. In the conventional approaches, for example arc-node data model, the arc spatial table is established by storing linear features and is managed using basic units of arc. The attribute table is then created and assigned to basic arcs. **Figure 2.6** and Table 2-2 present a road network topology in a road network. However, the main drawback is that adding an attribute for a segment that is partly located on an arc is impossible.

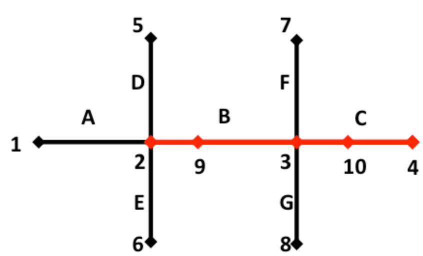


Figure 2.6. Arc-node model (Weigang and Guiyan, 2009)

Table 2-2. Arc-node relationship (Weigang and Guiyan, 2009)

Arc ID	A	B	C	D	E	F	G
F-DNode	1	2	3	5	2	7	3
T-DNode	2	9	10	2	6	3	8

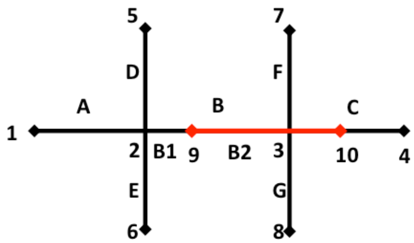
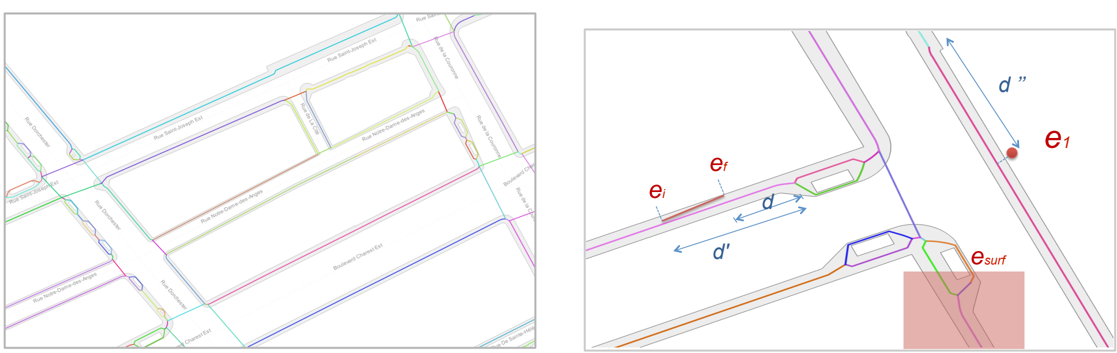


Figure 2.7. Dynamic segments (Weigang and Guiyan, 2009)

Table 2-3. Link-dynamic-node relationship (Weigang and Guiyan, 2009)

Arc ID	A	B	B	C	C	D	E	F	G
LinkID	A	B1	B2	C1	C2	D	E	F	G
F-DNode	1	2	9	3	10	5	2	7	3
T-DNode	2	9	3	10	4	2	6	3	8

In this process, the events are classified into punctual, linear, and surface (polygon) events. This process analyzes the influence of events on the permanent segments. The linear referencing is used only for visualization of accessibility level of each segment. **Figure 2.8** shows this process. Once the segmentation of pedestrian network is carried out, the accessibility of each segment can be assessed. The accessibility assessment process is explained in the following section.



a. Primary segmentation regarding the static parameters

a. Secondary segmentation regarding temporal parameters

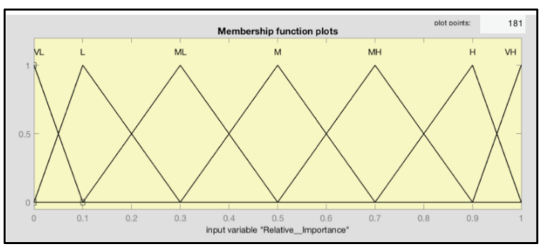
Figure 2.8. Segmentation process

2.4.2 Weighting process for parameters

Accessibility of a pedestrian network depends on several factors with different levels of impact. We need to weight these factors based on the individual's preferences and capabilities. The weighting approach might vary from one individual to another, and can be obtained in two ways: 1) assigning a rate directly for each criterion based on users' perceptions, or 2) calculating this rate using pair-wise comparison approaches such as the Analytical Hierarchy Process (AHP, Saaty, 2008).

2.4.2.1 Direct weighting with linguistic variables

One of the ways to weight different barriers is to ask the users to assign a rate value directly to each barrier. The rating process might be performed using a number or a linguistic variable with different range of values. For example, according to Chen (2000), linguistic variables for rating criteria can be categorized in seven classes: *very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H)* and *very high (VH)*. **Figure 2.9** shows fuzzy set values chosen by Chen (2000) for rating classes related to PWMD's accessibility criteria (see section 2.4.3 below for more details on the definition and use of fuzzy logics)..



Fuzzy set	Fuzzy numbers
Very low (VL)	(0,0,0,0.1)
Low (L)	(0,0.1,0.1,0.3)
Medium low (ML)	(0.1,0.3,0.3,0.5)
Medium (M)	(0.3,0.5,0.5,0.7)
Medium high (MH)	(0.5,0.7,0.7,0.9)
High (H)	(0.7,0.9,0.9,1.0)
Very high (VH)	(0.9,1.0,1.0,1.0)

Figure 2.9. Membership function, fuzzy sets, and fuzzy numbers of potential rate of criteria (Chen, 2000)

2.4.2.2 Indirect weighting employing the pairwise comparison approaches

The analytical hierarchy process (AHP) is a pairwise comparison method that can facilitate comparing physical and social barriers for accessibility assessment. The AHP developed by Satty (1980) is based on mathematics and psychology and is defined as a method to analyze complex decisions. This decision making approach is employed in various applications such as determining dynamic priorities, conflict resolution, planning and development, alternative optimization, resource allocations, and optimization (Vaidya and Kumar, 2006).

In related research relevant to our study, Kasemsuppakorn and Karimi (2009) used AHP to compare the difficulty level of barriers (Figure 2.10). Nardo et al. (2005) discussed the advantages and drawbacks of existing weighting approaches and highlighted two benefits of AHP, that is, as a technique that can be used for comparing both qualitative and quantitative data and its dependence on an expert opinion, not on technical manipulations.

Which parameter prevents your mobility more than the other?

Parameter	Extremely	Very Strongly	Strongly	Moderately	No Difference	Moderately	Strongly	Very Strongly	Extremely	Parameter
Slope					✓					Steps
Slope			✓							Width
Slope		✓								Distance
Slope						✓				Sidewalk surface
Slope				✓						Sidewalk traffic
Steps			✓							Width
Steps	✓									Distance
Steps			✓							Sidewalk surface
Steps		✓								Sidewalk traffic
Width		✓								Distance
Width									✓	Sidewalk surface
Width					✓					Sidewalk traffic
Distance									✓	Sidewalk surface
Distance			✓							Sidewalk traffic
Sidewalk surface	✓									Sidewalk traffic

Figure 2.10. An example of AHP (Kasemsuppakorn and Karimi, 2009)

Figure 2.10 depicts an example of AHP used for a comparison between segment properties. In this example, the criteria are weighted based on a scale value that is calculated using a pairwise comparison between all criteria (Kasemsuppakorn and Karimi, 2009). A scale range from 1-9 for the 'least valued than', to 1 for the 'equal', and to 9 for the 'absolutely more important than' is used to cover all possible comparisons (Vaidya and Kumar, 2006). An array that contains compared pairwise values is formed. This array, also called the judgmental array, is used for the priority computation. The Eigen value approach is applied to this array to derive the normalized Eigen vector as a vector of priorities.

2.4.3 Aggregating difficulty values

There are different methods that can be used for aggregating difficulty values assigned to barriers within the segments. The aggregation procedure is a key step in the whole process of evaluating the total accessibility value of a segment. Despite its simplicity, in some cases, common approaches such as weighted linear models might not properly model the final accessibility value in complex cases. To address this issue, a set of aggregating approaches including fuzzy logic, TOPSIS and fuzzy TOPSIS are explained in the following section.

2.4.3.1 Fuzzy logic approach

Fuzzy logic or the theory of fuzzy sets is a widely used approach in geographic information sciences for the presentation of boundaries of spatial objects that are not sharp. Zadeh *et al.* (1965) introduced fuzzy logic to model the vagueness that is associated with human cognitive processes. Fuzzy logic is also recommended for decision-making in frameworks where different sources of uncertainties exist. Fuzzy logic is also widely used for routing and transportation planning. In these applications, ambiguous input data such as perceived travel time in transportation is incorporated into models using fuzzy logic-based approaches ((Teodorovic and Kikuchi, 1990), and (Akiyama and Tsuboi, 1996)).

In routing applications, to define the impedance (cost) level for each sidewalk segment, Kasemsuppakorn & Karimi (2009) employed a fuzzy logic approach based on a wheelchair user's perception of sidewalk attributes that affect his or her mobility. In this method, the decision-making process was simulated to facilitate characterizing the uncertainties associated with sidewalk characteristics. In another similar research, Kasemsuppakorn and Karimi (2009) combined a Fuzzy logic method and an Analytical Hierarchy Process (AHP) technique to calculate the impedance value of each segment. Fuzzy decision systems were also used by Karimanzira *et al.* (2006) to eliminate impossible pathways with respect to the type of disability.

To employ a fuzzy logic method, three general steps must be followed (Figure 2.11): (1) build the rule set and define the membership functions (fuzzification), (2) make a fuzzy inference system (FIS) using if-then rules and analyze its behaviour and (3) merge the outputs of the rules and ensure defuzzification of the results using a different set of membership functions to derive output variables (Mamdani and Assilian, 1975). Employing a rule-based approach such as fuzzy logic, for aggregating the difficulty of overcoming barriers for each segment, allows assigning a unique difficulty scale (cost value) for each segment considering the user capabilities. Figure 2.11 illustrates an example of a fuzzy logic system including its components.

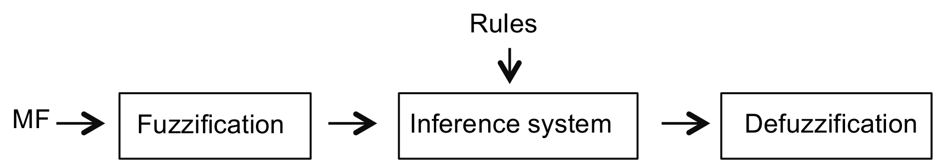


Figure 2.11. A general workflow a fuzzy logic system

One of the main challenges in developing fuzzy systems is defining accurate rules for reasoning about the information. Rules can be extracted from diverse sources including domain experts, data clustering, and machine learning algorithms. Using each of these methods might be associated with different questions. For example, can developers define the rules themselves? Can developers understand the expert well enough to transcribe accurate rules? Does an expert understand fuzzy logic? Can an expert define rules directly? Can an expert verify the rules created by a developer?

2.4.3.2 TOPSIS and Fuzzy-TOPSIS approach

In addition to a fuzzy logic system, a cost value computation process can be also framed on multicriteria decision-making approaches (MCDM). TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and the Fuzzy-TOPSIS approach (Chen, 2000) are examples of such multicriteria methods. TOPSIS is initially introduced and further developed by Hwang and Yoon (2012). It is a widely used approach to rank solutions in the MCDM, especially where limited subjective input is needed from decision makers (Olson, 2004). The basic principal of this method is to find a best alternative solution that has shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. The positive ideal solution maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria (Behzadian et al., 2012). In summary, the positive-ideal solution is composed of all best values attainable from the criteria, and the negative-ideal solution consists of all the worst values attainable from the criteria (Krohling and Pacheco, 2015).

For instance, in order to apply the TOPSIS approach to the accessibility measurement process, the following steps should be conducted: (1) Define a set of importance weights W_n for the optimisation criteria (ex. slope, width); (2) identify the ideal accessibility state (the best condition, A^*); (3) identify the worst accessibility state (the worst condition, A^-); (4) determine the distance of a given array from the ideal and worst case (d_i^- and d_i^*); and finally, (5) calculate the accessibility index as a ratio AI(accessibility index) equal to the distance to the worst state divided by the sum of the distance to the worst state and the distance to the ideal state. TOPSIS minimizes the distance to the ideal alternative while maximizing the distance to the worst.

The advantage of TOPSIS is its ability to identify the best alternative solution very efficiently (Olson, 2004; Parkan and Wu, 1997). An extension of the TOPSIS approach into the fuzzy environment is called Fuzzy-TOPSIS, which can be also be an appropriate solution to solve the problems characterized by the presence of uncertainties. The calculated AI can be used for the visualization of the accessibility level of a pedestrian network for the mobility of PWMD. Figure 2.12. shows an example of mapping of the accessibility levels where a "Not Accessible" segment is represented with a red line, "Low Accessible" segments are yellow, "Accessible" segments are green, and "Very Accessible" segments are dark green.

Figure 2.12. An example of accessibility visualization

2.4.4 Challenges related to the consideration of social factors for the mobility task

Environmental factors are characterized as physical or social. In previous sections, we attempted to analyze the impact of physical factors of the environment on the accessibility of urban areas. However, in some cases, the influence of social factors is more pronounced compared to physical factors. For instance, a patio on the sidewalk affects the accessibility of the sidewalk for PWMD. Although the presence of the patio belongs to the physical environment, the main cause is related to the municipal regulations, which allows the use of a major part of sidewalks by restaurants. These regulations can produce many obstacles for wheelchair users and passing the sidewalk becomes more difficult. In another example, **Figure 2.13** shows several physical entities on the sidewalk. These barriers affect the accessibility of this part of sidewalk for everyone, especially for PWMD. Although these entities belong to the physical environment, the main cause of the presence of these barriers is related to social behaviour or urban decisions and hence should be considered as a social factor.

Figure 2.13. Presence of barriers on the sidewalk because of inadequate social rules

According to the DCP model, the social dimension of an environment is very important and should be taken into account in the accessibility assessment of the pedestrian network. The social environment includes political, economic and cultural factors (Fougeyrollas, 2010; Oliver, 1996). As mentioned in previous sections, in the Human Development Model - Disability Creation Process (HDM-DCP) (Fougeyrollas, 2010, 1998), the environment is partitioned into two parts: physical and social. In this model, the relevant social factors are classified into political-economic and sociocultural factors (see the taxonomy in **Figure 2.14**). Political-economic factors include structures and operational modes and services of different systems of governance, whereas the sociocultural factors refer to structures and operational modes of an individual's relationships with other members of society. Norms, policies, culture, and financial issues are only a few examples of social factors.

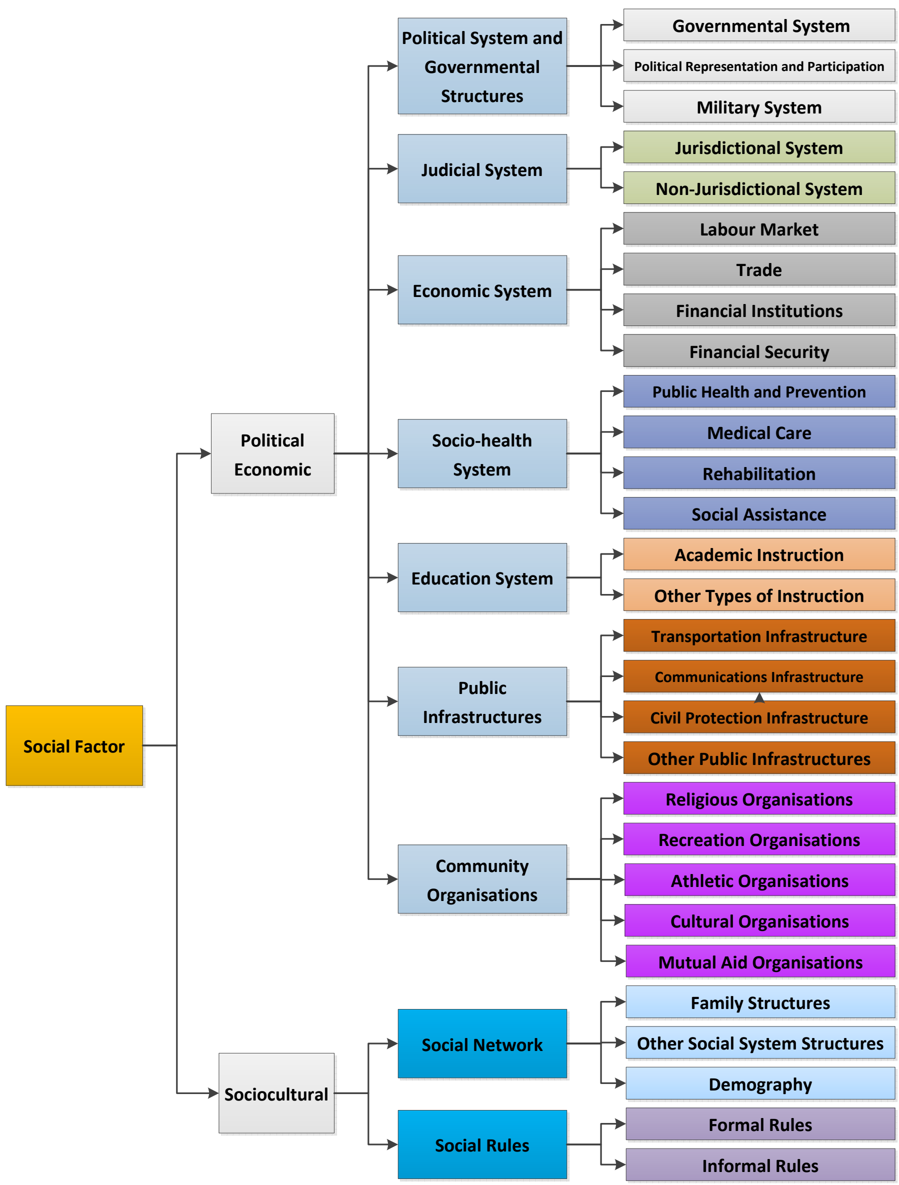


Figure 2.14. Social factors taxonomy (Fougeyrollas, 1998)

To our knowledge, there are only a few studies in the literature that consider how the social aspects of environment affect the mobility of PWMD (e.g., (Mackett et al., 2008), (Tansawat et al., 2015), (Anciaes and Jones, 2016), (Morales et al., 2014). Among these, Mackett et al. (2008) developed a software tool called AMELIA (A Methodology for

Enhancing Life by Increasing Accessibility) to show the impacts of transport policy, as a social factor, on the social inclusion of elderly people and PWD. They tested the influences of applying four new policies to improve the accessibility of downtown St Albans for PWD. The influence of policies was quantified and visualized on a city map. They showed that providing benches as an urban design policy would provide the most cost-effective policy to increase the accessibility of their study area. In another study, Tansawat et al. (2015) showed that the average income of families has a significant relationship with regard to social inclusion. This study investigated the influence of free public train policies on the improvement of the social participation of low-income people. Anciaes and Jones (2016) analyzed the influence of interventions, which sought to reduce barriers on the pedestrian network. These interventions include changing the layout of the local street networks and redesigning busy streets. They investigated how employing new interventions such as increasing the density and connectivity of the links available to pedestrians, adding crossing facilities, reducing the speed limit, or reallocating road space to pedestrians can affect the walking pattern in the pedestrian network. In another effort, Morales et al. (2014) investigated design solutions to improve the accessibility of sidewalks for seniors, wheelchair, and walker users during winter conditions. They observed that existing snow removal policies were not adequate enough to provide the accessibility required for PWMD. Morales et al. (2014) proposed applying new policies to remove snow from the sidewalks. Although most of these studies propose solutions in order to increase the social inclusion of PWMD, little evidence is offered to strongly support their assertions. Therefore, there is still need to investigate the effectiveness of the role of social factors on the accessibility of urban areas for PWMD, which can be used as a decision-making tool for the authorities of a city.

2.5 Computation of optimal accessible routes

Routing is a process that calculates an optimal route based on a criterion such as shortest distance, fastest travel time, least number of intersections, and absence of tolls, among others. The criterion adapted is applicable to the addresses of the origin-destination pairs. Required data for the routing is the road/sidewalk network that conclusively provides the topology of the network. Routing functions use exact or heuristic algorithms for the optimal route computation. All possible paths between origin and destination are considered in an exact algorithm, while in a heuristic algorithm, only a subset of possible solutions are considered based on experience (Karimi, 2011). Figure 2.15 presents an example of solutions proposed by exact and heuristic algorithms. Here, the heuristic algorithm clipped the entire network (solution space) to a smaller one (shown by a blue box in the plot); using the sub-network, only a few of routes are considered to find a solution, which may be acceptable but not optimal. In order to choose an exact or a heuristic algorithm, acceptable response time (especially in real time routing), network size (total number of nodes), and computational power of a navigation device should be considered.

Fig. 2.12 An optimal route computed by an exact algorithm and a non-optimal route computed by a heuristic algorithm

Figure 2.15. The computed routes employing an exact algorithm and a heuristic algorithm (Karimi, 2011)

For the determination of an optimal accessible route, the cost function simply sums the cost (i.e. accessibility index) of all segments of a given route. As explained earlier, the accessibility index is calculated by aggregating the characteristics of each segment. These characteristics include properties such as the length, slope, width, or surface quality of the segment. In general, an accessible route is obtained by solving the corresponding minimization problem. To provide a proper analysis framework to find the optimal route, depending on a particular choice of impedance (i.e. cost), several wayfinding algorithms are used including Dijkstra’s algorithm (Dijkstra 1959), the A* search algorithm (Dechter and Judea 1985), Bellman -Ford's algorithm (Cavendish and Gerla, 1998), and the Floyd-Warshall algorithm (Floyd 1962). Analysis of these algorithms is given in Table 2-4.

Table 2-4. Comparison of different wayfinding algorithms (Sanan et al., 2013)

Algorithm	Description	Advantages/Disadvantages
Dijkstra	1) A Greedy based algorithm and solves the single-source shortest path problems; 2) Doesn't work for negative weight edges; 3) Require global information of the network	1) The major disadvantage of the algorithm is the fact that it does a blind search there by consuming a lot of time waste of necessary resources; 2) It cannot handle negative edges. This leads to acyclic graphs and most often cannot obtain the right shortest path.
A*	1) A* algorithm is a graph/tree search algorithm that finds a path from a given initial node to a given goal node 2) It employs a "heuristic estimate" h(x) that gives an estimate of the best route that goes through that node. 3) It visits the nodes in order of this heuristic estimate. 4) It follows the approach of best first search and and finds a least-cost path from a given initial node to one goal node.	1) The algorithm is complete if the branching factor is finite and every action has fixed cost; 2) The speed execution of A* search is highly dependant on the accuracy of the heuristic algorithm that is used to compute h (n); 3) It has complexity problems
Bellman-Ford	1) Bellman-Ford is a Dynamic Programming based algorithm; 2) Bellman-Ford works for negative weight edges; 3) Uses only local knowledge of neighbouring nodes	1) We can minimize our cost when we build a network; 2) Bellman-Ford algorithm also can maximize the performance of your system. The algorithm will find the minimum path weight. Path weight is propagation delays for a system.
Floyd–Warshall	1) This algorithm solves all pair's shortest paths problem in an edge directed graph; 2) This algorithm works with positive or negative edge weights; 3) This algorithm does not work with any negative cycle; 4) This algorithm doesn't find the paths; 5) This algorithm finds only their minimum path lengths.	1) It helps to find the shortest path in a weighted graph with positive or negative edge weights; 2) A single execution of the algorithm is sufficient to find the lengths of the shortest paths between all pairs of vertices. 3) It is easy to modify the algorithm and use it to reconstruct the paths; 4) Versions of the algorithm can be used for finding the widest paths between all pairs of vertices in a weighted graph or transitive closure of a relation R.

2.6 Summary

In this chapter, the aim was to review the existing published research and its limitations concerning the accessibility assessment process as well as the computation of the optimal routes for PWMD. This literature review was organized around three main processing steps for the assessment of accessibility of a pedestrian network and the computation of an optimal accessible route for PWMD. First, we showed that the most important obstacles and facilitators from the PWMD perceptions need to be identified. To do so, relevant methods and tools from both the geographic information sciences and disability and rehabilitation domains were investigated and their strengths and limitations were discussed. Next, the accessibility assessment process based on the wheelchair user's capabilities was investigated. We showed that existing approaches have significant limitations in terms of the considering the user capabilities in their route choices. Next, we showed that most of the existing solutions for the mobility of people with disabilities do not consider the role of social factors in the assessment of accessibility for the mobility of PWMD. Finally, as the third processing step, methods for computing optimal routes for a pair of origins and destinations were reviewed. We explained that the existing personalized optimal route applications have weaknesses with respect to considering the direction of the routes.

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3 Ontologie de la mobilité

3.1 Résumé

Contexte: Notre compréhension contemporaine d'un handicap est enracinée dans l'idée que le handicap est le produit des processus d'interactions « humain-environnement ». Les personnes peuvent être limitées sur le plan fonctionnel, mais cela ne devient un handicap que lorsqu'elles s'engagent dans leurs environnements social et physique immédiats. Toute tentative visant à résoudre les problèmes de mobilité par rapport aux personnes handicapées devrait être fondée sur une ontologie englobant cette compréhension. *But:* L'objectif de cette étude est de fournir une méthodologie pour intégrer les environnements social et physique dans le développement d'une ontologie de la mobilité pour les PMR. *Méthodologie :* Nous proposons de créer des sous-classes de concepts basés sur une distinction « nature-développement » plutôt que de créer des sous-classes sociales et physiques distinctes. Cela permet de modéliser les relations entre les éléments sociaux et physiques de manière plus compacte et efficace en les spécifiant localement au sein de chaque entité et de mieux prendre en compte les complexités des interactions « humain-environnement ». Sur la base de cette approche, une ontologie de la mobilité des PMR considérant quatre éléments principaux, soit les facteurs environnementaux, sociaux et physiques, les facteurs humains, les habitudes de vie liées à la mobilité et les objectifs possibles de mobilité, est présentée. *Conclusion :* Nous démontrons que l'utilisation de la perspective « nature-développement » facilite le processus de développement d'ontologies utiles, en particulier pour définir les relations entre les parties sociales et physiques de l'environnement. C'est une question fondamentale pour la modélisation de l'interaction entre les humains et leurs environnements social et physique pour un large éventail d'applications, y compris le développement de technologies d'assistance géospatiales pour la navigation des PMR.

Corps de l'article

Titre: Integration of the social environment in a mobility ontology for people with motor disabilities

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Revue: Disability and Rehabilitation: Assistive Technology

3.2 Abstract

Background: Our contemporary understanding of disability is rooted in the idea that disability is the product of human-environment interaction processes. People may be functionally limited, but this becomes a disability only when they engage with their immediate social and physical environments. Any attempt to address issues of mobility in relation to people with disabilities should be grounded in an ontology that encompasses this understanding. *Purpose*: The objective of this study is to provide a methodology to integrate the social and physical environments in the development of a mobility ontology for people with motor disabilities (PWMD). *Methods*: We propose to create subclasses of concepts based on a *Nature-Development* distinction rather than creating separate social and physical subclasses. This allows the relationships between social and physical elements to be modeled in a more compact and efficient way by specifying them locally within each entity, and better accommodates the complexities of the human-environment interaction as well. *Based on this approach,* an ontology for mobility of PWMD considering four main elements – the social and physical environmental factors, human factors, life habits related to mobility, and possible goals of mobility – is presented. *Conclusion:* We demonstrate that employing the *Nature-Development* perspective facilitates the process of developing useful ontologies, especially for defining the relationships between the social and physical parts of

the environment. This is a fundamental issue for modeling the interaction between humans and their social and physical environments for a broad range of applications, including the development of geospatial assistive technologies for navigation of PWMD.

Keywords: Ontology, mobility, disability, social environment, physical environment, GIS, models, semantic networks

3.3 Introduction

An obvious way to assist PWMD in their efforts to move around in urban areas is to provide them with information concerning accessible paths, that is, taking into account their functional limitations. Indeed, ensuring safe, usable and accessible navigation in urban areas for PWMD can substantially enhance their opportunities for full social participation and the exercise of their fundamental human rights. Several attempts have been made to develop navigation tools for PWMD, for example, within pedestrian networks. In most of these projects, perspectives from communities such as geomatics, computer science, cognitive science, health and rehabilitation science are used to identify and define environmental obstacles and facilitators for mobility of PWMD. Heterogeneity in specification of concepts and their definitions often complicates the collaboration and knowledge sharing between these disciplines. To address this issue, an ontology can provide an appropriate solution to integrate the diverse semantics and thereby provide a common frame of reference, so as to share vocabulary (Kuhn and Raubal, 2003), facilitate knowledge sharing, and build a collaboration framework across such different disciplines (Timpf, 2002).

In philosophy, an ontology is considered to encapsulate the underlying nature of a thing, that is, categories of reality and being(Landau, 1937), while in linguistics, ontologies are independent terminologies of a common thing in different communities (Chiarcos, 2012). In Artificial Intelligence (AI) and computer science, on the other hand, ontology refers to "a formal, explicit specification of a shared conceptualization" (Gruber, 1993). Here a conceptualization is understood to be an abstract and simplified model of how people think about things in the world. Components required for such an ontology include a set of concepts (i.e. concerning entities or things), their definitions, properties, and the relations among these concepts and their properties (Landau, 1937). Concepts represent a class or a set of entities that are related to each other by taxonomical or associative relationships. Within taxonomies, the concepts (and the entities they refer to) are organized into subclasses or super classes, whereas associative relationships relate concepts across the construction of conceptual trees (Winston et al., 1987).

A mobility ontology identifies the entities from the real world necessary to ensure a person's mobility. Significant efforts have been made to define navigation ontologies of urban areas. For example, a wayfinding ontology developed by Timpf(Timpf, 2002) proposed multiple transportation modalities from two distinct perspectives, that of a traveler and that of a public transportation system designer. Urban ontologies proposed by Berdier and Roussey (Berdier and Roussey, 2007) included those devoted to road systems, to urban mobility, and to issues of urban renewal. Berdier (Berdier, 2011) also developed an ontology for urban mobility by integrating a road system ontology and an urban mobility ontology. Sen (Sen, 2008) presented a case study that focused on extracting knowledge about the affordances[1] of road networks. All these diverse efforts focus on the interaction between a user and the environment in the context of mobility. One of the weaknesses, however, in many of these ontologies is that they rarely take into account the social aspects of the environment. They are almost entirely focused on the physical elements and their characteristics. An effective ontology, however, needs to address the design and implementation of mobility infrastructures as well as their usage and diverse semantics, including those that describe the social domain, and both must be integrated into a global approach. This study attempts to provide a methodology to integrate the social and physical environments in the development of such an ontology.

The social dimension is an integral part of the environment, and should be understood to include political, economic, and cultural factors as well as strictly social concerns. Mobility initiatives for PWMD cannot be limited to the physical dimensions of the problem only; social issues need to be addressed in our understanding of disability (Fougeyrollas, 2010; Oliver, 1996). For example, in the Human Development Model - Disability Creation Process (HDM-DCP) (Fougeyrollas, 2010, 1998), a model of disability widely used in

[1] The possibility of an action on an object(Gibson, 1977)

rehabilitation in Quebec, the environment is partitioned into two parts – physical and social. The authors of this model classified the relevant social factors into two groups, political-economic and sociocultural factors. Political-economic factors include the structures and operational modes and services of different systems of governance, whereas the sociocultural factors refer to the structures and operational modes of an individual's relationships with other members of society. Norms, policies, culture, and financial issues are only some examples of social factors. The integration, management, and analysis of such factor with the physical environment in tools such as Geographic Information Systems (GIS) is a challenging task. However, this is essential to provide a better foundation for the assessment and representation of disabilities within such systems. To address this issue, we propose to explore semantic structures that could accommodate these elements as well as to identify the most appropriate classifications or nomenclatures to be adopted. It should be noted that this effort is consistent, even convergent, with the recent interest in "placial information systems" in contrast with "spatial information systems" within the geographic domain (Cloke et al., 1991; Tuan, 1977). According to this approach, 'space' is considered as a location with no social dimensions, whereas 'place' is understood to be a location created by human experience which carries meaning.

Most existing mobility ontologies (e.g. ontologies for pedestrian networks, etc.) have not taken into account human characteristics and, in particular, the limitations experienced by PWMD (Berdier, 2011; Berdier and Roussey, 2007; Sen, 2008; Timpf, 2002). Furthermore, although existing disability models such as the DCP model (Fougeyrollas, 2010, 1998), the International Classification of Functioning, Disability and Health (ICF) (Organization, 2001), and the Institute of Medicine (IOM) model (Brandt Jr and Pope, 1997) situate the human-environment interaction as essential to the fulfillment of daily activities and social roles, none of these models effectively allows the direct determination of a specific ontology for handling the mobility of PWMD, due to their limited level of detail and the shifting importance given to each domain in their environmental taxonomies. For example, in the DCP model, the interactions between environmental and personal factors as well as life habits is fairly exhaustive, however environmental factors and their relations are presented in general terms which does not fully provide the level of detail required to develop a mobility ontology.

Hence, there appears to be a demand for detailed ontologies addressing issues related to the mobility of PWMD. The objective of this study is to provide a methodology to integrate the social and physical environments in the development of such an ontology for the mobility of PWMD. In our approach, we propose to begin by explicitly formalizing the social environment in ways commensurable with the requirements of a mobility ontology for PWMD. Second, we integrate the main parts of the human-environment interaction within the mobility ontology, including the human, social and physical dimensions. This also requires modeling the possible goals of the mobility activity – mobility is undertaken by users as a function of their life habits and activities(Fougeyrollas, 2010).To implement the proposed approach within the Geographic Information Systems (GIS), a scenario is played out for an individual to select a path to reach his destination in Saint-Roch, Quebec City. The proposed ontology framework could bridge several domains, including disability, rehabilitation, social science, and computer science, by reconciling nomenclatures between these domains, and hence reducing the heterogeneity of terminologies among them. Although this ontology is designed to address mobility issues for PWMD, it will also provide a good basis for the development of mobility ontologies across other applications.

It should be noted that, throughout the paper, we make a distinction between the concepts included within the ontology, and the entities they describe in the social and physical environments, which concern us. Hence, whenever we present environmental elements, we use the term "entity" and whenever we discuss the ontology and its organization, we generally use the term "concept." We are aware that the term "entity" may be associated by some readers with the entity/relation duality used in conceptual modeling (Chen, 1976), but we do not believe our usage of the term is incompatible with such a reference, although, admittedly, we use the term with a different goal in view.

The remainder of this paper is organized as follows: Section 3.4 explores the prominent role of the environment in the disability and rehabilitation domain, with a special focus on its social dimensions. Section 3.5 presents a framework that conceptually integrates the social and the physical environment. Section 3.6 introduces the main parts of a specific outdoor mobility ontology for PWMD, including pertinent concepts, their definitions and the relationships between them. Finally, Section 3.7 presents conclusions and future work.

3.4 The role of the environment in human-environment interactions

Before the 1970s, the environment was not considered to play an important role in the definition of disability. The concept of disability was treated as the result of or related to diseases and injuries and was closely related to the medical model of disability (Oliver and BOCHEL, 1991; Shakespeare, 2006). Criticisms of this paradigm led to the development of a new approach – the social model – in the late 1970s. The social model(Edwards et al., 2014; Oliver, 1996) proposed that disability is a product of inadequate social organization. Within this approach, impairments are treated as physical properties of the body, while disability results when society fails to provide a barrier-free environment, which does not discriminate on the basis of impairment. Furthermore, social attitudes of exclusion can lead to isolation and inadequate social participation. As a consequence, in the social model, socio-economic systems are considered the main factors affecting disability, while the older medical model views disability as a characteristic of the individual body(Edwards et al., 2014).

In contrast with the medical model of disability, the environment is considered to be one of the most central elements in contemporary disability models (which are all grounded on the social model). For instance, in the DCP model (see Figure 3.1), introduced(Fougeyrollas, 1998) and further developed (Fougeyrollas, 2010) by Fougeyrollas, the social participation of PWMD is viewed as the result of interactions between personal and environmental factors as well as life habits. In this model, environmental factors have been divided into social and physical factors that can be either obstacles or facilitators to the realization of life habits understood as social activities. The DCP model classifies physical factors into natural and developmental sub-classes, and social factors into political-economic and sociocultural sub-classes.

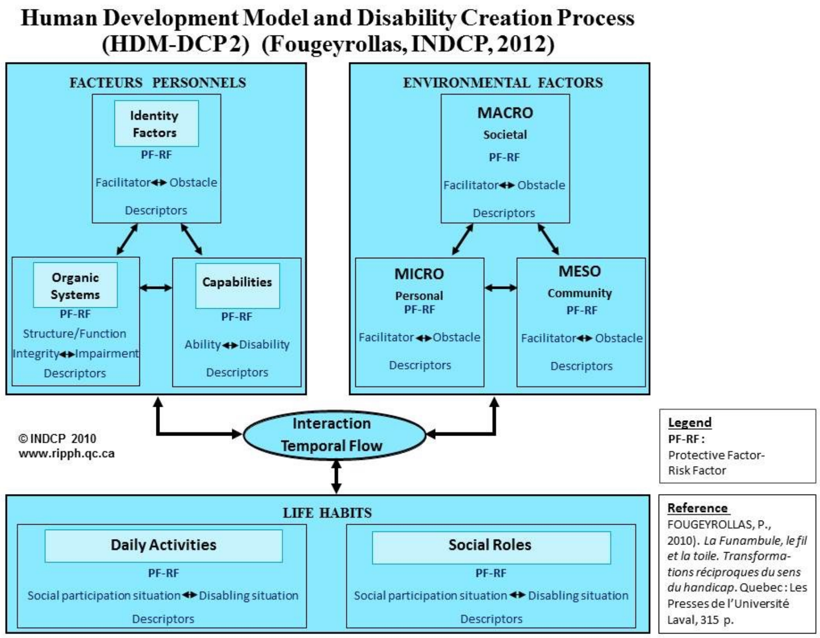


Figure 3.1. Disability Creation Process Model(Fougeyrollas, 2010)

Similar models to the DCP are the ICF model (Organization, 2001), and the IOM model (Brandt Jr and Pope, 1997), all well-known disability models, propose that the environment plays a fundamental role in the disability creation process and “disability cannot be fully understood without considering the environmental context” (Whiteneck et al., 2004). However, these models vary slightly in how detailed their taxonomies describe and specify social and physical environmental factors, as well as the importance given to each of these factors. The prominent similarity among these models is the inclusion of both physical and social factors of the environment. Furthermore, in all three models, the human-environment interaction can be examined on three scales: the micro [2] (personal), the meso [3] (community/services), and the macro [4] (societal/systems) scales (see, for example, (Bronfenbrenner, 1992); for more discussion of this see (Edwards et al., 2014; Fougeyrollas, 2010)). In addition, the taxonomies of environmental factors derived from these models are mostly global ontologies without the specific elements that participate in the disabling process from an operational perspective. However, it can be argued that the

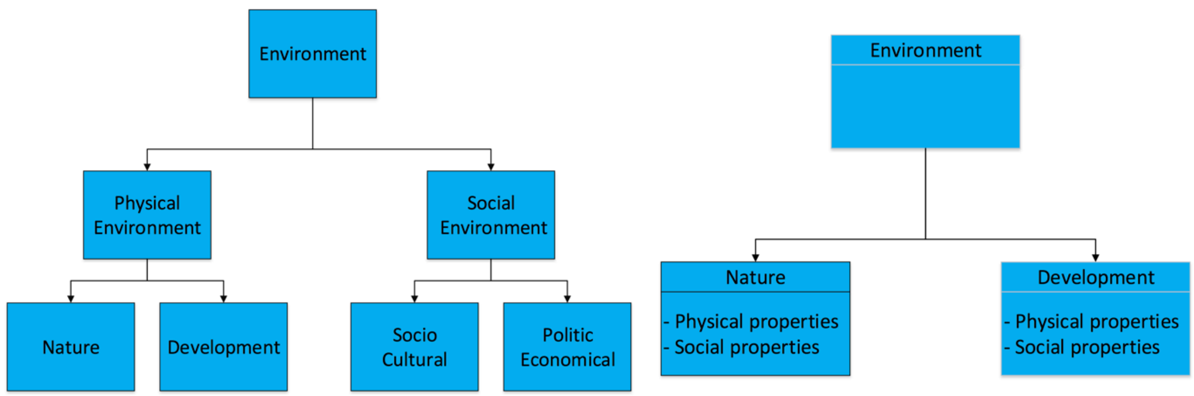
[2] Micro refers to all environments which can be adapted for specific individuals such as the home or the office.
[3] Meso refers to the collective context, which can only be collectively designed. The Meso environment is related to public places and community life.
[4] Macro environment is considered as societal space.

DCP is the most complete of the three models. This model ensures a mutually exclusive conceptualization between what belongs to the individual, to the environment and to social participation or life habits (Badley, 2008; Imrie, 2004; Whiteneck and Dijkers, 2009). In addition, it is worded positively and it attributes the responsibility of whether life habits are realized or not to the interactions with environmental factors rather than to the person and his/her capabilities. This perspective fits our interpretation of disability and will be used as the basis for the determination of a mobility ontology.

3.5 Integrating the social and physical environments

In order to conceptualize the environment for a given application (e.g. mobility), it is necessary to identify relevant concepts and their relationships. Hence, if we were to use the social-physical subdivision of the environment proposed by the DCP, this would lead to a first-level classification split (see Figure 3.2a); but we would also need to explicitly define the relationships between these two subclasses. In reality, there are many influences, both direct and indirect, between social and physical environments. We would need to proceed by identifying pertinent relationships one by one. In addition, the cardinality of the relationships between the social and physical environment concept sets is generally not "one-to-one" or "one-to-many," but "many-to-many" (Figure 3.2a). For example, driving culture is an entity belonging to the social environment that affects noise, air pollution, and traffic congestion, while, traffic, a physical entity, is affected by costs of gasoline and oil, the working hours of public and private organizations as well as the driving culture. Identifying all the many relationships between these concepts may well be too large an undertaking.

Furthermore, it is important to note that the effects of social entities are often materialized in relevant physical entities. This adds more complexity to the identification of the relations between these concepts. For example, driving cultures, and snow removal policies are two social entities that affect the movement of traffic on the streets, which is an entity belonging to the physical environment. These entities have connections with streets, cars, snow, air pollution, noise, and other entities. By employing the social-physical perspective, the culture of driving and the snow removal policy are placed into the social category while the streets, cars, snow, air pollution, and noise are placed into the physical category. Defining the relationships among these concepts, as pointed out, is not only a complex but also a time-consuming process. To avoid these complexities, instead of using a social-physical perspective, we propose a new perspective to subdivide concepts that we refer to as the *Nature-Development* perspective (Figure 3.2b).



a. Social-Physical perspective (based on the DCP model) b. Nature-Development perspective

Figure 3.2.Comparison of the *Nature-Development* and Social-Physical perspectives

In the *Nature-Development* perspective, each entity belongs either to the natural environment (such as a tree or snow) or to the built environment (such as the sidewalks, intersections, and steps), which is part of the Development environment. We have considered these two categories because the relationship between social entities and natural elements (e.g. snow) is different from that between social entities and man-made elements (e.g. sidewalk). Environmental entities, either natural or built, have both dimensions, the physical and the social. The physical dimension is related to the physical properties, whereas the social dimension encompasses the sociocultural and political-economic aspects of these environments. In this approach, each entity has both physical and social properties where the social properties affect the physical and vice-versa. For example, slope, width, height, surface quality, and surface type are physical properties of a pedestrian network (CEREMH, 2011; Jonietz et al., 2013; Kasemsuppakorn and Karimi, 2009; Kirby et al., 2002; Hugh Matthews et al., 2003; Rushton et al., 2011). Social properties include Norms (defined by municipalities or other instances) regarding slope, width, and surface material as well as maintenance and cleaning policies. These social properties might affect the physical properties of the entities to which they apply. For example, the policy of weekly trash collection from the sidewalks is a social rule that can be considered as a social characteristic of the use of sidewalks, which in return, affects the level of accessibility of the sidewalk as it may compromise usage for someone using a wheelchair. Both social and physical properties can be either permanent or temporary (see **Figure 3.3**).

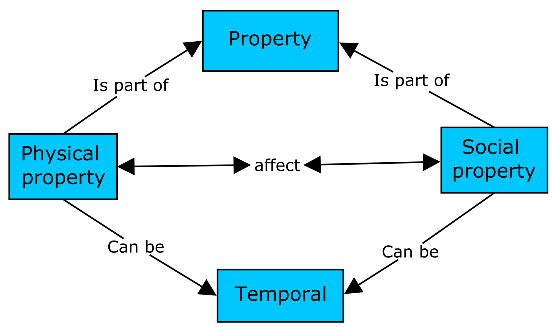


Figure 3.3. Two sub-classes of a property

Since entities in built or natural environments have relationships with each other, these relationships affect their properties as well. For example, the restaurant patio located on the sidewalk along a street has different properties than those of a sidewalk in a different context. In some cities, for example municipal regulations allow restaurants to occupy part of the sidewalk surface. These possible differences in properties can affect the resulting interaction between the person and the environment and the manner by which a person carries out his or her life habits. Indeed, these regulations can create obstacles for individuals with motor limitations or visual impairments and using the sidewalk can therefore become difficult or even impossible. Therefore, to analyze the level of accessibility of pedestrian networks for PWMD, using the ontology we want to develop, not only do we need to consider the physical and social properties of the pedestrian networks, but also the influence of other entities in relationship with them.

Snow as a seasonal and fluctuating phenomenon is another entity that interacts with sidewalk use. This entity is categorized as belonging to the natural environment. Once snow is on the sidewalk, if functions as an entity that influences it, and it may affect the sidewalk properties. For example, it affects walkability by decreasing the friction coefficient between the user and the sidewalk. It can also affect the social properties of the sidewalk. For example, the policy regarding the prioritization of snow removal from sidewalks emerges once the sidewalk, snow, and school – as one of the prioritized places for removing the snow – are brought together. This policy affects the accessibility level of pedestrian networks in cities for PWMD. Furthermore, sometimes, the social properties of an entity can affect the physical properties of another entity. For example, the snow which is removed from the sidewalk and accumulated elsewhere to form a bank becomes a built entity – it links the entity of the snow and the snow clearing or plowing operations, and thus provides a dual entity which belongs to both the natural and development categories. To better understand the *Nature-Development* perspective, here is a detailed example.

A sign is an entity that belongs to the development entity with two sets of properties, social and physical. Signs serve to provide information to users. A sign is made of certain materials such as aluminum or acrylic. It has size semantic properties such as dimension, and height. It also has semantic properties related to purpose such as using the sign for car navigation. In addition, its social properties include policies, norms, maintenance issues, its meaning, representations, narratives it may convey, and symbolic associations that have been defined by its use in public contexts (Highways), 2000). Table 3-1 shows the pertinent social and physical properties of a “sign”.

Table 3-1. Properties of a Sign

Concept	**Physical Properties**	**Social Properties**
Sign	Material (IsMadeOf) Size (Dimension, Height) Shape-Form (Square-Round) Location (IsLocatedOn) Purpose (UsedFor)	MaterialNorms SizeNorm ShapeFormNorm LocationNorm MaintenacePolicies CleaningPolicies Meaning

Consequently, instead of the social-physical division, if the *Nature-Development* perspective is applied, cascading down the ontology will be significantly simplified. This approach also facilitates and simplifies the integration of the social dimension for a more effective assessment of disability within the Geographic Information System (that is, the implementation of the ontology). The *Nature-Development* approach, therefore, includes four steps: 1) determine the entities in each category; 2) present a definition for each entity; 3) define relationships between entities; and 4) define the social and physical properties of each entity as well as their inter-relationships. This approach is employed for the construction of a mobility ontology for PWMD and is explained in more detail in the following section.

3.6 Implementation of a specific mobility ontology for people with motor disabilities

According to Uschold and King (Uschold and King, 1995) and Lopez (López, 1999), the first step required to build an ontology is "ontology capture," itself based on four tasks: "1) Identification of the key concepts and relationships in the domain of interest, that is, scoping; 2) Production of precise unambiguous definition for such concepts and their relationships; 3) Identification of terms to refer to such concepts and relationships; and 4) Agreeing on all of the above." Ontologies are then classified into three levels in terms of generality(Guarino, 1998) – top-level, domain/task level, and application level.

According to this categorization, top-level ontologies describe very general concepts, task and domain ontologies describe the vocabulary of a generic task and domain, and the application ontology is a specialization of task and domain ontologies in a particular domain. In this paper, we propose to develop application ontology for mobility of PWMD, first, and then derive the domain and the task ontology by abstraction of the application ontology concepts. The resulting ontology will include concepts and relations from both natural and built environments, as well as addressing human factors and life habits relevant to the mobility of these people.

3.6.1 Identification of the key concepts

The first step in constructing an ontology is to identify the pertinent concepts. This step is conducted by undertaking bibliographical searches of the literature on mobility, disability and related models, data sources, and research papers that have been reviewed. Some of the models and tools studied by members of our team at the Center for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS) include: the *Human development model - Disability Creation Process* (HDM-DCP) model (Fougeyrollas, 2010, 1998), the *Wheelchair Skill Test* (WST) (Kirby et al., 2002), the *Wheelchair Use Confidence Scale* (WheelCon) (Rushton et al., 2011), and the *Measure of accessibility to urban infrastructures for adults with physical disabilities* (MAUAP)(Gamache.S and McFadyen.B, Routhier.F, Beauregard.L, 2012), which are all suitable to the urban context. We have also drawn on related studies such as the Modeling Access with GIS in Urban Systems (MAGUS) (Hugh Matthews et al., 2003), AccesSig (CEREMH, 2011), the personalized routing for wheelchair navigation system (Kasemsuppakorn and Karimi, 2009) and the “Practical Guide To Universal Accessibility” (Marie-Josée Savard, 2010). Definitions of the selected concepts, as the next step of the ontology construction process, were taken from the DCP model as well as from WordNet[5].

There are three strategies to identify the key concepts in the ontologies: 1) from the most detailed to the most abstract (called bottom-up process), 2) from the most abstract to the most detailed (called top-down process), and 3) from both directions of the most relevant to the most abstract and to the most detailed (called middle-out process)(López, 1999). According to Uschold and Gruninger (Uschold and Gruninger, 1996), the middle-out technique is the most recommended methodology compared to the top-down and bottom-up ones. They showed that identifying the key concepts by the middle-out strategy could decrease the risk of instability, inconsistencies, and the need for re-working the results. The middle-out strategy can also “strike a balance in terms of the level of detail” (Uschold and King, 1995). This strategy has been carried out successfully by many researchers (Grüninger et al., 1995; Uschold et al., 1998), (Blazquez et al., 1998). Therefore, we employed the middle-out strategy by identifying the most important concepts for mobility of PWMD, first, and then defined higher-level and detailed concepts as appropriate. The

[5] WordNet is an online lexical database of English developed by the Cognitive Science Laboratory at Princeton University. WordNet is a "reference system organized as a semantic network based on psycholinguistic theories of human lexical memory”. Although it is not designed to be an ontology, it is used as an upper level ontology by a number of applications, especially for Natural Language Processing" (Landau, 1937). See (Fellbaum, 1998) for full reference.

use of this approach helps us to control the level of detail of the ontology – if too detailed, the task risks becoming monumental. This process was carried out for four main parts of our ontology – the environment, the person, the life habits related to mobility, and the possible goals of the mobility.

3.6.1.1 Environmental concepts related to outdoor mobility for people with motor disabilities

Many elements of the environment interact with the humans to produce a particular action. These elements are called entities in our ontology and they may either obstacles or facilitators as a function of the user's capabilities. As explained in Section 3, these elements are subdivided into the two categories of natural and built (development) environments and include both physical and social properties. This section attempts, first, to determine some of the most important environmental concepts for outdoor mobility and then to construct and present the semantic network. Figure 3.4 shows the relationship between these concepts.

Pedestrian network. A pedestrian network is an entity belonging to the built environment. It is one of the most important entities with which PWMD interact in their daily mobility activities. It can be classified into subclasses such as sidewalks, crosswalks, footpaths, building entrances, and trails, each with their own sets of properties and associated geometry (segments).

Pedestrian network's objects. All objects located on the pedestrian network. These objects might be either obstacles or facilitators based on the person's capacities. They might be categorized as either natural or built. These objects are categorized into permanent objects (e.g. manholes, fire stations, and signs and temporary objects (e.g. snow and crowd congestion(Rushton et al., 2011)).

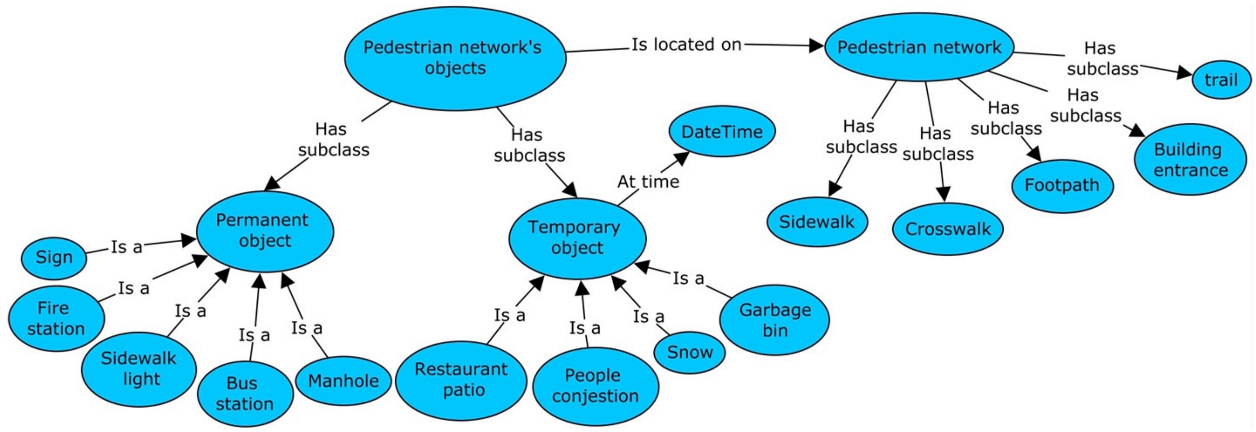


Figure 3.4."Pedestrian network" in relation with its temporary and permanent objects

As previously mentioned, pedestrian networks are among the most important entities in outdoor mobility environment and they incorporate both physical and social semantic properties. Some of these properties are inherently related to their spatial dimensions such as their slope. Other properties emerge from interactions between these spatial properties and other entities. For example, once snow is on the sidewalk and functions as an entity that influences it, properties such as "Is Covered by snow" are added to sidewalk's physical properties. This property is a temporary property and will disappear after a period of time. **Table 3-2** shows the social and physical semantic properties of pedestrian networks.

Table 3-2. Properties of pedestrian networks

Concept	Physical Properties	Social Properties
Pedestrian networks	Slope	Slope Norms
	Width	Width Norm
	Surface type	Surface type Norm
		Surface quality Norm
	Surface quality	Maintenance Policies
		Cleaning Policies
	Geometry	
	Purpose (Used For)	
	Is covered by snow	Snow removal policies
	Has curb cut	
	Is crowded	People attitude Activity policies
	Contains garbage bins	Trash collection policies
	Is under construction	Construction rules

3.6.1.2 Concepts defining human factors in relation with their mobility

Modeling human-environment interactions to characterize the mobility of PWMD is complex. These interactions should be defined and characterized by considering not only environmental factors but also human factors that affect mobility. Hence, in order to model this interaction, environmental factors must be considered in relation to human factors. Environmental factors do not constitute absolute obstacles by themselves; it is only through their relationship with human factors that they can allow, hamper or render impossible the realization of a life habit. For example, based on the user's capabilities, a sidewalk segment can be accessible for some while inaccessible for others even if the nature of the disability is the same. As a matter of fact, the level of one's confidence and the learned strategies might both be influential in the subjective evaluation of the level of accessibility of the sidewalk. Human factors are defined by the characteristics, capabilities, and organic systems of a person(Fougeyrollas, 2010, 1998). Here are the most important concepts related to the person in the context of outdoor mobility for PWMD:

Personal characteristics. Personal characteristics imply properties related to personal identity. These include subclasses such as age, sex, sociocultural identity, sexual orientation, values, beliefs, life goals, education, and income level.

Capability. Capabilities represent "the potential of a person to accomplish mental or physical activities"(Fougeyrollas, 1998). Capabilities are divided into subclasses, such as language, behavior, perception, and, those most related to our study, motor activity capabilities(Fougeyrollas, 1998). In this case, locomotion is the most pertinent subclass considered.

Locomotion. Locomotion is the capability of a person to move from one point to another point on the pedestrian network. This capability can be categorized into physical and perceived capabilities. The presence of permanent and temporary objects as well as certain properties of pedestrian network sections can influence this capability. Ascends 5° incline, descends curb, and avoids moving obstacles are three example of skills influenced by the Wheelchair Skill Test (WST) approach(Kirby et al., 2002).

Organic system. The organic system is "a group of bodily components, all sharing a common function." Hence it is another human factor that includes entities such as the nervous system, the muscular system, and the skeletal system(Fougeyrollas, 2010). Although some of the organic system's entities are necessary to ensure mobility, discussing these is beyond the scope of the current study.

3.6.1.3 The goal of mobility in an urban area

Mobility is presented as a life habit in the DCP model (Fougeyrollas, 2010, 1998). According to the definition given by this model, life habits are defined as "daily living activities and social roles valued by the person or sociocultural context according to his/her characteristics (age, sex, sociocultural identity, etc.)." These life habits include nutrition, fitness, personal care, communication, mobility, community life, education, employment, etc. They are assessed using a concept that is called "life habit accomplishment quality." This concept is a scale ranging from full social participation to a totally disabling situation. The concept of a disabling situation (see Fougeyrollas(Fougeyrollas, 1998)) refers to "the reduced accomplishment of life habits, resulting from the interaction between personal factors (impairments, disabilities and other personal characteristics) and environmental factors (facilitators and obstacles)". Disabling situations and social participation concepts play an important role in our ontology. Although these concepts could be justified as properties of mobility, in the ontology we implemented they are employed as concepts that semantically justify the mobility accomplishments of PWMD.

Mobility is comprised of "habits related to mobility over short or large distances with or without means of transportation"(Fougeyrollas, 1998). Sometimes a life habit might be a goal for other life habits. For example, the goal for mobility, instead of going from one point to another, can be to enable nutrition, community life, education, employment, and so on. Whether these goals are practical, aesthetic or linked to entertainment, they vary from one individual to another and they also may vary for the same life habit. For example, mobility can enable one to "reach a place," "get a sandwich" or "have fun." Also, "walking to work" or "taking a walk" set different goals for the same life habit. Defining every possible goal goes beyond the scope of this work, however, these goals can affect the choice of a path in the mobility context. Hence, the mobility ontology should include the mobility goals as well as mobility enablers, obstacles, and so forth. Incorporating the goals of mobility into the ontology requires the identification of relationships between mobility and other life habits.

3.6.2 Connecting different parts of the ontology

As mentioned in previous sections, modeling human-environment interactions to characterize the mobility of PWMD needs to consider environmental factors, human factors, and relevant life habits, including mobility itself, as well as possible goals of the mobility activity. These parts have been elaborated in previous sections; however, in order to create an integrated ontology, a connection between these parts is required. Concepts such as "assistive technologies" are defined once such a set of connections is developed. Assistive technologies play an important role in our ontology as they have a significant impact on the relationships between PWMD and the pedestrian network in outdoor mobility. Assistive technologies are defined as assistive, adaptive, and rehabilitative devices for PWMD facing the challenges in their everyday lives. These technologies are developed to facilitate the lives of people with diverse disabilities (Yaagoubi and Edwards, 2008). Manual wheelchairs, motorized wheelchairs, and walkers are three examples of this class.

Figure 3.5 demonstrates a top-level schematic view of the proposed ontology. In this ontology, blue represents environmental elements, purple the person, and orange the life-habit elements. This ontology is a conceptual representation of the human-environment interaction in the mobility context that forms a formal basis for the design of a database for mobility issues adapted to the needs of PWMD. In the following section, the proposed ontology is applied in a scenario-based approach, for a person traveling along sidewalks and intersections to reach his destination.

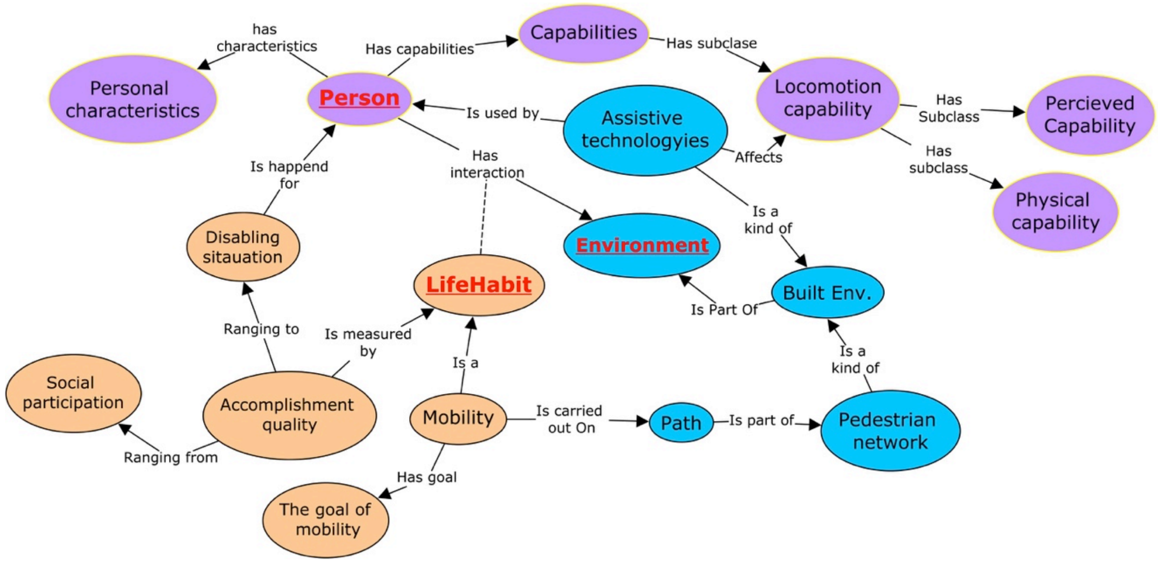


Figure 3.5. A top-level schematic view of the mobility ontology for people with motor disabilities

3.6.3 Scenario: Assessing mobility of a person with a manual wheelchair in an urban area

To identify the parameters that affect the mobility, some of the items of the Wheelchair Use Confidence Scale-Manual (WheelCon-M) are utilized. WheelCon-M is a questionnaire that was specifically developed for manual wheelchair users. This questionnaire includes 65 items identified by a three round Delphi survey among a panel of experts (43 experts) to generate the consensus on the content of the draft WheelCon-M, of which 30 percent of the experts were wheelchair users. This approach is one of the more reliable approaches for evaluating capabilities of wheelchair users (Rushton et al., 2013). Since the items are not selected only for outdoor mobility issues, we chose the most relevant items for our research work. Selected items are as follows: moving the wheelchair 1) around furniture, 2) over grass, 3) through snow, 4) along a bumpy sidewalk, 5) along a sidewalk with potholes, 6) along a gravel path, 7) across the street at a crosswalk with/without traffic lights, 8) up/down a steep slope, 9) through a crowded sidewalk, 10) on narrow sidewalks, 11) up/down a curb cut, 12) up/down a curb with no curb cut. These items are employed as the most important parameters for manual wheelchair users to analyze their mobility in an urban area. To implement the developed ontology within Geographic Information Systems

(GIS), a scenario-based approach for an individual is applied, naming this person David for ease of use. The scenario as played out includes implementation–level details such as segments and fixes that is elaborated within the explanation of the scenario.

David has been experiencing mobility limitations for the past 10 years and he uses a manual wheelchair to deal with this. In this scenario, which was carried out on the 5th of February, 2016, in Quebec City, David used the MobiliSIG (Mostafavi, 2013) application as an assistive technology to select a path to reach his destination during the winter festival of Quebec City. MobiliSIG is a multimodal mobile assistive technology for the navigation of PWMD in urban areas that is developed by our multidisciplinary team at the Center for research in Geomatics (CRG) and the Center for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS). Employing the MobiliSIG technology allows us to access a suitable pedestrian network database that includes appropriate parameters for Quebec City. Figure 3.6 shows a spatial representation of these parameters in the Saint-Roch area of Quebec City.

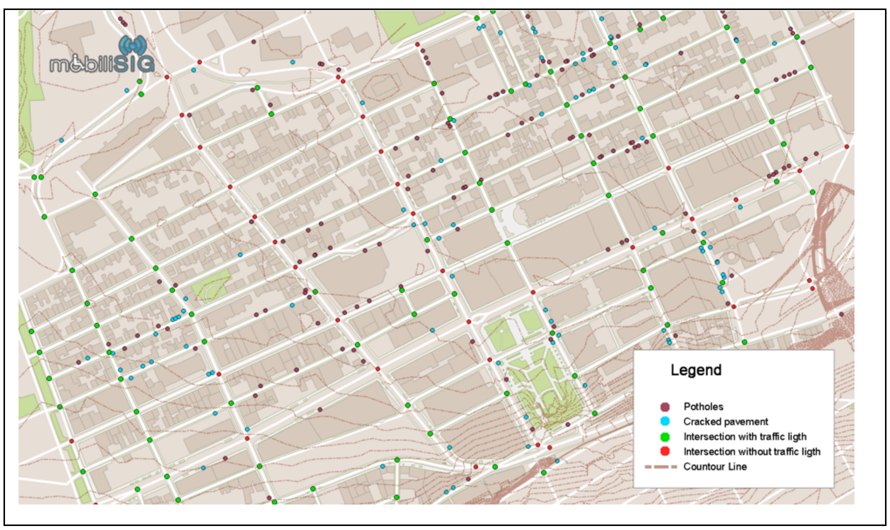


Figure 3.6. Spatial representation of potential barriers in Quebec City

In this scenario, a path is defined to reach a restaurant on Charest Avenue as the destination from David's work place as the origin. This path is divided into segments and fixes. Two points, starting from one location and ending at another, define a segment. They are defined based on changing the attributes of a segment or presence of permanent/temporary obstacles on a segment. Fixes are defined as the spatiotemporal points as $\{x_i, y_i, t_i\}$. These points imply the objects' position at a specific time(Hu et al., 2013). As previously mentioned, these concepts (segments and fixes) are utilized as implementation–level details within the GIS and not part of the environment being modeled. **Figure 3.7** shows this route and its segments. This path includes six segments where each segment has different parameters that affect David's mobility. Starting from his work place, David should use the sidewalk of Rue du Parvis in the Northwest direction (segment 1). Then he crosses Rue Fleurie (segment 2); then he goes ahead using Rue du Parvis's sidewalk (segment 3). Again, he should cross the second street that is called Rue Sainte-Hélène (segment 4) in the same direction. He continues this way to reach Boulvard Charest Avenue (segment 5). Finally, from Rue du Parvis / Boulvard Charest, he turns onto Boulvard Charest in the Northeast direction to reach his destination (segment 6).

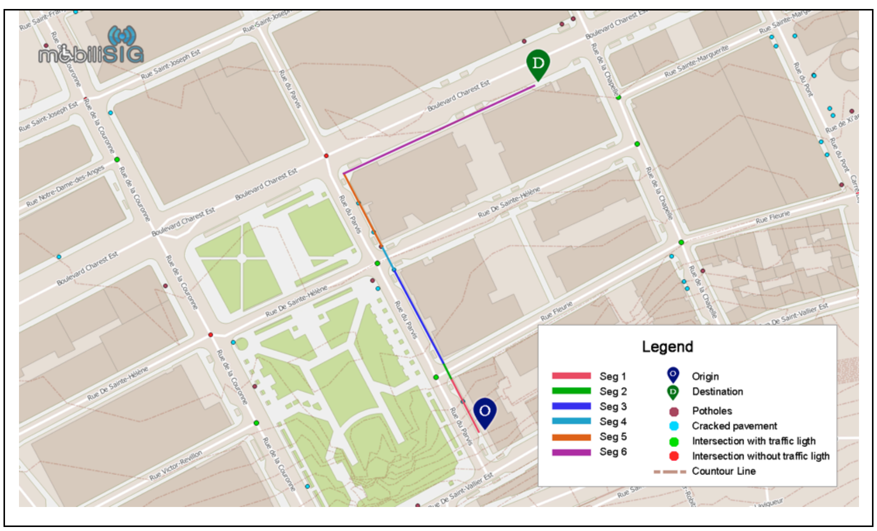


Figure 3.7. The map of Route scenario

In the first segment, snowy surface conditions and a steep slope are part of the physical properties of this segment. The slope of the segment is not compatible with what is recommended by the municipality of Quebec City(Marie-Josée Savard, 2010). This issue is related to one of the social properties of this segment. In the second segment, the steep slope, and the presence of a crosswalk with no traffic light are two of the physical properties. In this segment, municipal policies for adjusting the slope of the pedestrian networks as well as municipal rules for the deployment of pedestrian traffic lights belong to the social properties. The third and fourth segments' properties are similar to those of the first and second segments. At the fifth segment, the user encounters a snow-bank, a temporary object. This object is an obstacle to mobility, which is related to snow removing policies. The snow removal policy, as a social property of snow-sidewalk assemblage, affects the user mobility. In this segment, he is struggling also with garbage bins located on the sidewalk that decrease the width of the sidewalk and affects David’s mobility. This issue might be due to the policy of weekly trash collection from the sidewalks. Finally, in the sixth segment congestion due to crowding – a temporary object – becomes another obstacle for the user and leads to some difficulties for moving along this segment. The density of the crowd and the location of people on the sidewalk belong to the physical properties of this obstacle. This congestion also has social properties such as people's attitudes and municipality rules for managing crowded sidewalks. As explained in previous sections, the social properties of an entity affect its physical properties. In this case, for example, the attitude of people can lead to changes in the location of encumbrances on the sidewalk and consequently, the mobility of the wheelchair user can be facilitated. Furthermore, to analyze the user’s mobility on the pedestrian network, both actual and perceived capabilities in interaction with environmental factors should be considered. In this scenario, user confidence is utilized as a criterion to assess the user’s perceived capabilities by employing the WheelCon-M approach. In this approach, the user’s confidence level is evaluated by choosing a corresponding number among the rating scale from 0 to 100. **Table 3-3** shows the specification of David's path segments as well as his confidence values in dealing with the barriers on his path.

Table 3-3. Specification of David's path segments

Seg No.	Starts at	Ends at	Segment type	Physical property	Social property	David's confidence
1	(x_{11},y_{11},t_{11})	(x_{12},y_{12},t_{12})	Sidewalk	Snowy surface Steep slope	Snow removal policies Not compatibility with municipality norms	50
2	(x_{21},y_{21},t_{21})	(x_{22},y_{22},t_{22})	Crosswalk	No traffic lights on Steep slope	Municipal rules Not compatibility with municipality norms	55
3	(x_{31},y_{31},t_{31})	(x_{32},y_{32},t_{32})	Sidewalk	Poor surface Presence of potholes on Snowy surface	Maintenance policy of municipality Maintenance policy of municipality Snow removing policies	60
4	(x_{41},y_{41},t_{41})	(x_{42},y_{42},t_{42})	Crosswalk	No traffic lights on Presence of potholes on	Municipal rules Maintenance policy of municipality	65
5	(x_{51},y_{51},t_{51})	(x_{52},y_{52},t_{52})	Sidewalk	Contains snow-bank Presence of Garbage Bins on Narrow width	Maintenance policy of municipality Municipal policy for weekly trash collection	55
6	(x_{61},y_{61},t_{61})	(x_{62},y_{62},t_{62})	Sidewalk	Dense crowd Location of people on segment	Municipal rules for managing crowded People’s attitudes	45

3.7 Discussion and conclusion

The main purpose of this research was to integrate the social dimension of the environment with the physical dimension in a mobility ontology for PWMD. To address the challenges in social-physical integration, three well-known disability models were briefly reviewed and to provide a comprehensive understanding of the problem the social dimension of the environment and its role for defining a mobility ontology was presented. Following this, the traditional classification of the environment into social and physical categories was challenged. We demonstrated that employing the social-physical division for the environment complicates the process of developing useful ontologies, especially for defining the relationships between the social and physical parts of the environment. This is a fundamental issue for modeling the interaction between humans and our social and physical environments in a broad range of domains, including Geographic Information Systems. A new approach based on a Nature-Development perspective was proposed as a solution. Built upon the conceptualization proposed by the HDM-DCP model, this perspective facilitated the integration of the social and physical environment by defining the social properties in such a way that these are local to each entity. It should be noted that the Nature-Development perspective may actually have much broader interests beyond the issue of disability – much of the interesting dynamics in city development arises from the interaction between human-developed components – the built environment and its associated entities – and natural or organic components. This approach would be helpful in designing tools aimed at assessing human-environment interactions. It would allow disability scholars to map the complexity of a given situation by identifying the relationships between physical and social aspects of an entity directly.

The applicability of this approach was shown by developing the mobility ontology for PWMD and a top-level mobility ontology for PWMD including four main components – environmental and human factors, life habits related to the mobility, and possible goals of mobility – was presented. The proposed ontology was the conceptual step towards the development of an assistive geospatial information technology to support the mobility of PWMD. This implicated that we need to model all the factors that might affect the mobility of PWMD in physical and social environments in conceptual level. Most of the existing spatial databases for the purpose of routing and mobility were created based on the standard view of the capacity of people and do not consider the specific needs of PWMD for their mobility. Hence, the proposed ontology put more emphasis on these specific needs in the development of more adapted assistive technologies for the mobility of PWMD. In addition, the significant effect of social dimension of the environment in evaluation of the accessibility of pedestrian networks for the mobility PWMD was argued. Different applications can benefit from the proposed ontology. This may include applications ranging from evaluation of the accessibility of pedestrian network to personalized route planning for PWMD. The proposed ontology can be extended to include concepts related to the mobility of other groups of people with disabilities such as visually impaired people or cognitively impaired people. It should be noted that the proposed ontology is not exhaustive and it can be further developed to consider more detailed concepts related to the mobility of PWMD.

Acknowledgements

This research was supported by the MobiliSIG project, thanks to a research grant provided by the Canadian Institutes of Health Research and the Natural Science and Engineering Research Council of Canada. We are grateful to all members of the MobliSIG project for their valuable contributions to the discussions that led to this paper.

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4 L'évaluation de l'accessibilité

4.1 Résumé

Un moyen évident d'aider les personnes handicapées dans leurs déplacements dans les zones urbaines est d'offrir des informations sur les segments de chemins accessibles qui prennent en compte leurs besoins spécifiques. Assurer une navigation sure dans les zones urbaines pour les personnes handicapées peut considérablement améliorer leurs possibilités de pleine participation sociale et l'exercice de leurs droits fondamentaux. Afin d'offrir à ces personnes des informations sur les chemins accessibles, nous devons évaluer l'accessibilité des réseaux piétonniers. L'accessibilité est le résultat d'interactions entre l'humain et l'environnement. Ces interactions doivent être examinées plus attentivement lorsque nous évaluons l'accessibilité pour les personnes handicapées. Cet article propose une nouvelle approche de l'accessibilité, basée sur la confiance des utilisateurs lors de leurs déplacements dans l'espace urbain. À des fins de validation, l'approche proposée est appliquée dans la région de Saint-Roch à Québec. Les résultats sont présentés et discutés et d'autres perspectives supplémentaires de recherche sont proposées.

Corps de l'article

Titre: A confidence-based approach for the assessment of accessibility of pedestrian network for manual wheelchair users

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Chapitre du livre: Advances in Cartography and GIScience

4.2 Abstract

An obvious way to assist people with disabilities in their efforts to move around in urban areas is to offer information regarding accessible path segments that take into account their specific needs. Providing safe navigation in urban areas for people with disabilities can substantially enhance their opportunities for full social participation and the exercise of their basic rights. In order to offer these people information on accessible paths, we need to assess the accessibility of pedestrian networks. Accessibility is the result of interactions between the individual and the environment. These interactions need to be more carefully considered when we evaluate accessibility for persons with disabilities. This paper proposes a new approach for assessing accessibility, based on user confidence while moving around in urban space. For validation purposes, the proposed approach is applied in the Saint-Roch area of Quebec City using confidence information from 127 manual wheelchair users. The results are presented and discussed and further research perspectives are proposed.

Keywords: Accessibility, pedestrian networks, confidence, wheelchair user, modeling, dynamic segmentation

4.3 Introduction

Ensuring full social participation of people with disabilities is a challenging issue. This is because the special needs of these people are often not taken into consideration in the development of cities, public places, new technologies and services. People with disabilities who cannot move about autonomously cannot carry out their daily activities such as going to work and school, shopping, or participating in community and family life. The needs for better participation in social activities by people with disabilities are usually referred to as "hidden demands” (Marston & Golledge, 2002). These are activities that people with disabilities are unable to carry out despite their desire to do so. According to a Canadian survey on disability, pain, motor disability[6] and lack of adapted services, are the most common causes for social exclusion among Canadian adults. Indeed, mobility problems constitute 7% of the aforementioned disability issues (CSD, 2012). Providing people with disabilities with assistive technologies to improve their mobility will help to increase their effective participation in society. To address this issue, the research reported here aimed to develop a new approach for evaluating the accessibility of pedestrian networks for people with motor disabilities. Since mobility is a result of interactions between humans and their environment (Gharebaghi and Mostafavi, 2016), our approach was to focus on human capabilities and their confidence levels across a range of environmental interactions during displacements.

Several studies have attempted to address this issue by modeling the interactions between humans and the environment. For example, Warren (1984) analyzed the dynamics of an human-environment system using Gibson's affordance theory (Gibson, 1977). He showed, for example, that stair climbing is made possible by the interaction between leg length and stair height. Jonietz et al. (2013) modeled the suitability of urban networks in relation to different types of agents, with and without motor disability. In similar research, Matthews et al. (2003)and Beale et al. (2006) developed a GIS-based system for modeling access for wheelchair users in urban areas. Kasemsuppakorn and Karimi (2009) developed a personalized routing model for wheelchair users focusing on user priorities and sidewalk

[6] Disabilities related to the movement and maintenance of body position (Fougeyrollas, 1998).

properties. Jonietz et al. (2013) and Jonietz and Timpf (2013) proposed a framework for modeling spatial-suitability of pedestrian networks based on affordance theory[7]. This framework sought to assess suitability determined by characteristics of agents, environments, and actions. Tajgardoon and Karimi (2015) proposed an approach based on a weighted linear model for different characteristics of sidewalk segments to evaluate the accessibility of sidewalks for persons with disabilities. Although all of these studies proposed valuable methods to model the human-environment interactions, a) they did not fully consider the individual's capabilities for implementation of their approaches, b) their validation are not generally supported by human involvement and finally c) each of them identified and employed their own set of properties describing pedestrian networks. However, it does not appear that they fully took into account users' perception of these properties. As a result, the users' requirements are not fully met.

We propose a new approach that considers the perception and capabilities of manual wheelchair users to evaluate the accessibility of pedestrian network for persons who use a manual wheelchair in their daily activities. We account for both actual and perceived capabilities of the users. User confidence is considered as a criterion to measure the user's perceived capabilities. The accessibility assessment process is undertaken in seven steps: 1) capturing the pedestrian network data, 2) partitioning the pedestrian networks into segments, 3) gathering the user profile information, 4) linking segment properties with the corresponding user confidences, 5) aggregating the confidence levels for each segment, 6) evaluating the accessibility level of each segment based on the total confidence, and finally, 7) visualizing the accessibility level of each segment on the pedestrian network map.

The remainder of this paper is organized as follows: In Section 4.4, we determine a specification for the database that will contain the information about the pedestrian network, identifying the most important environmental criteria in relation to the mobility of people with manual wheelchairs. In addition, we describe the segmentation process. Section 4.5 proposes the confidence-based framework to the assessment of the accessibility of the pedestrian networks for manual wheelchair users. Section 4.6 presents the results of the

[7] The affordances of the environment are what it offers the animal, what it provides or furnishes, whether for good or ill (Gibson, 1977).

accessibility assessment for the Saint-Roch area of Quebec City. Finally, Section 4.7 presents conclusions and future work.

4.4 Pedestrian network database

One of the fundamental components of a navigation system is a geospatial database. A geospatial database provides the necessary information for performing navigation, mapping and routing functions. Nowadays road network databases are designed to serve divers navigation applications. However, these databases are not in general usable for navigation persons with disabilities. Pedestrian network databases require information about the environment in much greater detail such as obstacles on the sidewalks. In addition, to employ such databases for navigation by persons with different capabilities, these databases should be adapted to their needs. Therefore, a suitable database for navigation by persons with disabilities should have both information on user profiles including their capabilities as well as about the pedestrian network itself and its characteristics in relation to the mobility task.

A pedestrian network is one of the most important environmental entities in outdoor mobility that persons with disabilities interact with in their daily activities. It contains the geometric and topological relations between pedestrian path segments (Karimi and Kasemsuppakorn, 2013). Pedestrian networks are typically classified into sidewalks, crosswalks, footpaths, building entrances, trails, pedestrian bridges, and tunnels, each of these consisting of several segments. Two points, starting from one point and ending at another, define a segment. Each segment has properties that can be either permanent or temporal. The spatial database for enabling the mobility of people with disability should take into account both permanent and temporal properties (events) using appropriate algorithms (see below for more details about these processes). To create these algorithms, first it is necessary to determine the most relevant entities of the pedestrian network that will affect the mobility of persons with motor disabilities. Following this, the segmentation of the network can be carried out based on the static and dynamic nature of those entities.

4.4.1 Determining the most important environmental criteria for enabling the mobility of persons with manual wheelchairs

As mentioned above, the variation of the characteristics of pedestrian networks or the presence of different obstacles on the pedestrian network may affect the network segmentation process. Furthermore, this set of characteristics may vary from one context to another. For example, while the quality of the pavement is likely to be of central importance for persons with motor disability, it may not be a significant factor for persons with hearing impairment. Therefore, to evaluate the accessibility of a segment for persons with disabilities, the main properties that affect their daily activities should be determined. So far, a number of studies have investigated these properties. For example, Matthews et al. (2003) used width, length, slope, sidewalk surface, steps, sidewalk conditions and sidewalk traffic. Kasemsuppakorn and Karimi (2009) considered slope, sidewalk width, steps, segment length, surface type, cracks, manhole covers, uneven surfaces, and sidewalk traffic. Although pertinent, there is no evidence that these properties were determined according a rigorous study involving the perception of people with disabilities or the experience of expert groups. To overcome the limitation of these works, we use properties that are identified in the Wheelchair Mobility Confidence Scale (WheelCon) (Rushton et al., 2011). This survey instrument is a questionnaire that was developed specifically for studying the mobility of wheelchair users. WheelCon is one of the most reliable approaches for evaluating capabilities of wheelchair users. The questionnaire includes 65 items, which were identified by a three round Delphi survey among a panel of experts (43 experts), of which 30 percent were wheelchair users.

Here, we are specifically interested to the characteristics of outdoor environments that affect the mobility of people with disabilities. For this reason, we have generated a short version of the main questionnaire that includes only items related to outdoor mobility tasks. A statistical process was used to analyze and sort out the items in terms of relevancy, correlation, and adaptation. The WheelCon questionnaire includes 65 items. Among them, 17 are especially relevant to this study. Data from 127 participants indicated that those selected items could effectively predict the 65-item WheelCon total score (SPSS 23; linear regression; adjusted $R^2 = 0.923$; $p < .0001$). A principal component analysis on these 17 items identified two factors that caught respectively 65% and 9% of the total variance. The sampling adequacy was high (Kaiser-Meyer-Olkin index = 0.93). In order to further reduce the number of items of an abridged version of the WheelCon specific to our study, we iteratively removed one item at a time in order to check the impacts of this removal on the adjusted R^2 and KMO index. In order to preserve the most detailed information, we followed the strategy to remove first the item with the smallest variance. Optimally, this process identified a set of 12 items that has a minimal impact on the adjusted R^2 (0.888; $p<0.0001$) and the KMO index (0.92). These 12 items are similarly sensitive to two components that caught respectively 67% and 10% of the total variance. **Figure 4.1** outlines this process.

As a result of the explained process, 12 items among the 65 original items of WheelCon were selected. These items are used to guide the segmentation of the pedestrian networks. They are classified into seven categories related to the segments that include slope, curb cut, surface quality, potholes, presence of snow on the segment, intersections with and without traffic lights, and sidewalk traffic. Among these properties, the slope, curb cut, and intersections are classified as permanent properties and surface quality, pothole, snow, and sidewalk traffic are classified as temporal properties. Different algorithms for the segmentation of the pedestrian network are proposed for each class of properties. These algorithms are described in the following section.

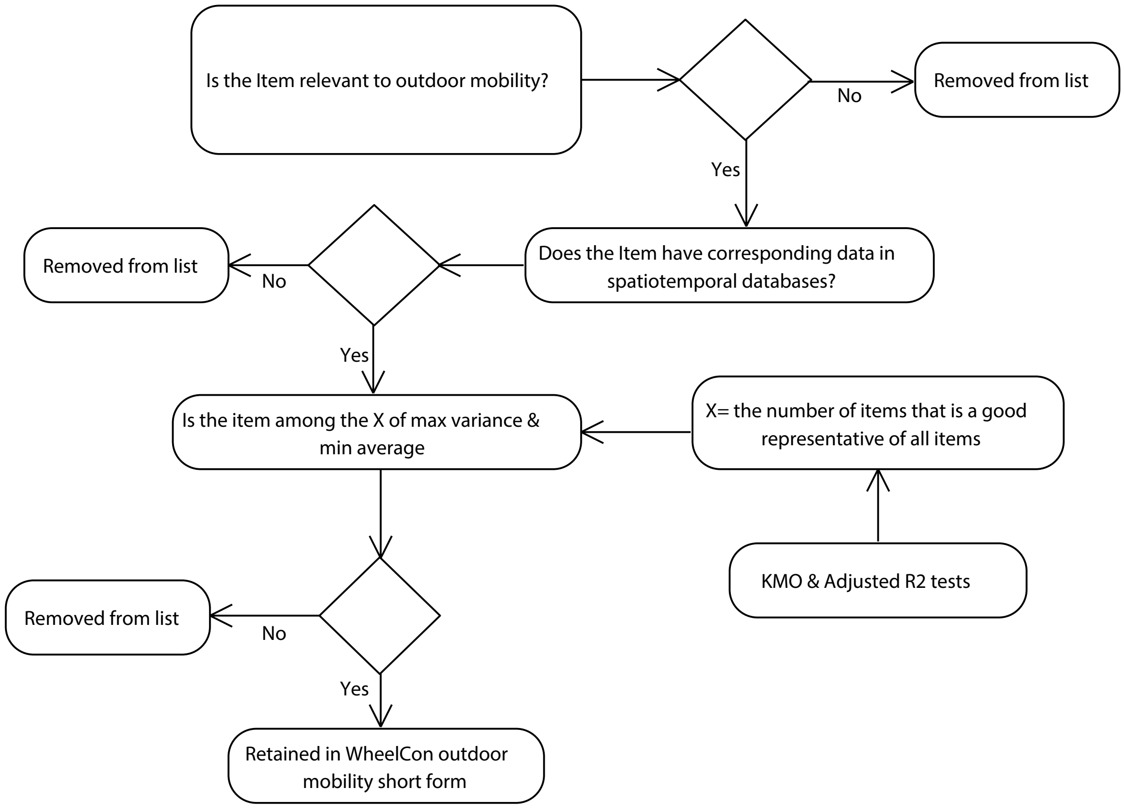

Figure 4.1. Selection of the most pertinent items for the mobility of manual wheelchair users from WheelCon questionnaire

4.4.2 Pedestrian network segmentation

The segmentation of the pedestrian network is the first step for its accessibility assessment and mapping. The segmentation should be carried out based on both the relevant properties of the network as described earlier and the user requirements. This process includes four steps: 1) extracting the centre lines of the network, 2) ensuring their connectivity and topological consistency, 3) carrying out the segmentation based on its permanent properties, and 4) and carrying out the segmentation based on the temporal properties. Figure 4.2_a shows the permanent segmentation in our research area considering slope changes of more than 5°, as well as the presence of curb cuts. The process is extended to generate new segments based on temporal properties. Here we use a dynamic segmentation process (Weigang and Guiyan, 2009), which is a method for identifying segments with changing attributes in time. Instead of splitting segments whenever there is a change in attribute values, here we apply a linear reference system to indicate the start and end of a temporal property without splitting the segment (Cadkin, 2002). Figure 4.2_b shows an example resulting from this process. Once the segmentation of pedestrian network is carried out the accessibility of each segment can be assessed. The accessibility assessment process is explained in the following section.

a. Permanent segmentation b. Dynamic segmentation

Figure 4.2. Segmentation of the pedestrian network

4.5 Evaluating the accessibility of segments

In the context of urban mobility, accessibility is often defined by the ease of reaching a destination with respect to distance, time and cost constraints (Morris and Wigan, 1978). This definition was used at the basis of several statistical approaches to assess accessibility. In these approaches, count of accessible places, total distance, closest place, and absolute access are employed as the main criteria (Church and Marston, 2003). In each of these studies, accessibility is evaluated by measuring the cost value for each path. For example, in the case of automobile accessibility to a given location, although the cost is normally determined in terms of distance, it can be influenced by other factors such as surface type, speed limit and congestion (Beale et al., 2006; Martin et al., 2001; Lovett et al., 2002). For the mobility of a person, however, accessibility depends on the interactions between person and the environment. For example, a path can be accessible for some while it can be inaccessible for others. Therefore, the accessibility of each segment of a pedestrian network should be assessed considering not only the environmental factors but also the users' capabilities.

For evaluating the capability of a wheelchair user, approaches such as the Wheelchair Outcome Measure (WhOM) (Mortenson et al., 2007), the Wheelchair Skill Test (WST) (Kirby et al., 2002), and the Wheelchair Circuit (Kilkens et al., 2004) have been proposed. On the other hand, for evaluating the capability of a person, their confidence for performing a given task is a more reliable criterion than their skill alone (Rushton et al., 2011). A person might be able to perform a given task but not be confident enough to carry it out. In this research work, we employ user confidence to evaluate the accessibility of pedestrian segments. The accessibility of each segment is calculated by aggregating user confidence with respect to each attribute of the segment as follow.

$$A_{ijl} = \sum_{p=1}^{7} Con_{ijp} \qquad (1)$$

Where, A_{ijl} is the index of accessibility of segment j for person i by travel type l; Con_{ijp} is the confidence level of the person i for the segment j in relation to the property p;

User confidence levels are evaluated based on the Wheelchair Mobility Confidence Scale (WheelCon) approach (Rushton et al., 2011). Each segment has more than one property, so it will take more than one confidence value. These confidence values are aggregated for each segment and a total confidence value for a given segment is assigned. Hence, the accessibility assessment process is completed in three steps: 1) Setting the user profile information that includes the user confidence level via the 12 questions of the WheelCon short-form questionnaire, 2) aggregating the confidence levels for each segment with respect to its properties, and 3) evaluating the accessibility level of each segment based on the total confidence.

4.5.1 Aggregation of confidence levels

In order to assess the accessibility of each segment, the aggregation of confidence values related to properties of that segment is required. There are several methods that can be employed to aggregate these values such as weighted linear models and if-then rules approaches. Aggregation process is a very important step in the accessibility assessment approach. Weighted linear models might have some limitations in complex situations. For instance, in a scenario of mobility the user may a) move down from a standard curb, b) cross an intersection, and c) pass over a hole on the sidewalk. If the confidence level of the user with respect to each of these properties is at medium level, the aggregated confidence level might not be medium for this user. A weighted linear model would result a medium confidence level for this scenario, which does not reflect the reality.

Here we use If-then rules approaches, which provide more realistic values for aggregated confidence level. Fuzzy logic is a widely used if-then rule approach. Fuzzy logic is introduced by Zadeh et al. (1965) to model the vagueness that is associated with human cognitive processes. In recent years this approach has been widely used in many different applications including routing and transportation planning ((Kasemsuppakorn and Karimi 2009) and (Karimanzira et al. 2006)). To employ fuzzy logic, three steps must be followed: (1) build the rule set and define the membership functions (fuzzification), (2) make a fuzzy inference system (FIS) using if-then rules and (3) merge the outputs of the rules and ensure defuzzification of the results using a different set of membership functions to derive output variables (Mamdani and Assilian, 1975). The objective of the Fuzzification step is to transform the numerical confidence values to qualitative values (linguistic variables) by defining a membership function. For example, the values between 0-20 correspond to a very Low confidence. Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH) labels are defined for describing the confidence levels. Then the if-then rules are defined to aggregate the individual user confidences and, consequently, calculate the total confidence of the user for each segment. For example:

If (the confidence level of slope is low) & (the confidence level of poor surface is low) Then (the total confidence level is very low)

Table 4-1 indicates the defined rules. Rules are stated as if aggregation would be applied on two components, in case that we have more than two parameter the result of first aggregation would be aggregated with the next parameter and this process is continued till the total confidence is obtained. Since these rules directly affect the result of the process, they need to be validated. In our research, an expert who is also a wheelchair user carries out the validation step. However, we understand that further investigation is needed for a more rigorous validation of these rules by participation of experts and wheelchair users.

Table 4-1. If-Then rules

Rule No.	Confidence Level		Accessibility Level	Rule No.	Confidence Level		Accessibility Level
	p	q			p	q	
1	VL	VL	NA	9	L	VH	LA
2	VL	L	NA	10	M	M	LA
3	VL	M	NA	11	M	H	MA
4	VL	H	NA	12	M	VH	MA
5	VL	VH	NA	13	H	H	MA
6	L	L	NA	14	H	VH	A
7	L	M	NA	15	VH	VH	VA
8	L	H	LA				

Once the aggregation of confidence levels is achieved and a unique confidence level is calculated for each segment, a numerical confidence value must be recovered. To address this issue, a defuzzification technique should be applied to produce exact numerical values from the fuzzy values, based on the defined membership functions and rules. The output values are utilized for determining the accessibility levels of pedestrian network segments in four categories of Not Accessible (NA), Low Accessible (LA), Accessible (A), and Very Accessible (VA).

4.6 Case study

To illustrate the validity and utility of the proposed approach, the whole process of accessibility of the Saint-Roch area in Quebec City is assessed. To fulfill this assessment each user determines his/her confidence level by choosing a corresponding number from the rating scale from 0 to 100. The accessibility assessment process is visualized for two users. First, it is carried out for a 61-years-old female wheelchair user called user #1. In a second case, we suppose a user with median confidence called user #2. The mean confidence value is obtained using information from 127 users to assess the average accessibility of the study area. The data on users confidences was obtained in collaboration with another team who has conducted a survey on manual wheelchair users skills. The mean confidence values for 12 properties for a given segment in sidewalk are provided in **Table 4-2** In this example the mean values for the user #1 and user #2 are 17 and 52, respectively.

Table 4-2. Confidence values of manual wheelchair users for each parameter

N	User confidence items	Us	All
1	Can move your wheelchair up a standard height curb 15cm (6”) without a curb cut?	15	22
2	Can move your wheelchair down a standard height curb 15cm (6”) without a curb cut?	15	41
3	Can move your wheelchair across 3m (10ft) of flat, unpacked gravel?	15	51
4	Can move your wheelchair along a sidewalk with 5cm (2”) of snow?	0	51
5	Can move your wheelchair through a pothole that is wider than your wheelchair and	10	54
6	Can move your wheelchair along a flat dirt path or trail with some tree roots and	25	59
7	Can move your wheelchair up a dry steep slope (> 5º incline)?	30	68
8	Can move your wheelchair along a paved sidewalk that is cracked and uneven?	40	70
9	Can cross a street with light traffic at a crosswalk with no traffic lights?	10	73
10	Can move your wheelchair through a crowd of people without hitting anyone?	10	73
11	Can move your wheelchair across 3m (10ft) of flat, freshly mowed, dry grass?	10	74
12	Can manoeuvre your wheelchair to press the crosswalk button and cross the street	10	75
-	Mean confidence	17	52

The accessibility assessment process started with the segmentation step based on the properties of each segment and related events observed in the environment. Then, the attributes of each segment for selected properties were stored in a spatio-temporal database. Next, the confidence value of the corresponding attributes for each user is imported into the database. The fuzzification, aggregation, and calculation of the total confidence for each segment are carried out for each user. Finally, the accessibility level for each segment in the study area is evaluated and visualized. **Figure 4.3** shows the accessibility map for user#1 where "Not Accessible" segments are represented with red, "Low Accessible" segments are yellow, "Accessible" segments are green, and "Very Accessible" segments are dark green. As the accessibility map shows, there are a significant number of inaccessible segments for user#1. This process indicates that for this manual wheelchair user, 924 out of 2427 segments were not accessible. This represents 38% of the whole network. Most of the inaccessible segments were located in the intersections.

Figure 4.3. Accessibility map for a user (user #1)

The next map shown in **Figure 4.4** is generated for the same area employing the mean confidence values for all 127 users. Since the average confidence level for all participants was significantly higher than the confidence level of user#1, the number of inaccessible segments is negligible. According to the statistical analysis, 62% of the St-Roch area's pedestrian network is very accessible, 25% is accessible, 12% is low accessible, and about 1% is not accessible. This map can be used by city authorities as a valuable decision making tool to locate the inaccessible and low Accessible segments and propose an accessibility improvement plan in the area.

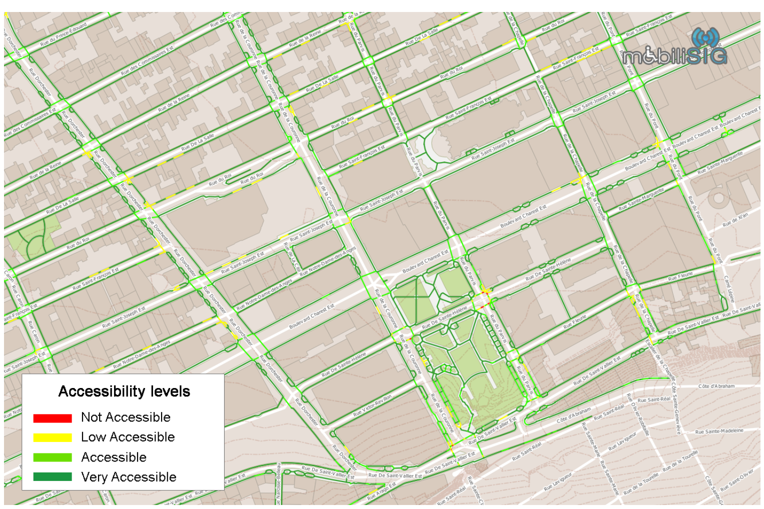

Figure 4.4. Accessibility map for a group of users (user #2)

4.7 Conclusion and future work

In this paper, we proposed a novel method to assess the level of accessibility of a pedestrian network for manual wheelchair users for their mobility. First we presented a segmentation process for pedestrian network incorporating a range of segment properties and related events. The study also drew on the results of the WheelCon survey for assessing accessible paths based on users' perceptions and capabilities, to identify a set of 12 characteristics. A key contribution of the present paper was to propose a confidence-based approach for the assessment of the accessibility of pedestrian networks. To our knowledge, this is the first time that a confidence based approach is used to evaluate the accessibility in an urban area. To illustrate the utility of the proposed approach, we presented two scenarios using data from the Saint-Roch area in Quebec City. The results demonstrated different levels of accessibility for a specific user compared to an average manual wheelchair user. City authorities for further analysis and decision-making could use the resulting maps. Further investigation is needed for more rigorous validation of the if-then rules proposed here for aggregating confidence values in relation to different segment properties. We also plan to carry out further validation process with experts and wheelchair users in more realistic application scenarios.

Acknowledgements

This research was supported by the MobiliSIG project, thanks to a research grant provided by the Canadian Institutes of Health Research and the Natural Science and Engineering Research Council of Canada. We are grateful to all members of the MobliSIG project for their valuable contributions to the discussions that led to this paper.

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5 Facteurs sociaux dans l'évaluation de l'accessibilité

5.1 Résumé

La Convention des Nations Unies relative aux droits des personnes handicapées reconnait le droit de ces personnes à la participation sociale standard la plus élevée possible, sans discrimination fondée sur le handicap. La mobilité des personnes handicapées est l'une des plus importantes habitudes de vie qui aident les personnes handicapées dans leur participation sociale. Fournir aux personnes handicapées des informations sur les chemins accessibles et les zones urbaines accessibles à l'aide de technologies d'assistance mobiles est essentiel pour améliorer leur mobilité. L'accessibilité des lieux urbains et du réseau piétonnier dépend de l'interaction entre les capacités humaines et les facteurs environnementaux que peuvent être divisés en facteurs physiques et facteurs sociaux. Une analyse optimale de l'accessibilité nécessite à la fois des facteurs sociaux et physiques. Bien qu'il y ait eu un travail considérable sur la prise en compte des facteurs physiques de l'environnement pour l'évaluation de l'accessibilité, les facteurs sociaux sont généralement négligés dans ce processus. Dans cet article, nous soulignons l'importance de la dimension sociale de l'environnement et considérons une approche plus intégrée pour l'évaluation de l'accessibilité. Nous insistons sur la façon dont les facteurs sociaux tels que les politiques peuvent être pris en compte dans l'évaluation de l'accessibilité du réseau piétonnier pour les personnes à mobilité réduite. Dans cet article, nous proposons un cadre pour évaluer l'accessibilité des segments du réseau piétonnier en tenant compte des confidences des personnes à mobilité réduite. Ce cadre est ensuite utilisé comme outil pour étudier l'influence des différentes politiques sur les conditions d'accessibilité du réseau piétonnier. La méthodologie est mise en œuvre à Saint Roch à Québec, et l'efficacité de trois actions stratégiques est examinée dans ce domaine.

Corps de l'article

Titre: The role of social factors in the accessibility of urban area for people with motor disabilities

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Revue: ISPRS International Journal of Geo-Information

5.2 Abstract

The United Nation's Convention on the Rights of People with Disabilities recognizes the right of people with disabilities to attain full social participation without discrimination on the basis of disability. Furthermore, mobility is one of the most important life habits for achieving such participation. Providing people with disabilities with information regarding accessible paths and accessible urban places therefore plays a vital role in achieving these goals. The accessibility of urban places and pedestrian networks depends, however, on the interaction between human capabilities and environmental factors, and may be subdivided into physical or social factors. An optimal analysis of accessibility requires both kinds of factors, social as well as physical. Although there has been considerable work concerning the physical aspects of the environment, social aspects have been largely neglected. In this paper, we highlight the importance of the social dimension of environments and consider a more integrated approach for accessibility assessment. We highlight the ways by which social factors such as policies can be incorporated into accessibility assessment of pedestrian networks for people with motor disabilities. Furthermore, we propose a framework to assess the accessibility of pedestrian network segments that incorporates the confidence level of people with motor disabilities. This framework is then used as a tool to investigate the influence of different policies on accessibility conditions of pedestrian

networks. The methodology is implemented in the Saint-Roch neighbourhood in Quebec City and the effectiveness of three policy actions is examined by way of illustration.

Keywords: people with disabilities, mobility, policy, physical environment, social environment, pedestrian network, and accessibility

5.3 Introduction

Despite significant efforts over the last decades, improving social participation of people with disabilities (PWD) is still a very challenging issue for our societies. This is because there is an important gap between the current design of urban environments and the way people with disabilities live and interact with such environments. Current urban infrastructures and services are generally designed based on a standard view of people without any deficiencies and the specific needs of PWD are often not taken into account in the development of cities, public places, new technologies and services. PWD who cannot move autonomously will not be able to accomplish their daily activities (such as go to work or school, go shopping, or participate in community and family life). To enable PWD to live independently and participate fully in all aspects of their life including effective participation in valued life activities, achievement of culturally and developmentally appropriate social roles, contribution to various aspects of community life, and full citizenship (Luc et al., 2015), a whole range appropriate issues needs to be taken into account. According to the United Nation's Convention on the Rights of PWD (UN, 2006), which is ratified by over 160 countries including Canada, equal access to urban places and services must be enshrined in law for everyone, regardless of any functional limits. To achieve this goal, Canada has put in place a number of actions including the adaption of related legislations and providing financial support to help community-based projects to improve the accessibility of buildings, vehicles, information and communication technologies, etc (UN Committee on the Rights of Persons with Disabilities (CRPD), 2015).

The UN convention has its roots in the social model of disability [4-6] which was developed to highlight the impact of environmental factors in the definition of disability. Before the 1970s, the role of the environment was not considered to be important in the definition of disability. According to the earlier medical model, disability was considered to be the result of or related to diseases and injuries (Edwards et al., 2014; Oliver, 1996; Oliver and Bochel, 1991; Shakespeare, 2006). Criticisms of this paradigm led to the development of the social model of disability. This model defined disability as a product of inadequate social organization. Within this approach, impairments are treated as physical properties of the body, while disability results when society fails to provide a barrier-free environment, which does not discriminate on the basis of impairment. Furthermore, social exclusion can lead to isolation and inadequate social participation. Hence, in the social model of disability, socio-economic systems are considered to be the main factors affecting disability, while the older medical model views disability as a characteristic of the human body (Edwards et al., 2014).

The mobility of people with motor disabilities (PWMD) is one of the most important life habits that significantly contribute to the social participation of PWMD. In order to assist PWMD in their mobility and social participation we need to provide them with information on accessible routes and accessible urban places as a function of their specific needs. The accessibility of a place or a route is assessed based on the interactions between human capabilities and environmental factors. Capability is an attribute of human behavior that differs from one person to another and is defined as a person's potential to accomplish a mental or physical activity (Fougeyrollas, 1998). On the other hand, the environment is composed of entities with different properties, each entity which may have several physical and social properties. In their physical dimensions, entities are characterized by their physical properties whereas in their social dimensions, socio-cultural and political-economic properties can be identified (Gharebaghi and Mostafavi, 2016). According to these properties, each entity in the environment affords several actions such as walk-ability or roll-ability, and these will, in turn, modulate issues such as accessibility and suitability. In some cases, a sidewalk may not afford accessibility regardless of human capabilities. For example, because of the presence of a barrier, a sidewalk may not afford walk-ability. These barriers may affect the level of accessibility of pedestrians and especially of those with disabilities.

As implied above, however, accessibility depends on the capability of a person too. While a path may be accessible for one person, it may be inaccessible for others. Therefore, an optimal analysis of accessibility requires integrating both human capabilities and environmental factors. Although environmental factors have two dimensions - physical and social - in early definitions of accessibility the focus has been defined primarily by architectural elements such as ramps and curb cuts, that is, physical properties. In this paper, the accessibility assessment process is carried out considering both the physical and social dimensions of the environment. The social environment involves many factors that may have no direct influence on the mobility of pedestrians (e.g. political systems, governmental structures, and judicial systems). However, it is increasingly being accepted that policies, norms, and regulations related to mobility should take into account explicitly the needs of people with disability.

Here we emphasize the way in which social factors, and in particular, policies, affect the accessibility of urban infrastructures. Linking policies to changes in accessibility can be explored by planners to test the creation of more accessible areas within policy interventions. Policies that regulate the design and construction of pedestrian networks may vary from one city to another or from one country to another depending on the context and the types of social decisions undertaken by different city authorities. For example, altering what is prioritized during snow removal may impact the importance of curb cuts as barrier reductions in countries that have high average snowfall such as Canada, Norway, and Russia; this in turn may impact the accessibility of urban environments for PWMD. In this paper, we propose an approach seeking to investigate the effectiveness of different policy actions on the accessibility of pedestrian networks and their constituent segments. The approach is implemented in Saint-Roch, Quebec City for three policy actions, namely enhancing the quality of existing curb cut pavements (width, slope, and surface quality), removing snow from intersections, and relocating existing electricity poles from the sidewalks.

The remainder of this paper is organized as follows. Section 5.4 reviews related work. Section 5.5 describes the proposed research methods. Section 5.6 explains the accessibility assessment process and illustrates its use in the study area as well as describing some policy actions that may affect accessibility. Section 5.7 presents the influence of policies and regulations on the accessibility. Section 5.8 elaborates the methodology implementation in the study area by investigation of impact of three potential policies on the accessibility maps and the results of tests are shown in section 5.9. And finally, Section 5.10 presents conclusions and future work.

5.4 Related Works

Over the past two decades, a great deal of research (e.g. Matthews et al., 2003; Beale et al., 2006; Kasemsuppakorn and Karimi, 2009; Jonietz et al., 2013; Jonietz and Timpf, 2013; Tajgardoon and Karimi, 2015; Gilart-Iglesias et al., 2015; Mora et al., 2017, 2016; Pérez-Delhoyo et al., 2017) have focused on the mobility of people with special needs. Matthews et al. (2003) and Beale et al. (2006) developed a model for navigation of wheelchair users in urban spaces, called MAGUS. The main objective of the MAGUS project was developing, testing and applying a GIS-based system for modeling accessibility for wheelchair users in urban areas. The process was subdivided into five steps including identifying the most frequently cited urban barriers such as surface quality and slopes; building the pedestrian route network by digitizing the centerline of pedestrian networks; employing the dynamic segmentation approach to generate segments with uniform attributes; quantifying barriers such as by mapping the terrain barriers and extracting slope values; and calculating the cost value for each segment and incorporating these into the proposed model. Kasemsuppakorn and Karimi (2009) developed a model to personalize routing for wheelchair users. The research was focused on user priorities and sidewalk parameters. Sidewalk parameters included slope, surface quality, sidewalk width, presence of steps, and sidewalk traffic. This research used three weighting methods for path optimization, including the Absolute Restriction Method (ARM), the Relative Restriction Method (RRM) and the Path Reduction Method (PRM). Each method was carried out in four steps: weighting the sidewalk parameters; quantifying the impedance value of each segment; modeling the routes for wheelchair users; and choosing the optimal route among many possible routes. The method successfully integrated Fuzzy and AHP (Analytic Hierarchy Process) approaches to develop a routing system for wheelchair navigation. Jonietz and Timpf (2013) proposed a framework for modeling spatial suitability of pedestrian networks based on affordance theory. This framework sought to assess suitability determined by characteristics of humans and their environment, as well as interactions between these. Their model calculated a suitability value by combining pairs of environmental properties and human capabilities. Environmental properties such as trip distance and sidewalk slope were used to rate the suitability of paths. This model was implemented in a navigation scenario for five persons with different abilities with respect to segment slopes and the presence of stairs. Tajgardoon and Karimi (2015) proposed a path determination approach based on a weighted linear model for different characteristics of sidewalk segments to evaluate the accessibility of sidewalks for PWMD. These characteristics included segment distance, slope, width, surface quality, and different sidewalk traffic zones. They developed this approach to simulate and visualize the accessibility for two groups of PWMD as well as for blind users. Finally, Gilart-Iglesias et al. (2015), Mora et al. (2016, 2017), and Pérez-Delhoyo et al. (2017) proposed systems for the analysis and evaluation of the effectiveness of urban accessibility, specifically for people with disabilities, using the latest advances in the information and communication technologies, global positioning systems (GPS), geographic information systems (GIS), smart sensing, and cloud computing. The proposed models provide automatic monitoring tools to dynamically discover, assess, and classify the accessibility of urban environments.

Although, all of these studies considered human-environment interactions in the evaluation of accessibility of a pedestrian network, they only evaluated the physical dimensions of the environment and ignored the impact of the social dimensions on the accessibility of PWMD. There are a few studies in the literature which consider the social dimensions of the environment in their studies concerning the mobility of pedestrians (e.g. Mackett et al., 2008; Tansawat et al., 2015; Anciaes and Jones, 2016; and Morales et al., 2014). For instance, Mackett et al. (2008) developed a software tool called AMELIA to show the impacts of transport policy, as a social factor, on the social inclusion of elderly people and PWD. They tested the influences of applying four new policies to improve the accessibility of the St Albans city center for PWD. The influence of policies were quantified and visualized on the city map. They showed that providing benches as an urban design policy would provide the most cost-effective increase in accessibility of the pedestrian network. In other work, Tansawat et al. (2015) showed that the average income of families has a significant negative relationship with respect to social inclusion. This study investigated the influence of a free train policy on the encouragement of low-income groups to participate more fully in a range of daily activities. Anciaes and Jones (2016) analyzed the influence of interventions based on the reduction of barriers within the pedestrian network. These interventions included changing the layout of the local street networks and redesigning busy streets. They investigated how employing new interventions such as increasing the density and connectivity of the links available to pedestrians, adding crossing facilities, reducing the speed limit, or reallocating road space to pedestrians could affect the way pedestrians walk within network. In another study, Morales et al. (2014) aimed to investigate some design solutions to improve the accessibility of sidewalks for seniors, wheelchair and walker users during winter conditions. They showed that existing snow removal policies were not adequate to provide the accessibility required for PWMD. This research proposed applying new policies to remove snow from the sidewalks.

Although most of these studies propose solutions in order to increase social inclusion and consequently to improve life quality, to our knowledge, none of them consider and quantify the impact of the social factors and policies in the estimation of the accessibility of the pedestrian networks in urban environment. In the present study, we analyzed the accessibility of the existing pedestrian network with the consideration of different policies and then estimate the effectiveness of proposed solutions and visualized them on the accessibility maps.

5.5 Methodology

Several definitions are presented for accessibility in different contexts. For example, in urban mobility, accessibility is often defined as the ease of reaching a destination with respect to distance, time and cost constraints (Handy and Niemeier, 1997). In the case of pedestrian mobility, however, accessibility depends on the interactions between the individuals and the pedestrian network itself. In our methodology, we quantify the accessibility level of different segments (as a cost value) by integrating a measure of confidence on the part of PWMDs with regard to their mobility. Assessing the accessibility level of each segment in this way, the accessibility map of the pedestrian network is then generated. This map is used as a tool to investigate the influence of different policies on the accessibility of the pedestrian network. Figure 1 displays an overview of this methodology. First, the most important barriers are identified based on the perception of the PWMD themselves. These, combined with other relevant properties, are then used to segment the pedestrian network. A user profile database is created which incorporates a range of different factors, and these, in turn, are matched to factors previously stored in the network database. The aforementioned databases are then used as inputs to a fuzzy logic system used to calculate the cost value of each segment and then generate a map of the accessibility of the pedestrian network. Finally, in order to evaluate the influence of possible policies, the network database can be updated based on the effects of new policies. Using the updated database, all of the processing steps can be repeated to generate new accessibility maps and evaluate the effectiveness of proposed policies.

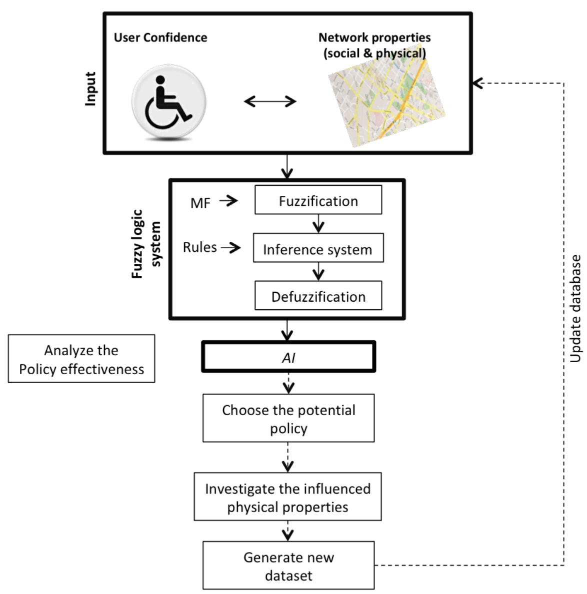


Figure 5.1. An overview of the proposed methodology

5.6 Accessibility assessment framework for people with motor disabilities

The accessibility assessment process is carried out in three steps including generate the pedestrian network, gathering the user profile information, and evaluating the accessibility level of each segment based on the user confidences.

5.6.1 Generate the pedestrian network database

One of the major issues related to existing navigation systems is that the map data has generally been designed for car navigation and is not appropriate for pedestrians. Pedestrian networks are parts of urban areas that play a significant role in the outdoor mobility of PWMD. Pedestrian networks are typically classified into sidewalks, crosswalks, footpaths, building entrances, trails, pedestrian bridges, and tunnels (Karimi and Kasemsuppakorn, 2013). Besides sidewalks, which have significant influence on the mobility of PWMD, intersections including crosswalks and curb cuts are also considered as important subclasses of pedestrian network elements for PWMD (Mobasheri, 2017). Crosswalks are designated to indicate the crossing places for pedestrians and curb cuts assist wheelchair users (or any wheeled device) to transit easily from sidewalk to crosswalk (or road surface in general) and vice-versa. In the literature, all of these classes are analyzed in similar ways. However, the perception of PWMD is different regarding each of these classes and their properties. For instance, from their perception, the influence of a pothole located on the crosswalk on their mobility is completely different than one located on the sidewalk.

Hence, in order to assess the accessibility of pedestrian networks for PWMD, there is a need to analyze each type of class separately. Thus, our pedestrian network includes three types of components, namely sidewalks, curb cuts, and crosswalks. In addition, in order to assess the accessibility level of each component, these are divided into segments with similar properties. Each segment has parameters that can be either static or temporal. As a result, the pedestrian network contains decision points connected by sidewalk, curb cut, and crosswalk segments, where each segment is represented as a vector with properties. In our previous work, we investigated in details which of these properties were required for PWMD, and how these should be divided into static and temporal factors (for details see Gharebaghi et al. (2017)). Table 5-1 shows the barriers most frequently identified by PWMD, the range of values, their fuzzy classes, and their definitions. Thus, the properties (*S, W, SuT, SuQ, SeT, SeL, HC* as presented in Table 1) are categorized in the fuzzy set classes by predefined defined membership values. For example, the surface quality values are classified into three sets including *Poor*, *Fair*, and *Good*. A segment with quality value of 3.5, for example, belongs to the fuzzy set *Poor* with the membership value 0.5, and to the fuzzy set *Fair* with a membership value of 0.5 (for more details see Kasemsuppakorn and Karimi, 2009).

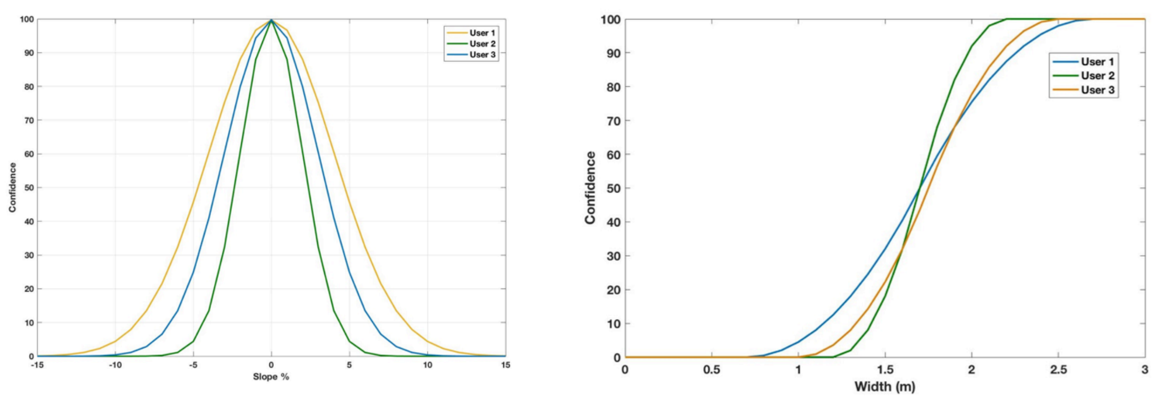
Table 5-1. Most identified potential barriers for PWMD

Barrier	Temporality	Definition of the barrier
Slope (S)	Static	The slope value of a segment that can be gentle, moderate, and steep
Width (W)	Static	The width of a segment that can be not passable, narrow, moderate, and wide
Surface type (SuT)	Static/Temporal	The type of a segment that can be asphalt, concrete, brick, gravel, and cobblestone
Surface quality (SuQ)	Static/Temporal	The quality of a segment that can be poor, fair, good, and excellent
Segment type (SeT)	Static	The type of a segment that can be sidewalk, curb cut, and crosswalk
Segment length (SeL)	Static	The length of a segment that can be short, medium, and long
Height changes (HC)	Static	The elevation change in a segment that can be ignorable, small, moderate, and big
Snow (Sn)	Temporal	The depth of snow that covers the segment and can be small, moderate, and big

5.6.2 User Profile database

The accessibility of the pedestrian network for PWMD is evaluated in relation to the interaction between the user's capabilities and the surrounding environment. For example, a segment can be accessible for some while inaccessible for others even if the type of disability is the same. In order to evaluate the ability of a wheelchair user, approaches such as the Wheelchair Skill Test (WST) (Kirby et al., 2002), the Wheelchair Circuit (Kilkens et al., 2004), and the Wheelchair Outcome Measure (WhOM) (Mortenson et al., 2007) have been proposed. In this paper, we measure the perceived ability (i.e. confidence) of a person for performing a given task. Confidence has been identified as a potential contributor to wheelchair mobility via a search of the wheelchair skills training literature (Best et al., 2005) and the evidence suggests a user's confidence is a stronger predictor of performance than the skill itself (Rushton, 2010). A person might be able to perform a given task but not be confident enough to carry it out. According to (Rushton, 2010; Rushton et al., 2011) confidence is a more reliable criterion than actual ability.

To quantify the confidence level of individuals, the *wheelchair use confidence scale* (WheelCon, Rushton, 2010) was employed. According to this approach, the user's confidence level for a mobility task is expressed using a value between 0 (low confidence) to 100 (high confidence) (Rushton, 2010). Hence, we characterised the individual's confidence regarding each class of barrier using a value in the range of [0,100]. Figure 5.2 situates the relationship between the values of slope and width of a segment and confidence level for three different users. The confidence values were then fuzzified into fuzzy set classes by membership values including *Very Low, Low, Medium, High, or Very High*. For example, a segment with slope value of 8% is associated with the fuzzy set *Moderate* while *Steep*, which depends on the user profile, might belong to the fuzzy set of *Medium confidence* or *Low confidence*. So, we replace the values of variables (*S, W, SuT, SuQ, SeT, SeL, HC, and Sn*) with corresponding user confidence fuzzy values ($\widetilde{S\_Con}$, $\widetilde{W\_Con}$, $\widetilde{SuT\_Con}$, $\widetilde{SuQ\_Con}$, $\widetilde{SeT\_Con}$, $\widetilde{SeL\_Con}$, $\widetilde{HC\_Con}$, $\widetilde{Sn\_Con}$).



a. Slope values relationship with the confidence level

b. Width values relationship with the confidence level

Figure 5.2. A simulation of the relationship between the slope and width values of a segment with the confidence level of users

5.6.3 Compute the cost values

In order to evaluate the accessibility level of each segment, a cost value representing the accessibility level of that segment was calculated. To determine this cost value, the different values associated with the segment's properties, which are crisp values, need to be aggregated. However, in many cases the precise quantitative values are often inadequate to describing real-life situations and people use a more qualitative way to characterise environmental factors that affect mobility (e.g. narrow sidewalks). In our study, the fuzzy logic approach is utilized to meet these requirements. Fuzzy logic, introduced by Zadeh et al. (1965), is widely used in many different applications including routing and transportation planning (e.g. Kasemsuppakorn and Karimi 2009; Karimanzira et al. 2006) to model the vagueness that is associated with human cognitive processes. To employ fuzzy logic, three steps must be followed: (1) build the rule set and define the membership functions (fuzzification), (2) develop a fuzzy inference system (FIS) using if-then rules and (3) merge the outputs of the rules and ensure defuzzification of the results using a different set of membership functions to derive output variables (Mamdani and Assilian, 1975).

To carry out the fuzzy logic approach, first, the transformation from the pre-determined accessibility values into a non-crisp fuzzy environment was conducted. This process is called fuzzification and is performed by defining membership functions. A membership function is a mathematical function which maps the association of a value to a set between 0 and 1 (Beynon, 2004). In this paper, the membership functions for all variables were expressed in trapezoidal fuzzy numbers. Thus, the accessibility values (S, W, SuT, SuQ, SeT, SeL, HC, and Sn) were transferred into fuzzy set classes using predefined membership values. For example, slope can be defined as gentle, moderate, or steep. A slope value, for example, 3%, corresponds to the gentle and moderate subsets according to the membership function. Following this, the fuzzy membership of each attribute of a segment must be transformed to generate a user confidence level (e.g. S_Con). In our case, there were five fuzzy sets including VL, L, M, H, and VH, and nine variables including S, W, SuQ, SuT, SeL, SeT, HC, and Sn. The If-Then rules were subsequently defined to aggregate the individual user confidences and, consequently, calculate the accessibility level of each segment as the output variable. For example:

If (the S_Con is very low) & (the SuQ_Con is low) Then (the segment is not accessible)

In order to cover all possible combinations of fuzzy sets for diverse variables, it is necessary to define m^n rules where *m* is the fuzzy set number and *n* is the number of variables. Therefore, we needed to define 5^8 rules. Table 5-2 presents the rule definitions, which are stated as if aggregation can only be applied to two components; in cases where more than two parameters result from an earlier aggregation, each element of a parameter pair is aggregated with the next parameter and this process is continued until the total confidence is obtained. Since these rules directly affect the result of the process, they need to be validated. In our research, an expert who is also a wheelchair user carried out the validation step. However, we understand that further investigation is needed for a more rigorous validation of these rules by participation of experts and wheelchair users.

Table 5-2. Defined if-then rules between two variables of p & q

Rule No.	Confidence Level		Accessibility Level	Rule No.	Confidence Level		Accessibility Level
	p	q			p	q	
1	VL	VL	NA	9	L	VH	LA
2	VL	L	NA	10	M	M	LA
3	VL	M	NA	11	M	H	MA
4	VL	H	NA	12	M	VH	MA
5	VL	VH	NA	13	H	H	MA
6	L	L	NA	14	H	VH	A
7	L	M	NA	15	VH	VH	VA
8	L	H	LA				

Once the rules are defined and the aggregation step is performed, the accessibility index of each segment can be derived. To address this issue, a defuzzification technique should be applied to produce exact numerical values from the fuzzy values based on the defined membership functions and rules. The output values were utilized for determining the accessibility levels of pedestrian network segments via five categories: Not Accessible *(NA)*, Low Accessible *(LA)*, Medium Accessibility *(MA)*, Accessible *(A)*, and Very Accessible *(VA)*.

5.7 The influence of Policies and regulations on the accessibility

Mobility initiatives for PWMD cannot be limited to the physical dimension of the problem only; social issues need to be addressed too (Fougeyrollas, 2010; Oliver, 1996). In the Human Development Model - Disability Creation Process (HDM-DCP) (Fougeyrollas, 2010, 1998), a model of disability widely used in rehabilitation, the environment is partitioned into two parts – physical and social. The social part of the environment involves many factors (see the taxonomy in **Figure 5.3**), many of which may have no direct influence on the mobility of pedestrians (e.g. political systems, governmental structures, and judicial systems). However, it is increasingly being accepted that policies, norms, and regulations related to mobility should take into account explicitly the needs of those who have special needs.

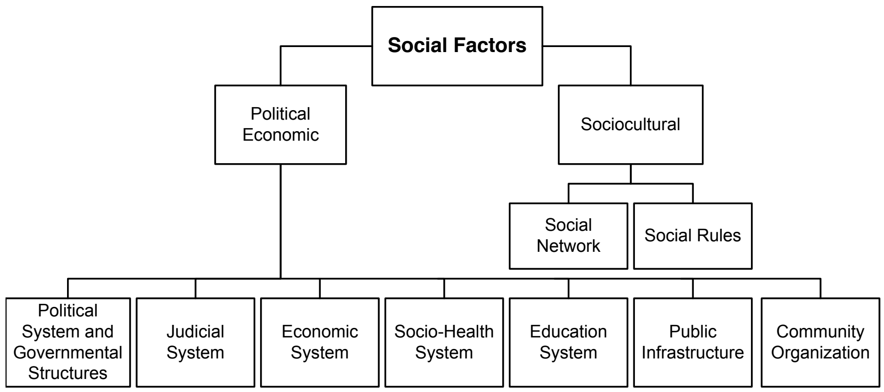


Figure 5.3. Social factors taxonomy (Fougeyrollas, 1998)

In the context of pedestrian network accessibility, in some cases, the influence of social factors is more noticeable than their physical counterparts. For example, **Figure 5.4** shows the physical entities on the sidewalk including accumulation of snow and presence of trash bins. These barriers affect the accessibility of sidewalk segments for everyone, but especially for PWMD. Although these entities belong to the physical environment, the main cause of the presence of these barriers is related to social behaviour and hence these should be considered as social factors. This implies that these barriers should be considered in relation to the snow removal and weekly trash collection policies of a municipality, or to the culture or behaviour of the people living in the neighbourhood of the sidewalk. These are examples of social factors that affect the level of accessibility of the sidewalk.

In order to analyze the effective influence of social factors on the accessibility of pedestrian networks, we propose to investigate the influence of different policy actions on the generated accessibility map for wheelchair users. To address this issue, our proposed methodology quantifies the influence of applying the policies and applies the results to the accessibility map. To do so, first, we select the given policy action and generate new data corresponding that policy action. The generated data then replaces the original data in the pedestrian network database, the accessibility evaluation process is carried out again anew, and the resulting accessibility map is regenerated. Finally, the retrieved results and the effectiveness of that policy are investigated. In the following section, this whole process is implemented for the Saint-Roch neighbourhood in Quebec City.

Figure 5.4. Examples of barriers on the sidewalk

5.8 Implementing the methodology

We apply the whole process of accessibility assessment for an area located in the old part of Quebec City and visualize the accessibility maps for manual wheelchair users. To fulfill this assessment each user determines the confidence level by choosing a corresponding number from 0 to 100. The data on users' confidences for over 120 manual wheelchair users are collected. Table 5-3 shows the age distribution by gender of the participants. In this scenario the confidence mean value is calculated for the wheelchair users and the accessibility assessment process is visualized for all participants employing their mean confidence (i.e. 52 out of 100).

Table 5-3. Age distribution by gender of the participants

Age	Men	Women	Years with Diagnosis=<5	Years with Diagnosis>5
50-60	41	30	8	63
60-70	29	15	3	41
70-80	6	5	5	6
80-90	1	2	1	2

On the other hand, we need to collect the detailed data regarding the pedestrian network. Collecting, preparing, and structuring such database is time consuming and costly tedious job. Nowadays, using data generated from the Volunteered Geographic Information (VGI) has become a hot topic for various applications including routing and navigation. However, there are still many concerns regarding the quality of such datasets (Mirri et al., 2014; Mobasheri et al., 2018, 2017; Qin et al., 2016; Zipf et al., 2016). In order to provide a reliable and accurate data for the pedestrian network database, in this paper, we used several existing data sources including the collections of the Ville de Québec, 2015, the web portal of the Ville de Québec (i.e. S, W, SeL, SuT, and SuT), and a complementary field survey (i.e. SuQ and HC). Additional data related to details of curb cuts including slope, width, surface quality, surface type, and snow were also collected in the field for over 200 segments. The snow data was collected on February 17, 2017. To visualize the accessibility map, the framework described here was executed in a web-based GIS tool (MobiliSIG application- Mostafavi et al., 2017). **Figure 5.5** illustrates the accessibility map generated for the Saint-Roch area of the city. In the accessibility map, "Not Accessible" segments are represented in red, "Low Accessible" segments are identified in yellow, "Accessible" segments are green, and "Very Accessible" segments are dark green. According to the statistical analysis, 81% of the segments in the study area are accessible, 5% of the segments are of low accessibility, and 14% of the segments are not accessible for a user whose confidence corresponds to the average confidence level obtained from all the wheelchair users.

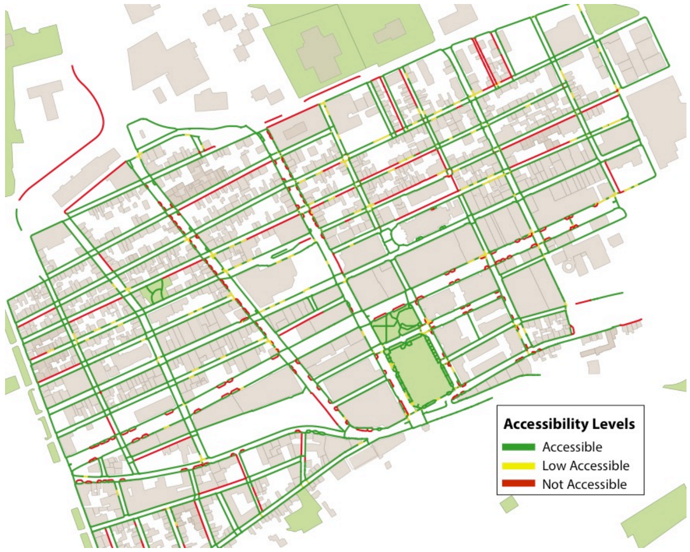


Figure 5.5. Accessibility map of Saint Roch, Quebec City for 127 wheelchair users

According to the generated map, there are several sidewalk segments that are not accessible for the participants. One of the reasons might be a design policy poorly oriented towards the development of an inclusive city based on the universal design approach. For example, locating electric poles on the middle of sidewalks is one significant barrier, which is identified in the study area. The second reason for inaccessible segments is the existence of steep curb cuts in the area, another poor design feature. This sector is a part of the historical and cultural patrimony of the city and hence there are more restrictive rules for renovation activities. Hence, there is a need to implement new policies that respect those restrictions but consider the specific needs of PWMD at the same time. Modifying these criteria and regenerating the accessibility maps showcases the value of such changes in urban design policy. We investigated this potential by modifying three policies and simulating the changes in the accessibility maps. The chosen policies included "enhancing the quality of existing curb-cut pavements (width, slope, and surface quality)", "cleaning snow from intersections and curb cuts by applying proper snow-removal policies" for intersections, and "relocating electricity poles from the sidewalks". Because the implementation of these policies is tied to other issues such as economical factors, the study of the interconnection between these factors is beyond the scope of this paper.

Policy 1: Improving the characteristics of existing curb cut pavements

According to our accessibility assessment process, a significant number of the inaccessible/low accessible segments were located at the intersections. This can be recognized on the generated maps (see Figure 5.6). On the other hand, the security of PWMD is highly affected while they are crossing the streets. Intersections usually are considered as challenging points for the mobility of PWMD in the pedestrian network where they make a transition from sidewalks to an intersecting road surface (e.g. Bennett et al., 2009; Calder, C Jill; Lee Kirby, 1990; Gaal et al., 1997; Kirby, A., R Lee; Ackroyd-Stolarz, G., Stacy; Brown, A., Murray; Kirkland, A., Susan; Macleod, A., 1994; Ummat, Samira; Kirby, 1994; Xiang, H; Chany, A-M; Smith, 2006). The risk of tipping over or falling from the wheelchair or having a car accident always threatens wheelchair users in the intersections.

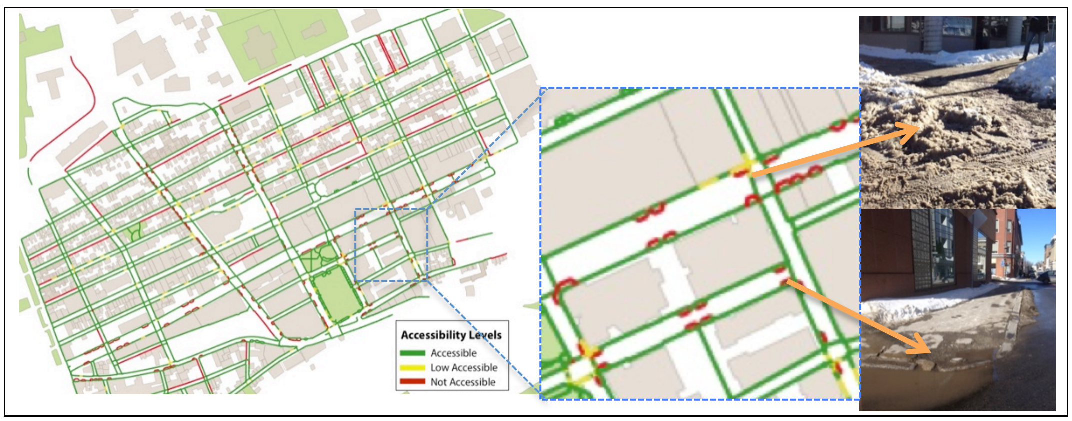


Figure 5.6. The accessibility condition of the curb cuts in the study area

Therefore, there is a need to pay more attention to the intersections as the most challenging places for the mobility of PWMD. The curb cuts are constructed to assist wheelchair users to ease transit from sidewalk to crosswalk and vice-versa. Curb cuts play an important role in these transitions. Here, we investigate the impact of improving the characteristics of the curb cuts on the accessibility of the pedestrian networks. To do so, in our case study we simulated the implementation of a policy of A) eliminating steep segments, B) improving surface quality, and C) widening the narrow spans of existing curb cuts where possible in the Saint-Roch area of Quebec City. Indeed, applying each policy led to changes in the value of corresponding variables and then the cost value of that segment was recalculated considering the new data. For example, consider a segment *i* with the values of (*Si, Wi,* *SuTi, SuQi, SeTi, SeLi, HCi, Sni*) where Si is steep. By applying policy A, the slope value of this segment changes to moderate and then the accessibility level of this segment is recalculated. We evaluated the accessibility level of the segments after applying each policy change and then visualized the results in the accessibility map. Table 5-4 shows the influence of applying these policies on the accessibility of curb cuts, in such a way that each change is carried out independently of the others. The table clearly shows that the policy change could lead to substantial gains in segments normally considered to have low accessibility.

Table 5-4. The results of the policy actions (a, b, c) effectiveness on the accessibility

	Existing situation	Policy A	Result (%)	Policy B	Result (%)	Policy C	Result (%)
Examined segments	233	233		233		100	
Accessible segments	93	120	29	113	22	97	4
Low Accessible segments	95	68	28	75	21	136	43
Not Accessible segments	45	45	0	45	0	0	100

Policy 2: Cleaning snow from curb cuts by applying proper snow-removal policies

Snow is always considered as a big challenge for PWMD in urban areas. It is ranked as the third most difficult item indicated by our pilot study of over 120 wheelchair users. This challenge is more highlighted in countries that have high average snowfall such as Canada, Norway, and Russia. Snow always affects the social participation of people especially PWMD living in these countries during the winter season. Although snow removal is prioritized on sidewalks during the winter, however, the level of accessibility of the pedestrian network for PWMD is still limited. For example, improper snow removal procedures will impede the accessibility for individuals with motor disabilities because of accumulated snow on places such as curb cuts. This issue is also investigated by incorporating new technologies to improve snow removal. For example (Morales et al., 2014) proposed using an electrical system for snow-melting under the curb cuts.

Here, we investigated how altering snow removal policies such as the use of novel technologies, may change the accessibility maps. To test this policy change, the data on the state of the curb cuts for over 200 curb cuts in our study area were collected. The data were collected on February 17, 2017, just two days after a snowfall in Quebec City. Table 5-5 demonstrates the accessibility level of segments before and after the simulated use of the new policy. As was the case for Policy 1, it is projected that this policy change would lead to improvements in low accessibility segments.

Table 5-5. The results of the policy action "2" effectiveness on the accessibility

	Existing situation	After employing policy action	Results (%)
Examined segments	233	233	
Accessible segments	93	108	16
Low Accessible segments	95	80	16
Not Accessible segments	45	45	0

Policy 3: Relocating the existing line of electricity poles on the sidewalks

As mentioned, electric poles on the middle of sidewalks are significant barriers that limits or blocs the mobility of wheelchair users. This can be clearly recognized by the generated maps (see **Figure 5.7**).

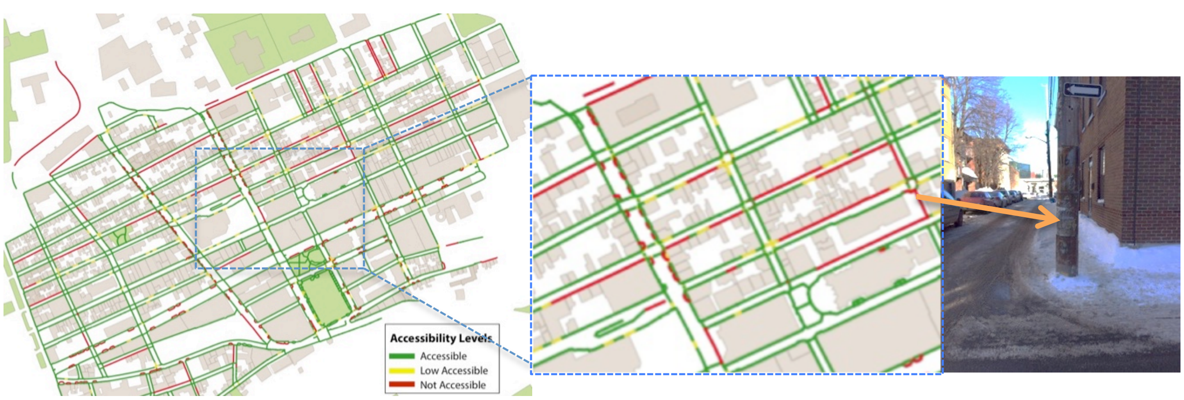


Figure 5.7. The accessibility condition of the sidewalks in the study area

The existence of poles on the sidewalks leads to reduce the width of sidewalk and consequently decrease the accessibility. Relocating the existing line of electricity poles on the sidewalks can be investigated as another feasible policy that has impact on the accessibility of sidewalks in our study area. The results obtained by the implementation of this scenario show that moving electrical and telecommunication lines underground would be an option to clear the sidewalk that allows PWMD to move without restrictions. Table 5-6 indicates the accessibility level of curb cuts in the existence situation as well as after employing the policy action. In the following section, we investigate the results of the proposed policy tests.

Table 5-6. The results of the policy action "3" effectiveness on the accessibility

	Existing situation	After employing policy action	Results (%)
Examined segments	2622	2622	
Accessible segments	1936	1972	2
Low Accessible segments	378	383	1
Not Accessible segments	308	267	13

5.9 Analyze the effectiveness of policy actions

The results demonstrate that implementing the policy 1-a (eliminating steep segments) leads to reduce 27 segments of the low accessible curb cuts while implementing the policy 1-b (improving the surface quality) improves only 20 segments' accessibility level. In addition, a significant impact of the implementing of the policy 1-c (widening the narrow widths) is noted. Hence, in total the implementation of this policy may improve the accessibility of 45 segments. According to the results, cleaning the snow from curb cuts reduces only 15 segments of not accessible segments. The results are summarized and ordered in Table 5-7.

Table 5-7. Order of the different policy actions

Policy order	Policy action	Segment type	Number of improved segments' accessibility
1	Widening the narrow segments	Curb cut	45
2	Relocating the existing line of electricity poles	Sidewalk	41
3	Eliminating steep segments	Curb cut	27
4	Improving the surface quality	Curb cut	20
5	Cleaning snow from the segments	Curb cut	15

We noticed that the cause of 19% of not accessible curb cuts is related to the width where 8% is reduced by employing the snow policy test. It is because of the existence of a correlation between the presence of snow and reduction of sidewalk width. The snow dataset is collected on February 17, 2017, two days after snowfall event in Quebec City. Obviously, the correlation would be prominent when the snow dataset is collected in the snowfall day or a day after. As shown in Figure 6, the impacts of policy changes can be investigated separately. That is, the impacts of other barriers will be measurable only once an appropriate policy change is applied. It is quite obvious that inaccessible/low accessible segments would disappear if all barriers were removed concurrently.

Figure 5.8. Visualization of implementation of the policy tests on the curb cut

Figure 5.9 shows a view of the study area after the implementation of the third policy test. In this figure, the accessibility map is re-generated by excluding the existing electricity poles from the sidewalks. As shown, the accessibility level of these parts of the sidewalk is changed from not accessible to accessible. According to the statistical results, the implementation of this policy test improves the accessibility of 41 segments in the study area.

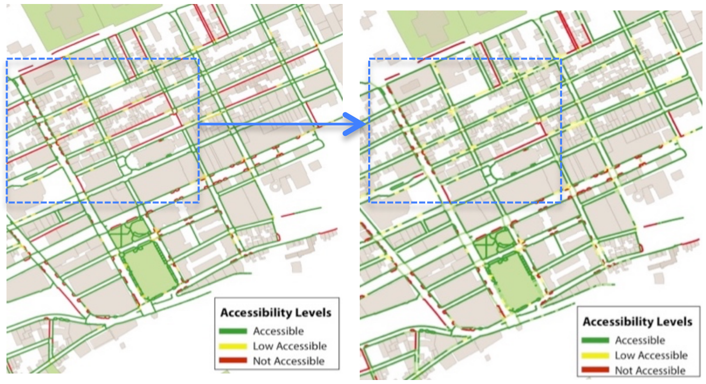


Figure 5.9. Accessibility map after implementation of Policy 3

5.10 Conclusion and Future Work

For people with disabilities to live independently and fully participate in all aspects of daily life, they need to have access on an equal basis to the physical environment, to the transportation infrastructure, and so forth. To address this issue, finding accessible paths within the pedestrian network is a way for enhancing their effective mobility and their social participation within society. In this paper, we focused on ways in which policies (i.e. social factors) can be considered in the assessment of the accessibility of a pedestrian network. We aimed to investigate the influence of the implementation of policy changes on the accessibility of the intersections and sidewalks by means of simulation. Among various policies, we tested the impact of three policies, namely enhancing the quality of existing curb cut pavements (width, slope, and surface quality), removing snow from intersections, and relocating the existing line of electricity poles on the sidewalks. The influence of these policies were quantified and visualized on the accessibility map generated for the Saint-Roch sector in Quebec City.

The results demonstrated the impact of the different policy changes on the accessibility of curb cuts for PWMD. It was shown that decreasing the slope of steep curb cuts, widening the narrow widths, and cleaning the snow from curb cuts would significantly improve the accessibility level of pedestrian networks for everyone, and especially for PWMD. We have seen that the impact of improving the surface quality of the curb cuts is almost negligible compared to that of other factors. In addition, the implementation of the third policy change was investigated and a significant improvement of the accessibility level of sidewalks was noted. The proposed scenario-based accessibility assessment analysis together with appropriately generated accessibility maps and the statistical results might be useful for city authorities to explore different policy options and to understand and quantify their impacts. Decision-makers can compare the impacts of different policies and decide which ones are the most effective. One of the most challenging issues in this research was to collect precise and detailed data about the pedestrian network, as this is a very time consuming and costly task. Therefore, we have limited the study area to perform our analysis. Furthermore, the environmental factors are temporal and change in time. Temporality of the characteristics of environment raises the complexity of the accessibility assessment process. Thus, as future work, we will develop an effective approach to generate a relatively quick and low-cost detailed spatiotemporal data for the accessibility assessment purposes. In addition, we plan to integrate other social factors that may play a prominent role in the accessibility of pedestrian networks for PWMD.

Acknowledgments

This work is supported by the Canadian Institutes of Health Research (CIHR) and the Natural Sciences and Engineering Research Council (NSERC). The authors would also like to acknowledge interesting inputs from MobiliSIG team during our various group discussions.

Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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6 Planification d'itinéraire personnalisée

6.1 Résumé

Tout le monde profite des réseaux piétonniers. Les personnes sans handicap peuvent ne pas trouver difficile de marcher sur un trottoir étroit, de marcher sur des nids-de-poule, etc. Cependant, les PMR peuvent trouver difficile de faire face à ces obstacles. Pour les PMR, les voyages de routine peuvent souvent occasionnés plusieurs problèmes, de nombreux obstacles limitant leur mobilité et rendant par conséquent difficile leur participation aux activités sociales et récréatives. Les difficultés potentielles et les dangers associés aux déplacements des PMR pourraient être considérablement réduits si le système de guidage routier leur fournissait un itinéraire personnalisé. Parmi les divers besoins en mobilité des PMR, y compris l'accessibilité, la sécurité, le confort et le plaisir, l'accessibilité des réseaux piétonniers est le besoin fondamental pour le calcul des itinéraires optimaux. L'accessibilité est le résultat d'interactions entre l'individu et l'environnement. Par conséquent, les itinéraires personnalisés doivent tenir compte des capacités personnelles des PMR et des propriétés environnementales du réseau d'acheminement. Pour résoudre ce problème, nous proposons une approche de routage pour les PMR qui considère exclusivement leurs perceptions, leurs préférences et leurs confidences. Nous enquêtons sur les critères d'accessibilité, générons des réseaux de routage en fonction de ces critères, quantifions l'indice d'accessibilité (IA) et calculons enfin les itinéraires optimaux. La méthode Fuzzy-TOPSIS est affinée en utilisant les confiances des utilisateurs pour agréger les valeurs des critères et l'algorithme de Dijkstra est modifié pour calculer les routes optimales. Afin de vérifier l'exactitude de la méthodologie, nous comparons le niveau d'accessibilité d'un graphique simple en utilisant l'approche proposée et les If-Then rules. Le processus de routage est appliqué à Saint-Roch pour trois utilisateurs de fauteuils roulants manuels.

Corps de l'article

Titre: Accessible routes for wheelchair users; A fuzzy multi-criteria algorithm

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Revue: Submitted to International Journal of Geographical Information Science

6.2 Abstract

Everyone benefits from pedestrian networks. People with no disabilities may have little difficulty walking on narrow sidewalks, over potholes, and so on. However, people with motor disabilities (PWMD) may find it more difficult to deal with such obstacles. For PWMD, even routine trips are often fraught with problems, with many different obstacles restricting their mobility and consequently rendering their participation in social and recreational activities difficult. The potential difficulties and dangers associated with travel for PWMD could be significantly reduced if route guidance systems provided them with appropriate personalized routes. Among the diverse needs for the mobility of PWMD, including greater accessibility, enhanced safety, comfort, and pleasure, the accessibility of the pedestrian network constitutes the principal requirement for the computation of appropriate optimal routes. Accessibility is the result of interactions between the individuals and their environments. Hence, the calculated routes should consider the PWMD's personal capabilities as well as the environmental properties of the routing network. To address this issue, we propose a routing approach for PWMD that takes into account their perceptions, preferences, and confidences. We investigate criteria for accessibility, generate routing networks based on these criteria, quantify an accessibility index (AI), and finally calculate optimal routes. A fuzzy-TOPSIS method was used that

incorporates user confidence to aggregate the values of relevant criteria. Furthermore, we applied the Dijkstra's algorithm to compute optimal routes. In order to verify the accuracy of the methodology, we compared the accessibility of simple graphs that incorporate the accessibility criteria and if-then rules. The routing process was applied to the Saint-Roch neighbourhood in Quebec City to support the mobility of three manual wheelchair users.

Keyword: Routing, Accessibility, Disability, Fuzzy-TOPSIS, Fuzzy Logic, Confidence

6.3 Introduction

According to the Convention on the Rights of People with Disabilities (Assembly, 2006), ratified by over 160 countries, there is consensus concerning the need for access to the physical environment, transportation services and so on, on an equal basis with others. This should be possible regardless of any functional limits of people with disabilities (Noreau et al., 2015). People with motor disabilities (PWMD) represent a large portion of the overall population and a significant number of potential users of pedestrian networks. Most commonly used route planning applications do not consider the special needs of people with disabilities in determining routing. For PWMD, routine trips are often fraught with problems, with many different obstacles restricting their mobility. For example, they may experience diverse encumbrances on city pavements, including high curbs, steps or uneven surfaces as well as long inclines. These may be especially challenging in an unfamiliar environment. The reduced ability of PWMD to move around will impact negatively on their ability to fully participate in society, which is a right guaranteed by law.

The most important obstacle to developing and proposing routing applications that could be effective for PWMD, is the lack of effective navigation systems that incorporate information about pedestrian networks (Völkel and Weber, 2008), including information about encumbrances and obstacles. Furthermore, because of the diverse capabilities of PWMD, these navigation systems must include information about the personal capabilities of users to be effective. A one-size-fits-all solution will not be functional. Third, it has been demonstrated (Rushton et al., 2013) that user confidence concerning the ability to traverse a given travel segment is also a factor that should be incorporated into navigational aids.

According to *the hierarchical model of walking needs* developed by Alfonzo (2005), the decision-making process during walking is categorized into five levels. These levels range from the most fundamental concerning the feasibility of walking (i.e. related to personal limits), to higher order levels (i.e. related to urban form) including the needs for accessibility, safety, comfort, and pleasure. The same hierarchical structure can be employed to prioritize the needs of PWMD for a routing computation for wheelchair mobility. In this model, feasibility is considered to be a factor affected by the user's physical condition, age, and weight. In our research, we assume that a PWMD is capable of using his/her mobility assistive technology such as wheelchair – hence the feasibility level is implicitly addressed. Instead, accessibility would become the basic need while safety, comfort, and pleasure would correspond to higher levels. For PWMD, a higher order need could not be addressed if the most basic need was not already met. For example, the landscape and scenery of a route may provide pleasure, but if the accessibility of the route is not suitable, these considerations become redundant.

To satisfy these requirements, there is a need to create accurate datasets that include information on both user profiles (e.g. user capabilities and preferences) and aspects of the environment in relation to the mobility task. Relevant environmental characteristics include information on accessibility (e.g. surface quality of the sidewalks), safety (e.g. number of crossings), comfort (e.g. wide sidewalks), and pleasure for the user (e.g. point of interests). Beyond the issue of data, there is also need for an information system that is responsive to the requirements of PWMD. Navigation systems are examples of dedicated geographical Information Systems (GIS), that is, they are powerful tools that exploit geospatial databases. They can be used to construct, model and analyze pedestrian networks and corresponding user profiles, and to represent computed routes. In this paper, the accessibility of pedestrian networks is considered as a fundamental requirement for determining an optimal route. We investigate the criteria necessary for assessing accessibility, we generate routing networks based on these criteria, we calculate the cost values of each segment (i.e. based on the accessibility index (AI)), and finally, we compute the optimal routes. In order to determine the accessibility index, a Fuzzy-TOPSIS method (Chen, 2000) is refined using user confidences. In our proposed framework, confidence values representing the difficulty level for traveling along each network segment are determined in such a way that these values can be aggregated and used to calculate the cost value of each segment. To our knowledge, this is the first time that user confidence levels have been used to evaluate the accessibility in an urban area. To validate the proposed method for the calculation of the accessibility index, these AIs are re-calculated using the Zadeh Fuzzy Logic method and if-then rules. The proposed method is implemented in the neighbourhood of Saint-Roch, Quebec City for three manual wheelchair users and the results are presented.

The paper presents the methodology for determining route selection algorithms to be used within the MobiliSIG project. *MobiliSIG* is a multimodal mobile assistive technology for the navigation of PWMD in urban areas that is developed by a multidisciplinary team at the *Center for research in Geomatics (CRG)* and the *Center for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS)*. The paper is organized as follows: Section 6.4 provides information on related research concerning routing for PWMD. In section 6.5, the methodology of the proposed approach is described. Section 6.6 presents a simulation of the proposed methodology for a simple context. In Section 6.7, the proposed approach is implemented for three manual wheelchair users in Saint-Roch, Quebec City and their personalized routes are presented and finally, the paper is concluded in Section 6.8.

6.4 Related Research

The past decade has seen the rapid development of route planning systems for PWMD. Several attempts have been made to design and develop personalized routing approaches (Beale et al., 2006; Kasemsuppakorn et al., 2014; Kasemsuppakorn and Karimi, 2009; Matthews et al., 2003). The main characteristics stated in most of these approaches include identifying the routing criteria based on the perception and experience of PWMD, generating accurate routing network databases in a scalable and affordable manner, developing models and algorithms that reflect the exact needs and preferences of PWMD, and capturing and quantifying adequately all the parameters that affect routing choices (Kasemsuppakorn et al., 2014). In this section, we present some of these studies along with their advantages and limitations. Note that all routing algorithms function within a graph or network in which nodes are linked via segments (Kasemsuppakorn, 2011). The first challenge is therefore to find ways of converting a geospatial database into an appropriately structured routing network.

Matthews et al. (2003) and Beale et al. (2006) used a Geographical Information System (GIS) to generate accessibility maps for wheelchair users in a paper called *Modeling Access with GIS in Urban Systems (MAGUS)*. MAGUS employed the feedback of wheelchair users to identify the most important barriers, to quantify these, and consequently to incorporate them into the GIS model. They identified and quantified 10 key barriers that impede access and mobility in urban environments including steps, deep gutters, narrow pavements, ramps/local slope, cambers, poor pathway maintenance, raised manhole covers, fixed street furniture, and (un)supervised crossings. In MAGUS, the impedance value (traversal difficulty) of each network segment is calculated using mathematical models and then optimal routes are calculated. These calculations take into account six routing criteria, namely, shortest distance, minimum barriers, fewest slopes, minimizing bad surfaces, using only controlled crossings, and limiting the number of road crossings. This model is sophisticated and necessitates information on sidewalk parameters involving user perceptions.

Kasemsuppakorn and Karimi (2009) developed a model to personalize routing for wheelchair users. The research was focused on user priorities and sidewalk parameters. Sidewalk parameters included slope, surface quality, sidewalk width, steps, distance, and sidewalk traffic. This research used three weighting methods to modulate the relative importance of the different criteria within the routing calculation, including the Absolute Restriction Method (ARM), the Relative Restriction Method (RRM) and the Path Reduction Method (PRM). Each method was carried out in four steps: (1) weighting the sidewalk parameters, (2) quantifying the impedance value of each segment, (3) modeling the routes for wheelchair users, and (4) choosing the optimal route. They used an Analytical Hierarchy Process (AHP) method to derive a numerical weight for each sidewalk parameter based on user perceptions. A fuzzy logic approach was then used to quantify the impedance of each segment by aggregating parameter weights (e.g. slope weighted via user perceptions) and segment data values (e.g. slope is 2°). Finally, Dijkstra's algorithm was employed to compute optimal routes. This study included validation by five wheelchair users (Kasemsuppakorn et al., 2014). The study protocol covered three stages - pre-activity, activity and post-activity sessions. Pre-activity sessions sought to gather the personal information, level of fitness, and the relative importance of different potential barriers from the perspective of participants' perceptions. In the activity session, a comparison between personalized routes and shortest feasible route was carried out. Finally, during the post-activity session, they observed participants' feedback on their ratings for the parameters for two routes (e.g. width, slope, and surface quality) as well as their comfort levels.

Along similar lines, Hashemi and Karimi (2016) employed the AHP approach instead of fuzzy logic to assign an impedance value to each segment. They applied Z-test statistics to compare the accessibility of computed routes to those proposed by Kasemsuppakorn and Karimi (2009). This research showed that the AHP approach provided slightly more accessible routes than those generated using the fuzzy logic approach. In addition, a collaborative wayfinding approach was presented to update and augment the pedestrian database. In this approach, the feedback from the users was captured and reflected in the future optimal routes. In order to enhance the satisfaction of users regarding the computed routes, they assigned the feedback from diverse wheelchair groups only to that given group. The quality of the suggested routes were assessed by users and then employed to adjust the database. They stated that the proposed routes were more reliable as user's feedback was incorporated.

In another attempt, Neis (2015) introduced a novel approach to assess and evaluate a personalized routing algorithm for PWMD influenced by wheelchair users' restrictions and needs. The routing approach was embedded on a network, which was based upon the Volunteered Geographic Information (VGI) derived from Open Street Map (OSM). Since the VGI dataset quality is not completely consistent, the author proposed to use a reliability factor for the computed routes, by which wheelchair users could obtain extra information on the quality of the generated routes. The reliability factor was calculated by dividing the lengths of segments that contained values for potential barriers by the total length of that route multiplied by the individual weights. This algorithm was evaluated and tested for an area in Bonn, Germany.

In general, most of the above-mentioned studies did not thoroughly consider the capability of users - they only incorporated user assigned ratings concerning the different criteria. A key strength of the present study is that we use the perceptions of PWMD concerning both their preferences and capabilities, the latter expressed through confidence levels in order to assess optimal routes.

6.5 Methodology

The objective of this section is to describe the proposed approach for determining personalized routes for PWMD. Route-planning algorithms for people with special needs, in general, follow two steps, (1) the quantification of route preference criteria and (2) the route calculation itself (Kasemsuppakorn and Karimi 2009). The quantification of route preferences consists of determining weights for the criteria of each network segment based on individual preferences concerning what makes a segment favourable for travel. The weighted segments are then used for the optimal route calculation step. Segment weights vary in relation to concepts such as distance and time. For example, the cost function for the shortest route simply sums the lengths of all segments along a given route. Ordinarily the optimal route is calculated by solving a corresponding minimization problem. In this study, accessibility levels are assigned to the cost values of segments, which are in turn calculated by aggregating user capabilities with respect to multiple properties of each segment. This process is carried out based upon the Fuzzy-TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach. Fuzzy-TOPSIS is an extension of the TOPSIS approach within a fuzzy logic environment (Chen, 2000).

The TOPSIS method was initially introduced by Hwang and Yoon (1981) and further developed by Hwang and Yoon (2012). It is widely used as a means to compare several solutions for a given problem in multi criteria decision-making approaches (MCDM), especially where limited subjective input is needed from decision-makers (Olson, 2004). The basic idea is to find the best alternative solution that has the shortest vector distance from the positive ideal solution and the farthest vector distance from the negative ideal solution. The advantage of TOPSIS is its ability to identify the best alternative solution quickly and efficiently (Olson, 2004; Parkan and Wu, 1997). The Fuzzy-TOPSIS approach is used to compute personalized routes based on the user’s preferences and confidences, through a function that calculates an appropriate cost value for each segment of a pedestrian network. To address this issue, we propose a new method with four main steps including, identifying accessibility criteria and their relative importance, constructing normalized fuzzy vectors, quantifying an accessibility index (AI) to represent the cost of each segment, and computing the optimal routes. Figure 6.1 illustrates the steps of the proposed methodology.

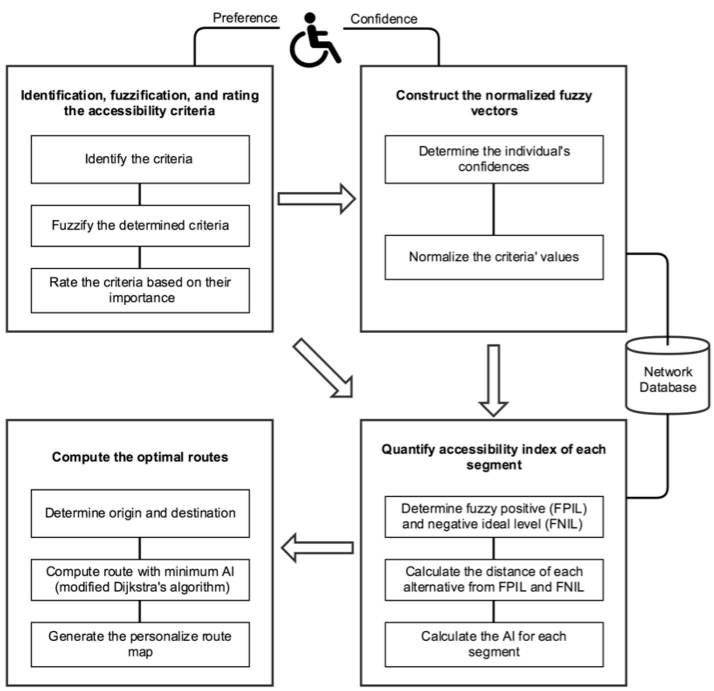


Figure 6.1. The overall view of the proposed approach

6.5.1 Identification, fuzzification, and rating of the accessibility criteria

6.5.1.1 Identifying relevant criteria from the perceptions of PWMD

To identify the relative significance of environmental criteria, we assessed those proposed by a number of different studies. Studies included in this assessment were: 1) Sobek and Miller (2006), 2) Kasemsuppakorn and Karimi (2009), 3) Beale et al. (2006), 4) Kirschbaum et al. (2001), 5) Karimanzira et al. (2006), 6) Kirby et al. (2002), 7) Rushton et al. (2011), 8) Neis and Zielstra (2014), 9) Neis (2015), and 10) CEREMH (n.d.). The criteria most often cited are shown in Table 6-1. In our previous work, we investigated in some detail the accessibility criteria required by PWMD, divided between static and dynamic factors (for details see Gharebaghi et al. (2017)). *Slope, width, surface type, surface quality, segment type, segment length, height changes, snow,* and *crowds of people* were selected as the most important accessibility criteria for routing networks. Since collecting data on dynamic factors such as snow and the presence of people on sidewalks is complicated, in this paper we address only the static characteristics of the environment.

Table 6-1. The most cited criteria in different studies

Criterion	Sobek and Miller (2006)	Kasemsuppakorn and Karimi (2009)	Beale et al. (2006)	Kirschbaum et al. (2001)	Karimanzira et al. (2006)	Kirby et al. (2002)	Rushton et al. (2011)	Neis and Zielstra (2014)	Neis (2015)	CEREMH
S	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SuQ		✓	✓	✓	✓	✓	✓	✓	✓	✓
HC		✓	✓	✓	✓	✓	✓	✓		✓
W	✓	✓	✓	✓	✓				✓	✓
ST		✓	✓	✓		✓	✓	✓	✓	
SL	✓	✓	✓		✓	✓			✓	✓
SeT			✓				✓	✓		✓

The criteria studied included: 1) *slope (S), 2) width (W), 3) surface type (SuT), 4) surface quality (SuQ), 5) segment type (SeT), 6) segment length (SeL)* and *7) height changes*. These criteria were analyzed for three different segment types, that is, sidewalks, curb cuts, and crosswalks. The range values for these criteria were retrieved from standards for accessible design such as those proposed by the Americans with Disabilities Act (ADA), the United States Access Board (2004) and the Guide pratique d'accessibilité universelle (Savard, 2010). These values were then classified into different subsets based on confidence measurements such as those presented by Rushton (2010). The range of values, their subsets, and the methods for collecting data for each criterion are summarized in Table 6-2.

Table 6-2. Accessibility criteria, the value ranges, subsets, and their collection methods

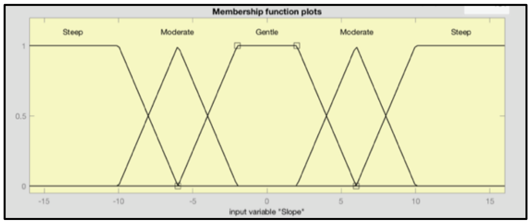
Criterion	Range of values	Subset	Data collection method
Slope (S)	(-15 15) %	{Gentle, Moderate, Steep}	Digital Elevation Model (DTM)
Width (W)	(0 3] m	{Narrow, Moderate, Wide}	Field survey
Surface type (SuT)	{1,2,3,4,5 }	{Concrete: 1, Asphalt: 2, Brick: 3, Gravel: 4, Cobblestone: 5}	Field survey/Image process
Surface quality (SuQ)	[0 10]	{Good, Fair, Poor}	Field survey/Image process
Segment type (SeT)	{1,2,3,4}	{Sidewalk: 1, Curbcut: 2, Crosswalk with traffic light: 3, Crosswalk without traffic light: 4}	Field survey/Image process
Segment Length (SeL)	(0 ∞) m	{Short, Medium, Long}	Field survey/Image process
Height changes (HC)	(0 15] cm	{Small, Moderate, Big}	LIDAR data/Field survey

6.5.1.2 Fuzzifying the criteria

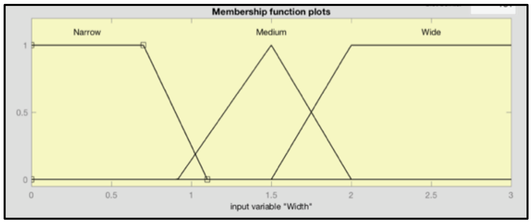
In reality, people use a qualitative way to characterise environmental factors that affect the mobility of PWMD (e.g. narrow sidewalk) - in many cases precise quantitative values are inadequate to describing real-life situations. To address this issue, the crisp values of the different environmental criteria were converted into non-crisp values using fuzzy logic. This process is called fuzzification (Zadeh et al., 1965) and is performed by defining membership functions. A membership function is a mathematical function that serves to map a given value to a set between 0 and 1 (Beynon, 2004). In this paper, membership functions for all the variables were expressed in trapezoidal fuzzy values. Thus, the criteria (*S, W, SuT, SuQ, SeT, SeL, HC* as presented in Table 1) were classified into the fuzzy set classes by predefined membership values. For example, the slope (S) can be defined as gentle, moderate, and steep. The slope value, for example 3%, corresponds to the gentle and moderate subsets according to the membership function. In mathematical terms, the fuzzy set A of a universe X is defined by a membership function $\mu_{\tilde{A}}(x_i)$ such that $X \rightarrow \langle 0, 1 \rangle$, where $\mu_{\tilde{A}}(\tilde{x}_i)$ is the membership value of $\tilde{x}_i$ in $\tilde{A}$ (Zadeh et al., 1965) as defined by Equation 1 below, where $\tilde{A} = (a, b, c, d)$ is a trapezoidal fuzzy number. Here, x_i represents a criterion that belongs to $\tilde{X} = [x_1, x_2, \dots x_n]$.

$$\mu_{\tilde{A}}(x_i) = \begin{cases} \mathbf{0}, & x_i \leq a \\ \frac{x_i - a}{b - a}, & a \leq x_i \leq b \\ \mathbf{1}, & b \leq x_i \leq c \\ \frac{d - x_i}{d - c}, & c \leq x_i \leq d \\ \mathbf{0}, & d \leq x_i \end{cases} \qquad \text{Equation 6-1}$$

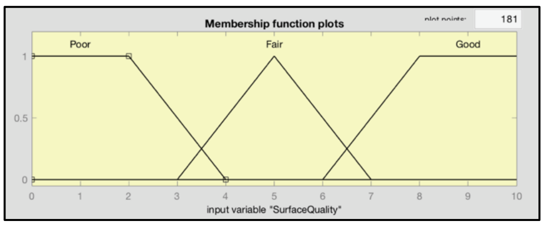
The membership functions of certain criteria are defined based on the values determined using the Americans with Disabilities Act (ADA), the United States Access Board (2004) and the Guide pratique d'accessibilité universelle (Savard, 2010). For example, in all these cases, the minimum value of width for a sidewalk is 91.5 cm and the maximum value of slope for a sidewalk as 8%. Figure 6.2 summarises the membership functions for all the criteria identified in the study.



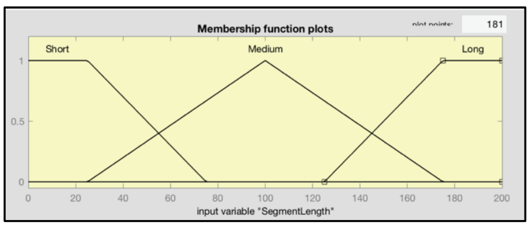
The slope values are classified into three sets including *Gentle*, *Moderate*, and *Steep*. A segment with slope value of (-) 4%, for example, belongs to the fuzzy set *Gentle* with a membership value of 0.5, to the fuzzy set *Moderate* with a membership value of 0.5.



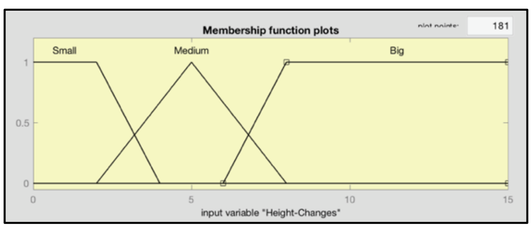
The width values are classified into three sets including *Narrow*, *Medium*, and *Wide*. A segment with width value of 1.75m, for example, belongs to the fuzzy set *Medium* with the membership value 0.5, and to the fuzzy set *Wide* with a membership value of 0.5.



The surface quality values are classified into three sets including *Poor*, *Fair*, and *Good*. A segment with quality value of 3.5, for example, belongs to the fuzzy set *Poor* with the membership value 0.8, and to the fuzzy set *Fair* with a membership value of 0.2.



The length values are classified into three sets including *Short*, *Medium*, and *Long*. A segment with length value of 140m, for example, belongs to the fuzzy set *Medium* with the membership value 0.47, and to the fuzzy set *Long* with a membership value of 0.3.



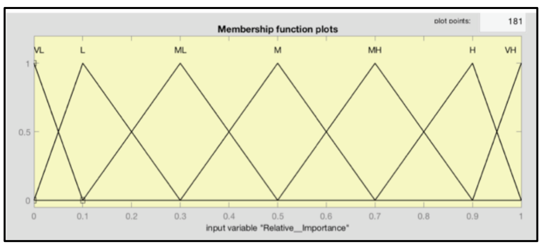
The height changes values are classified into three sets including *Small*, *Medium*, and *Big*. A segment with height change value of 3cm, for example, belongs to the fuzzy set Small with the membership value 0.5, and to the fuzzy set Medium with a membership value of 0.33.

Figure 6.2. Membership functions of accessibility criteria

6.5.1.3 Rating the criteria based on their importance as determined by user perceptions

The accessibility of a pedestrian network depends on several factors with different levels of impact. The objective of this step of our methodology is to rate the relative importance of the different criteria based on an individual's preferences. This rating varies from one individual to another; it can be obtained in two ways: 1) by assigning a relative importance directly for each criterion based on the users' perceptions, or 2) by calculating the relative importance using pair-wise comparison of the criteria via the analytical hierarchy process

(AHP, Saaty, 2008). Here, we determined the relative importance of the criteria by drawing on user perceptions. According to Chen (2000), the linguistic variables can be classified into seven classes, that is, very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H) and very high (VH). Based on Chen (2000)'s categories, a value's relative importance can be expressed using fuzzy set values as shown in **Figure 6.3** These values are used in the computation of the personalized route, which is described in section 6.5.3. In the following section, in addition to the individual's preferences, we show how the individual's capabilities can also be reflected in the computation of the accessible routes.



Fuzzy set	Fuzzy numbers
Very low (VL)	(0,0,0,0.1)
Low (L)	(0,0.1,0.1,0.3)
Medium low (ML)	(0.1,0.3,0.3,0.5)
Medium (M)	(0.3,0.5,0.5,0.7)
Medium high (MH)	(0.5,0.7,0.7,0.9)
High (H)	(0.7,0.9,0.9,1.0)
Very high (VH)	(0.9,1.0,1.0,1.0)

Figure 6.3. Membership function, fuzzy sets, and fuzzy values for each criterion

6.5.2 Constructing the normalized fuzzy vector based on user confidence levels

The objective of the normalization phase is to transform the values into a common scale so that aggregations and comparisons can be carried out. A common way to normalize these values is to transform them to scores ranging from 0 to 1 based on the maximum and minimum values (Chen, 2000). Here, a different approach is implemented. First, a corresponding confidence value is assigned to each criterion value (e.g. slope values). Following this, each individual's confidence for a corresponding criterion (e.g. confidences related to slope values) is normalized. By this method, the individual's confidence level for handling environmental elements is used rather than the value directly associated with the environmental variable (e.g. very low confidence instead of steep slope). We used confidence level as the parameter to measure the PWMD's perceived capabilities (for more details, refer to Gharebaghi et al. (2017)). Indeed, the confidence level of an individual is a more reliable way to characterise ability than their skill level alone (Rushton et al., 2011). This is because, although a person might be able to perform a given task, they may not be confident enough to carry it out. To quantify the confidence levels of individuals, the *wheelchair use confidence scale* (WheelCon, Rushton, 2010) was employed. According to this approach, the user's confidence level for a given mobility task is expressed using a value between 0 (low confidence) and 100 (high confidence) (Rushton, 2010). Hence, we measured the individual's confidences with respect to each criterion using a value in the range of [0, 100]. These values were then fuzzified into the fuzzy set classes by predefined membership values (*Very Low, Low, Medium, High, and Very High)*. For example, a segment with slope value of 8% belongs to the fuzzy set *Moderate* while *Steep* might correspond to the fuzzy set of *Medium confidence* and *Low confidence*. Hence, we replaced the values of the variables (*S, W, SuT, SuQ, SeT, SeL, and HC*) with their corresponding user confidence fuzzy values *(*$\widetilde{S\_Con}$*,* $\widetilde{W\_Con}$*,* $\widetilde{SuT\_Con}$*,* $\widetilde{SuQ\_Con}$*,* $\widetilde{SeT\_Con}$*,* $\widetilde{SeL\_Con}$*, and* $\widetilde{HC\_Con}$*)*. The normalized fuzzy vector is then denoted by $\tilde{R} = [\tilde{r}_1, \tilde{r}_2, \dots \tilde{r}_7]$.

$$\tilde{r}_i = \left(\frac{(a\_con)_i}{(d\_con)_i^*}, \frac{(b\_con)_i}{(d\_con)_i^*}, \frac{(c\_con)_i}{(d\_con)_i^*}, \frac{(d\_con)_i}{(d\_con)_i^*}\right) \quad (d\_con)_i^* = \max{(d\_con)_i} \quad \text{Equation 6-2}$$

where $(a\_con, b\_con, c\_con, d\_con)_i$ represents the individual's confidence level with respect to the criterion x_i and $(d\_con)_i^*$ represents the individual's maximum confidence level for that criterion. For example, the maximum confidence level of an individual to go up a slope would be the confidence level to go up a gentle slope $(d\_con)_i^* = (d\_con)_{Gentle}$

6.5.3 Quantifying accessibility indices as a function of the cost of each segment

Accessibility in the context of mobility is often defined by the ease of reaching a destination with respect to distance, time and cost constraints (Morris and Wigan, 1978). This definition is used as the basis of several statistical approaches to assess accessibility for pedestrian networks. In each of these studies, accessibility was evaluated by measuring the cost value for each path. In this paper, the cost of each segment and consequently the routes were determined by an accessibility index (AI). The objective of the AI assessment step was to quantify the accessibility level of each segment of a network for PWMD based on their capabilities. The AI was assigned to a range between [0 1], where 0 implies not accessible and 1 implies a maximum level of accessibility. In some cases, a segment may get two different AIs based on route direction. The user's confidence might be different to go up or down a given slope and then the segment will require two different AIs, one for each direction. In this study, the AI determined the vector distance of a given vector (i.e. assigned to a segment) from the fuzzy positive ideal condition (FPIC) scaled over the range of [FPIC, FNIC], where FNIC indicates the fuzzy negative ideal condition. It should be mentioned that all of the formulas presented here are adapted from Chen's fuzzy-TOPSIS algorithm. In order to calculate the cost of segments, first, the weighted normalized fuzzy vector was computed taking into account the importance of each criterion ($\widetilde{W} = [\widetilde{w}_1, \widetilde{w}_2, \ldots \widetilde{w}_7]$), which is defined by equation 4.

$$\tilde{V} = [\tilde{v}_1, \tilde{v}_2, \ldots \tilde{v}_7] \; where \;\; \tilde{v}_i = \tilde{r}_i(\cdot)\, \widetilde{w}_i \qquad \text{Equation 6-3}$$

The resulting weighted and normalized fuzzy vectors are then used to calculate the FPIC (the best condition, A^*) and the FNIC (the worst condition, A^-) (equation 5). Hence, A^* and A^-would be the most accessible and least accessible fuzzy value for a given user.

$$A^* = [\tilde{v}_1^*, \tilde{v}_2^*, \ldots \tilde{v}_7^*] \;\; where \;\; \tilde{v}_i^* = max\,\{\tilde{v}_{i4}\} \qquad \text{Equation 6-4}$$

$$A^- = [\tilde{v}_1^-, \tilde{v}_2^-, \ldots \tilde{v}_7^-] \;\; where \;\; \tilde{v}_i^- = min\,\{\tilde{v}_{i1}\}$$

Next, the vector distance of a given fuzzy vector from the ideal and worst case (d_i^- and d_i^*) was calculated, indicating how near and how far was the segment to the most accessible condition and from the less accessible condition, respectively.

$$d_i^* = \sqrt{\tfrac{1}{4}\textstyle\sum_i^7 (\tilde{v}_i - \tilde{v}_i^*)^2},$$

$$d_i^- = \sqrt{\tfrac{1}{4}\textstyle\sum_i^7 (\tilde{v}_i - \tilde{v}_i^-)^2} \qquad \text{Equation 6-5}$$

Finally, the AI is calculated as:

$$AI = \frac{d_i^*}{d_i^* + d_i^-} \quad \text{Equation 6-6}$$

The AI is closer to the FPIC (A^*) and further from FNIC (A^-) as it approaches 0. This means that a lower value of AI is preferable, so the index is referred to a cost value (Malczewski, 1999). The accessibility index was used as a cost value in the computation of accessible routes for PWMD, which is explained in the following section.

6.5.4 Optimal routing computation

As indicated earlier, the AI was used to compute an optimal route taking into account the accessibility for an origin-destination pair where the routes with the minimal sum of the costs for each edge were selected. In other words, the route with the lowest overall AI would be chosen. There are several well-known algorithms for computing an optimal route in a given network – these include Dijkstra's algorithm (Dijkstra, 1959), the A* method (Dechter and Pearl, 1985) and the Floyd-Warshall algorithm (Floyd, 1962). In this paper, the Dijkstra algorithm was used because it is more appropriate to solve the single source shortest-path problem, which guarantees an optimal solution (Kasemsuppakorn and Karimi, 2009).

Dijkstra's algorithm was modified to compute the most accessible route considering the direction (up or down the slope) and also prohibiting routing that includes segments that are not accessible. Since the individual's confidence for going up and down a segment involved either a slope or a height change (e.g. a curb without a curb cut), for each segment two AI including AI_{up} and AI_{down} were determined. Then, as a function of the direction taken along the route, a unique AI was assigned to the given segment. Any segment with a cost higher than 0.8 ($AI > 0.8$) was considered to be *an inaccessible segment* and was assigned a negative AI value, thereby prohibiting routing at that point in the network. Using Dijkstra's algorithm, all possible nodes in every direction without any constraint were examined. Therefore, this algorithm is computationally expensive because it follows many unnecessary search directions. Indeed, wheelchair route lengths are usually less than 10 km, which suggests that a directional version of Dijkstra's algorithm would be more appropriate (Neis, 2015).

6.6 Numerical example

We explored the application of our methodology via a numerical example on a simple graph containing six nodes, which are connected by eight links (shown by Figure 6.4.a). Table 6-3 demonstrates the attributes of the links of graph.

Table 6-3. Attribute table of the segments

	S (%)	W (m)	SuT	SuQ	SeT	SeL (m)	HC (Cm)
O-1	3	1.5	Concrete	Good	Sidewalk	100	0
O-2	8	1	Gravel	Bad	Crosswalk	250	-5
1-2	-2	2	Concrete	Good	Sidewalk	50	0
2-1	2	2	Concrete	Good	Sidewalk	50	0
1-4	4	1.5	Concrete	Fair	Sidewalk	200	0
2-3	3	1.5	Concrete	Fair	Sidewalk	150	0
3-4	2	1.5	Concrete	Good	Sidewalk	150	0
4-3	-2	1.5	Concrete	Good	Sidewalk	150	0
4-D	-7	1.3	Gravel	Bad	Crosswalk	50	-5
3-D	-4	1.7	Concrete	Fair	Sidewalk	100	0

We also simulated the confidence levels assigned by a wheelchair user to the different parameters of the segments of the routing network (shown in Table 6-4). The algorithm was used to calculate the accessibility level of the segments and the personalized routes between the origin node (O) and the destination node (D). In order to verify the accuracy of the algorithm, we determined the accessibility level for the same links using the Fuzzy Logic approach by defining appropriate rules (for more details refer to Gharebaghi et al., 2017). In order to compare the results derived by both approaches, the relative importance of the different criteria was considered to be equal in both methods.

Table 6-4. User confidences regarding the different criteria

	S (Up)			S (Down)			
Segment attribute	Gentle	Moderate	Steep	Gentle	Moderate	Steep	
User Confidence	90	65	20	100	80	40	
	W			SuQ			
Segment attribute	Narrow	Moderate	Wide	Good	Fair	Poor	
User Confidence	15	70	100	90	60	35	
	SeT		SeL			SuT	
Segment attribute	Sidewalk	Crosswalk	Short	Medium	Long	Concrete	Gravel
User Confidence	85	60	90	70	50	85	45
	HC (Up)			HC (Down)			
Segment attribute	Small	Medium	Big	Small	Medium	Big	
User Confidence	90	50	10	100	60	35	

6.6.1 Compute the *AIs* using proposed algorithm

In order to transform the crisp values into fuzzy values, membership functions were defined. The membership functions, including *S, W, SuT, SuQ, SeT, SeL,* and *HC*, were expressed as trapezoidal fuzzy values (see Table 6-2). Following this step, the membership values of the link attributes need to be determined. For example, a segment with a length value of 140m belongs to the fuzzy set Medium with the membership value 0.47, and to the fuzzy set Long with a membership value of 0.3. Table 6-5 shows these membership values.

Table 6-5. The membership values of each segment's criteria

	Fuzzy set	Fuzzy number	O-1	O-2	1-2	2-1	1-4	2-3	3-4	4-3	4-D	3-D
S (Up)	Gentle	(80,90,100,100)	1.00	-	-	1.00	0.66	1.00	1.00	-	-	-
	Moderate	(50,60,80,90)	0.25	0.50	-	-	0.50	0.25	-	-	-	-
	Steep	(0,0,10,20)	-	0.50	-	-	-	-	-	-	-	-
S (Down)	Gentle	(80,90,100,100)	-	-	1.00	-	-	-	-	1.00	-	0.66
	Moderate	(50,60,80,90)	-	-	-	-	-	-	-	-	0.75	0.50
	Steep	(40,50,50,60)	-	-	-	-	-	-	-	-	0.25	-
W	Narrow	(0,0,10,20)	-	0.33	-	-	-	-	-	-	-	-
	Moderate	(50,60,80,90)	1.00	0.16	1.00	1.00	1.00	1.00	1.00	1.00	0.66	0.60
	Wide	(80,90,100,100)	-	-	-	-	-	-	-	-	-	0.40
SuT	Concrete	(80,90,100,100)	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00
	Gravel	(10,20,40,50)	-	1.00	-	-	-	-	-	-	1.00	-
SuQ	Good	(80,90,100,100)	1.00	-	1.00	1.00	-	-	1.00	1.00	-	-
	Fair	(40,50,50,60)	-	-	-	-	0.50	1.00	-	-	0.50	0.50
	Poor	(10,20,40,50)	-	0.50	-	-	-	-	-	-	-	-
SeT	Sidewalk	(80,90,100,100)	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00
	Crosswalk	(40,50,50,60)	-	1.00	-	-	-	-	-	-	1.00	-
SeL	Short	(80,90,100,100)	-	-	0.50	0.50	-	-	-	-	0.50	-
	Medium	(50,60,80,90)	1.00	-	0.33	0.33	-	0.33	0.33	0.33	0.33	1.00
	Long	(40,50,50,60)	-	1.00	-	-	1.00	0.50	0.50	0.50	-	-
HC (Up)	Small	(50,60,80,90)	1.00	-	1.00	1.00	1.00	1.00	1.00	1.00	-	1.00
HC (Down)	Medium	(40,50,50,60)	-	1.00	-	-	-	-	-	-	1.00	-

The individual's confidence levels were then assigned to the normalized vector according to the derived membership values. Table 6-6 shows the confidence levels for the segments as a function of the different criteria.

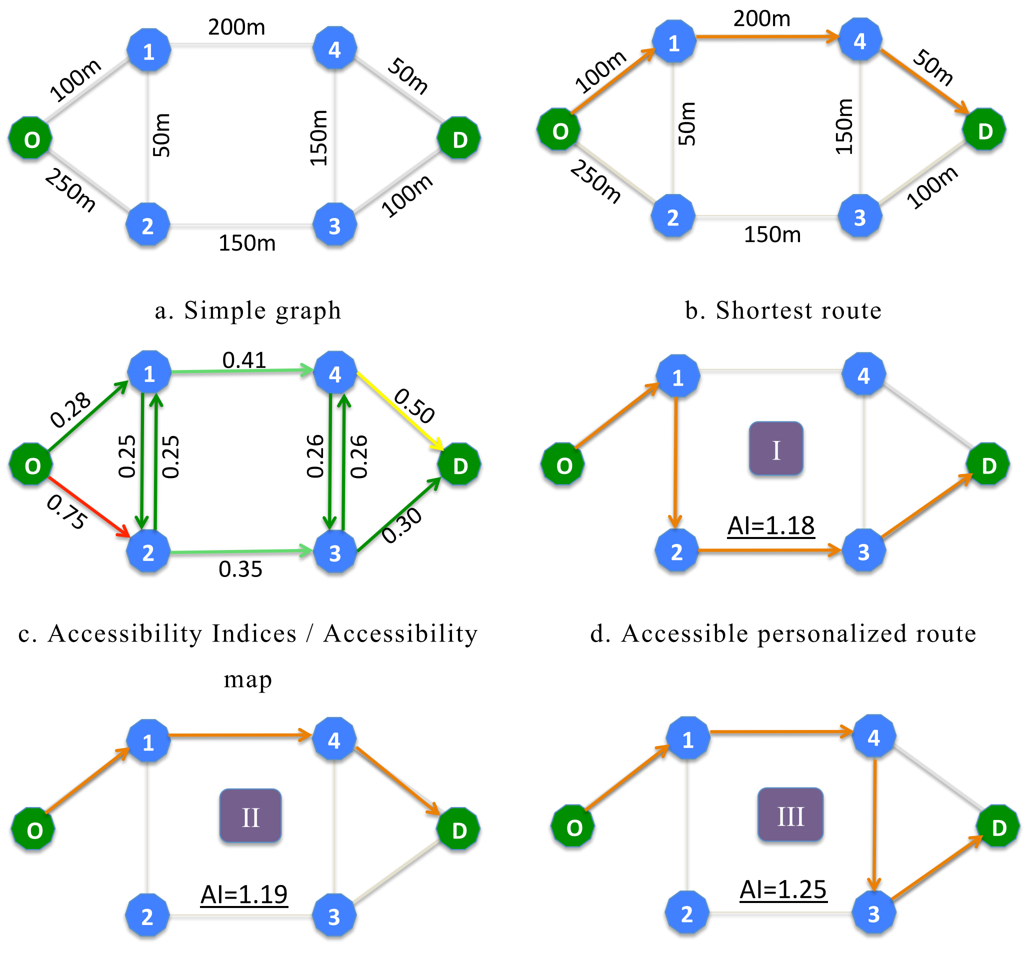
Table 6-6. Confidence fuzzy vector regarding each segment's criteria

	S_Con	W_Con	SuT_Con	SQ_Con	SeT_Con	SL_Con	HC_Con
O-1	(0.65,0.75,0.9,0.95)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.8,0.9,1,1)	(0.8,0.9,1,1)	(0.5,0.6,0.8,0.9)	(0.8,0.9,1,1)
O-2	(0.175,0.275,0.425,0.525)	(0.1,0.2,0.4,0.5)	(0.25,0.35,0.45,0.55)	(0.1,0.2,0.4,0.5)	(0.5,0.6,0.8,0.9)	(0.4,0.5,0.5,0.6)	(0.5,0.6,0.8,0.9)
1-2	(0.8,0.9,1,1)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.8,0.9,1,1)	(0.65,0.75,0.9,0.95)	(0.56,0.64,0.84,0.92)	(0.8,0.9,1,1)
2-1	(0.8,0.9,1,1)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.8,0.9,1,1)	(0.65,0.75,0.9,0.95)	(0.56,0.64,0.84,0.92)	(0.8,0.9,1,1)
1-4	(0.5,0.6,0.8,0.9)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.4,0.5,0.5,0.6)	(0.8,0.9,1,1)
2-3	(0.65,0.75,0.9,0.95)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.48,0.58,0.74,0.84)	(0.8,0.9,1,1)
3-4	(0.8,0.9,1,1)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.8,0.9,1,1)	(0.65,0.75,0.9,0.95)	(0.48,0.58,0.74,0.84)	(0.8,0.9,1,1)
4-3	(0.8,0.9,1,1)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.8,0.9,1,1)	(0.65,0.75,0.9,0.95)	(0.48,0.58,0.74,0.84)	(0.8,0.9,1,1)
4-D	(0.5,0.6,0.8,0.9)	(0.5,0.6,0.8,0.9)	(0.25,0.35,0.45,0.55)	(0.5,0.6,0.8,0.9)	(0.5,0.6,0.8,0.9)	(0.56,0.64,0.84,0.92)	(0.5,0.6,0.8,0.9)
3-D	(0.8,0.9,1,1)	(0.56,0.68,0.84,0.92)	(0.65,0.75,0.9,0.95)	(0.5,0.6,0.8,0.9)	(0.65,0.75,0.9,0.95)	(0.5,0.6,0.8,0.9)	(0.8,0.9,1,1)

In order to assess the cost for each segments, the vector distance of the fuzzy vector from the ideal and worst case (d_i^- and d_i^*) were determined, and consequently the *AI* were calculated using equations (5) and (6). **Table 6-7** shows the results. Figure 6.4.c shows the *AI*s (i.e. these are called AI_{FT}) and the accessibility map where *"Not Accessible"* segments are represented with red, *"Low Accessible"* segments are yellow, *"Accessible"* segments are green, and *"Very Accessible"* segments are dark green. Figure 6.4.b shows the shortest route determined without taking into account the user's confidence, and Figure 6.4.d, and Figure 6.4.e, and Figure 6.4.f demonstrate three accessible routes as a function of each user's confidence levels.

Table 6-7. Calculated AIs and distances from ideal and worst conditions

	O-1	O-2	1-2	2-1	1-4	2-3	3-4	4-3	4-D	3-D
d_i^*	0.16	0.47	0.13	0.13	0.23	0.18	0.14	0.14	0.29	0.16
d_i^-	0.4	0.15	0.40	0.40	0.32	0.34	0.40	0.40	0.29	0.37
AI_{FT}	0.28	0.75	0.25	0.25	0.41	0.35	0.26	0.26	0.50	0.30



a. Simple graph

b. Shortest route

c. Accessibility Indices / Accessibility map

d. Accessible personalized route

e. Second accessible personalized route

f. Third accessible personalized route

Figure 6.4. The computed accessible routes using the proposed algorithm

6.6.2 Compute the *AIs* using if-then rules

In the process of aggregating the values of the variables, the weighted linear models might have some limitations in complex situations. For instance, in a mobility scenario the user may a) move down from a standard curb, b) cross an intersection, and c) pass over a hole in the sidewalk. Even if the confidence level of the user with respect to each of these properties is at medium level, the aggregated confidence level might not be medium for a wheelchair user in the real situation. In order to validate the aggregation method conducted by the TOPSIS method, we used If-Then rules within a Fuzzy Logic approach. Fuzzy logic, introduced by Zadeh et al. (1965), was used to adapt the original TOPSIS method so as to develop the fuzzy TOPSIS approach. It is widely used in many different applications including routing and transportation planning ((Kasemsuppakorn and Karimi 2009) and (Karimanzira et al. 2006)) to model the vagueness associated with human cognitive processes. To employ fuzzy logic, three steps are usually followed: (1) build the rule set and define the membership functions (fuzzification), (2) develop a fuzzy inference system (FIS) using if-then rules and (3) merge the outputs of the rules and ensure defuzzification of the results using a different set of membership functions to derive output variables (Mamdani and Assilian, 1975).

The fuzzification step used the same procedure as that adopted by the TOPSIS method. We used the same fuzzy sets (e.g. gentle, moderate, and steep for slope) and their corresponding membership functions. We then transformed the membership functions for each segment attribute to determine the user confidence level (e.g. *S_Con*). The If-Then rules were then defined so as to aggregate the individual user confidences and, consequently, calculate the accessibility level of each segment as the output variable. For example:

If (the S_Con is very low) & (the SuQ_Con is low) Then (the segment is not accessible)

In order to cover all possible combinations of the fuzzy sets associated with the variables, we need to define m^n rules where *m* is the number of fuzzy set values and *n* is the number of variables. In our case, there were five fuzzy sets including *VL, L, M, H*, and *VH,* and seven variables including *S, W, SuQ, SuT, SeL, SeT, and HC.* Therefore, we needed to define 5^7 (i.e. 78125) rules. Table 5-2 presents these rules, which are stated as if an aggregation operation would only be applied to two components. In the cases where more than two parameters needed to be aggregated, the result of the first aggregation was aggregated to the next parameter and the process continued until the final confidence level was obtained. Since these rules can be expected to directly affect the result of the aggregation process, they need to be validated. In our research, an expert who is also a wheelchair user carried out the validation step. However, we understand that further investigation is needed for a more rigorous validation of these rules by participation of both external experts and wheelchair users.

Table 6-8. If-Then rules

Rule No.	Confidence Level		Accessibility Level	Rule No.	Confidence Level		Accessibility Level
	p	q			p	q	
1	VL	VL	NA	9	L	VH	LA
2	VL	L	NA	10	M	M	LA
3	VL	M	NA	11	M	H	MA
4	VL	H	NA	12	M	VH	MA
5	VL	VH	NA	13	H	H	MA
6	L	L	NA	14	H	VH	A
7	L	M	NA	15	VH	VH	VA
8	L	H	LA				

Once the rules were defined and the aggregation step was performed, the accessibility index of each segment could be derived. To address this issue, a defuzzification technique should be applied to produce exact numerical values from the fuzzy values based on the defined membership functions and rules. The output values were then used to determine the accessibility levels of the pedestrian network segments within five categories - Not Accessible *(NA)*, Low Accessible *(LA)*, Medium Accessibility *(MA)*, Accessible *(A)*, and Very Accessible *(VA)*. This procedure was applied to the simple graph described earlier. Figure 6.5 illustrates the outputs including the *AI*s (i.e. there they are called AI_{FL}), the accessibility map, and three personalized accessible routes.

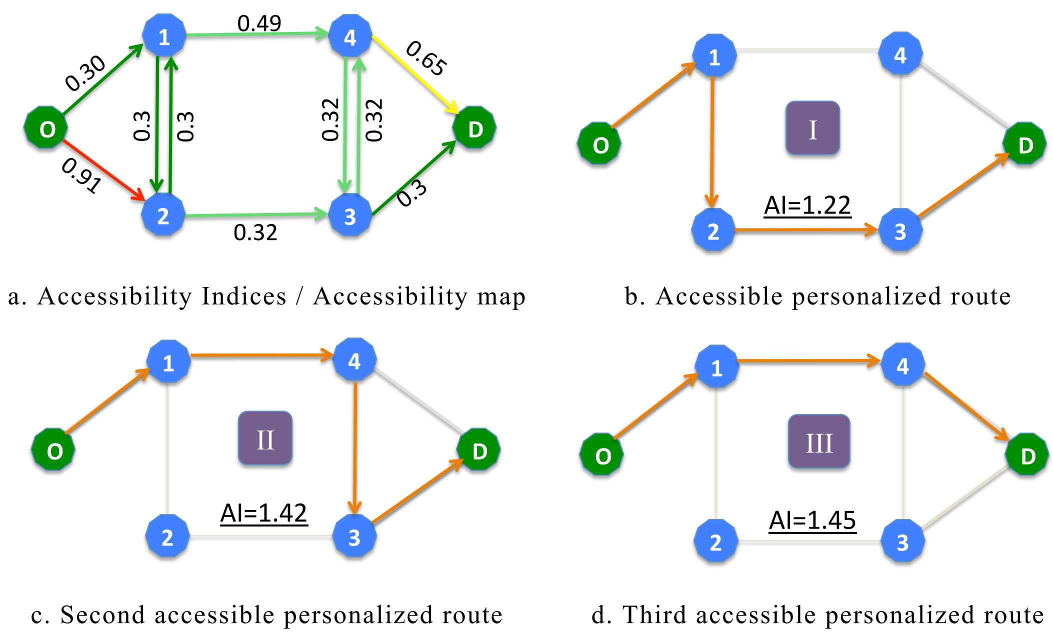


Figure 6.5. The computed accessible routes using if-then rules

6.6.3 Reliability of the proposed method

In order to verify the reliability of the applied methodology, we computed and compared the AIs by employing the Fuzzy Logic approach (AI_{FL}) as well as the fuzzy TOPSIS approach. The calculated AI_{FT} and AI_{FL} are shown in Table 6-9 and also shown in Figure 6.6. Next, we needed to evaluate the similarity between the two results. To fulfill this task, the Root Mean Square Error (RMSE) was determined. The RMSE is a widely used measure of difference between sets of values which is scale-independent (Hyndman and Koehler, 2005). The calculated RMSE of the results, AI_{FT} and AI_{FL}, was 0.09 which shows a very subtle disagreement between the two vectors.

Table 6-9. Computed AIs with different approaches

Segment	O-1	O-2	1-2	2-1	1-4	2-3	3-4	4-3	4-D	3-D
AI_{FT}	0.28	0.75	0.25	0.25	0.41	0.35	0.26	0.26	0.50	0.30
AI_{FL}	0.20	0.91	0.15	0.30	0.50	0.32	0.32	0.32	0.65	0.30

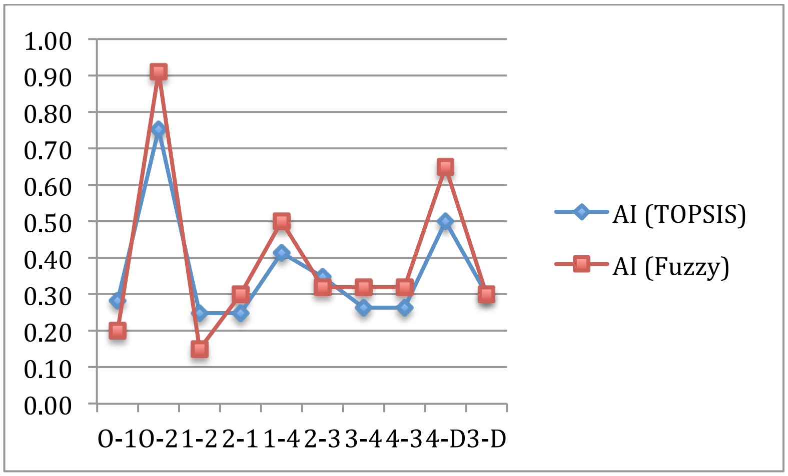


Figure 6.6. Computed AIs for both the Fuzzy Logic and TOPSIS methods applied to the same data

6.7 Model implementation

For the evaluation and illustration of the method in a real world routing situation, the proposed method was executed within a web-based GIS tool (the MobiliSIG application). Figure 6.7 presents a general view of the interface for this application. An experiment involving the participation of three manual wheelchair users was conducted. This experiment was performed in the Saint-Roch neighbourhood in Quebec City. To carry out the implementation, a graph of the pedestrian network containing nodes and segments from this area was constructed as explained in the following section. The data for Saint-Roch were collected from several existing data sources including the *Collections de la Ville de Québec, 2015* and the web portal of the *Ville de Québec* (i.e. *S, W, SeL, SuT,* and *SuT*), as well as a complementary field survey (i.e. *SuQ* and *HC*).

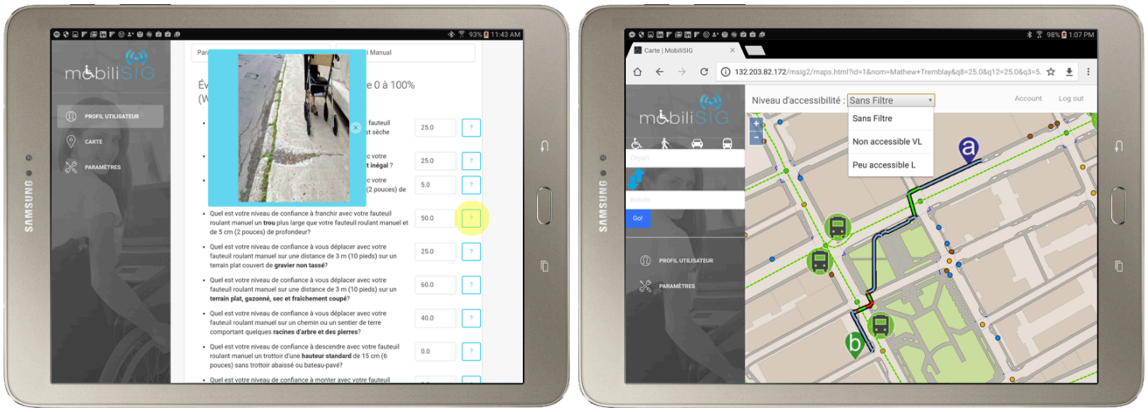


Figure 6.7. A general view of the MobiliSIG application

6.7.1 Collecting the user confidences and preferences

The objective of this step was to collect the confidence levels as determined by wheelchair users concerning the different parameters needed for the routing network, and to rate the criteria in order of importance. To achieve this, a questionnaire developed asking users to express their confidence with regard to the parameters of each route segment. The output of this questionnaire was used to calculate the cost value for each segment. One of the challenges of this questionnaire was the users' different understandings of what the criteria meant, which potentially could affect the accessibility assessment results. For example, different individuals might estimate slope subclasses differently. In order to resolve this problem, we proposed a method to extract the users' perceptions directly from their daily experiences.

Rating in order of importance each parameter in each segment along a trajectory in a real world experiment was then carried out. These experiments were carried out on the daily routes of wheelchair users. This helped ensure that different people treated difficulty levels similarly. The wheelchair users were asked to indicate their confidence level for each criterion for three different trajectories. The users chose two familiar trajectories, one they considered easy and the other difficult. The researchers determined the third trajectory. The reason for choosing three trajectories was to include nearly all-possible subclasses of the criteria. For instance, the trajectory considered by the user to be easy might have segments with gentle to moderate slopes while the difficult trajectory might have moderate to steep slopes. The third trajectory was chosen to cover all remaining subclasses of the parameters and/or to repeat already tested parameters in another context. The three wheelchair users were asked to express their feelings concerning the difficulty level of each parameter for each segment within the trajectory. Following this, the characteristics of each segment were analyzed to determine user confidence for each parameter. For example, user #1 indicated a rate of 30 out of 100 as his confidence level for traversing a segment. The width of this segment was 80 cm, which is categorized as narrow. The procedure was continued for all segments. Finally, the users are asked to express the relative importance of each criterion based on their own preferences. Table 6-10 presents the results of the confidence and preference values determined for the three wheelchair users.

Table 6-10. Users' confidences and preferences with respect to the criterion

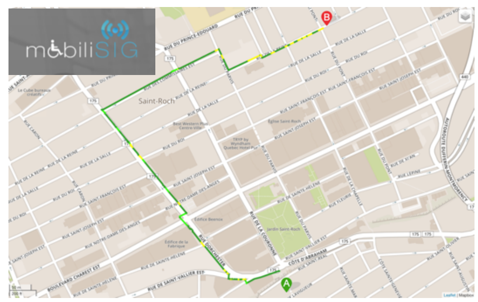
Criteria	Average Confidence Level [0 100]			Importance Rate		
	User 1	User 2	User 3	User 1	User 2	User 3
S	77	73	63	MH	MH	H
W	63	37	57	MH	VH	H
SuT	90	90	90	H	MH	MH
SuQ	70	57	57	MH	H	H
SeT	70	88	70	L	ML	M
SeL	83	70	50	ML	ML	MH
HC	60	80	80	VH	H	H

6.7.2 Calculating the *AI*s and computing the personalized route

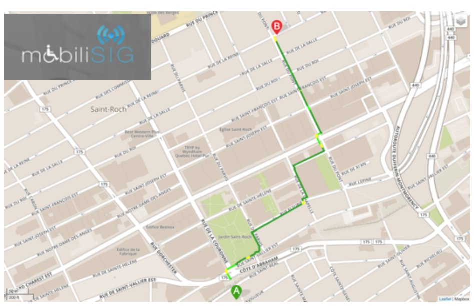
According to the confidence values and the relative importance of each criterion (shown in Table 6-10), the calculation of the *AI* was carried out for each segment in the Saint-Roch neighbourhood. These values were determined based on the Fuzzy-TOPSIS approach as explained in section 6.5. Computed *AI*s were then used as cost values so as to compute the personalized routes for a given origin-destination pair. The modified Dijkstra's algorithm was used to find the optimum route as explained previously. To illustrate the implementation of our methodology, accessible routes based on the different user profiles were determined for a selected origin and destination in the Saint-Roch area. Figure 6.8 shows the suggested routes for each participant and as well as the shortest between a given origin and destination. In this figure *"Not Accessible"* segments are shown in red, *"Low*

Accessible" segments are represented in yellow, while *"Accessible"* segments are shown in green. As can be seen in Figure 6.8.a, the shortest-path includes two segments that are not accessible for the first user. Although the shortest-path was the same for all users, the level of accessibility was different among the users. The shortest-path is not a priority for users with special mobility concerns in their daily life, what matters is a personalized accessible path; even though this might be longer. Figure 6.8.b, Figure 6.8.c, and Figure 6.8.d are personalized routes obtained by our algorithm for the three different user profiles. These maps illustrate how the confidence levels affect the optimal route calculations.

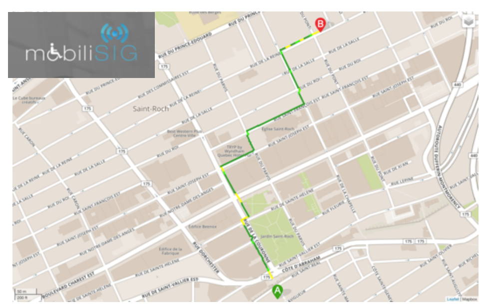
a. Shortest path for user #1 (760m)



b. Personalized route for user #1 (1210m)



c. Personalized route for user #2 (760m)



d. Personalized route for user #3 (775m)

Figure 6.8. Different computed routes for the three wheelchair users

6.8 Conclusion and future work

In this investigation, the main goal was to develop an approach to plan personalized routes for people with motor disabilities (PWMD). We presented their mobility needs and assessed their perceptions with regard to desirable routes by adapting the hierarchy of walking needs model. For PWMD, the deduced needs are, in order of declining importance, accessibility, safety, comfort, and pleasure. Among these needs, accessibility was selected as the fundamental need to compute optimal routes for PWMD. We then proposed a routing approach based on the accessibility levels of network segments. We investigated the accessibility criteria drawing on users' perceptions, generated routing networks based on these criteria, quantified an accessibility index (AI), and finally computed the personalized routes. The Fuzzy-TOPSIS approach was modified to allow aggregation of criteria values and Dijkstra's algorithm was modified to compute optimal routes. To validate the proposed method for the calculation of the AIs, the AIs were re-calculated employing another approach that applies if-then rules. Then, to evaluate the similarity between two obtained results, the Root Mean Square Error (RMSE) between the two vectors, AI_{FT} and AI_{FL}, was calculated. This showed a very subtle disagreement between the two vectors. The routing process was implemented for the Saint-Roch neighbourhood in Quebec City via the participation of three manual wheelchair users. The results were visualized on a multimodal mobile assistive technology (MobiliSIG) application. A key strength of the present study is that the route planning for PWMD takes into account their perceptions, preferences, and capabilities, the latter expressed via confidence levels. We demonstrated how the individual's preferences and confidence levels affected the computation of the optimal routes. However, one of the challenges in this research work remains the changing nature of PWMD's capabilities over time. Each individual's capability level may vary from one time (e.g. morning) to another (e.g. evening). These changes of state complicate the computation process. Therefore, it is recommended that further research be undertaken to extend the proposed approach for two situations, *fresh* and *tired.* In addition, we plan to further explore the inclusion of the other indices for routing, namely the safety, comfort, and pleasure indices. In future work, we will need to explore how the value of each index contributes to choosing the optimal route for PWMD.

Acknowledgements

This research was supported by the MobiliSIG project, thanks to a research grant provided by the Canadian Institutes of Health Research and the Natural Science and Engineering

Research Council of Canada. We are grateful to all members of the MobiliSIG project for their valuable contributions to the discussions that led to this paper.

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7 Conclusions et travaux futures

7.1 Résumé

Cette thèse porte sur l'évaluation et la représentation spatiale de l'accessibilité du réseau piétonnier pour le déplacement des personnes à mobilité réduite. Dans les chapitres 1 à 6, nous présentons différents aspects de recherche couverts dans cette thèse. Dans les paragraphes suivants, un résumé de chaque chapitre est donné.

Dans le premier chapitre, nous avons présenté le contexte et les problèmes abordés par cette recherche. Nous avons expliqué que le calcul des itinéraires accessibles pour les utilisateurs de fauteuils roulants nécessite de modéliser les interactions entre les humains et les environnements physiques et sociaux dans lesquels les PMR vivent. Nous avons discuté de la complexité de ces interactions en raison de l'hétérogénéité des profils d'utilisateurs ainsi que de l'hétérogénéité des barrières environnementales rencontrées par les PMR dans leurs activités quotidiennes. Dans ce contexte, la revue de la littérature existante nous a permis d'identifier plusieurs limitations des technologies de navigation existantes pour des personnes à mobilité réduite. Nous avons constaté que le plupart de ces systèmes ne considèrent pas spécifiquement les barrières environnementales et sociales en lien avec la mobilité des ces personne dans la planification et la navigation de trajet pour ces personnes. Nous avons également constaté que la plupart des outils existants pour la navigation ne considèrent pas la capacité et la confiance de l'utilisateur dans l'organisation de son trajet. Selon toutes ces limites, les problèmes spécifiques de cette dissertation sont présentés comme suit :

1. Manque d'une définition formelle des facteurs environnementaux et sociaux affectant le déplacement des personnes à mobilité réduite dans une zone urbaine;

2. Faibles prise en compte de la capacité des personnes à mobilité réduite par les modèles d'évaluation de l'accessibilité et par les outils de navigation existants;

3. Absence des facteurs sociaux dans l'étude de l'accessibilité des zones urbaines pour les personnes à mobilité réduite;

4. Limites des méthodes et outils existants dans le calcul des routages adaptés et accessibles pour les personnes à mobilité réduite.

Pour résoudre les problèmes de recherche et proposer et implémenter un cadre d'évaluation de l'accessibilité pour les PMR considérant les facteurs environnementaux ainsi que les capacités et la confiance des PMR, nous avons visé l'atteinte des objectifs spécifiques suivants : 1) développer une ontologie de mobilité pour les personnes à mobilité réduite qui considère à la fois les facteurs sociaux et les facteurs physiques de l'environnement, 2) proposer un méthode de l'évaluation de l'accessibilité du réseau piétonnier pour la mobilité des personnes à mobilité réduite en considérant spécifiquement les interactions entre les facteurs humains (capacité et confiance) et les facteurs physiques de l'environnement, 3) étudier le rôle des facteurs sociaux dans l'accessibilité des zones urbaines et finalement, 4) affiner les algorithmes existants pour calculer les itinéraires accessibles personnalisés pour les personnes à mobilité réduite en considérant leur profile.

Dans le chapitre 2, nous avons fourni une revue de la littérature sur les sujets liés au contexte de cette thèse : des modèles de processus de production de handicap, de la mobilité comme habitude de vie, de la représentation et de la segmentation du réseau piétonnier, des approches d'évaluation de l'accessibilité et des algorithmes de routage. Ce chapitre a permis de présenter les fondements théoriques en lien avec la recherche réalisée dans cette thèse. La revue de la littérature nous a aidé à identifier les problèmes de recherche et réviser les méthodes existantes pour aider les personnes à mobilité réduite dans leur déplacement. Cela nous a permis d'approfondir notre compréhension de ces méthodes et identifier les limites et les avantages de ces méthodes pour motiver notre recherche dans les chapitres subséquents.

Au chapitre 3, pour réaliser le premier objectif de la thèse, nous sommes concentrés sur l'intégration de la dimension sociale de l'environnement avec la dimension physique dans une ontologie de la mobilité pour les PMR. Ce chapitre a démontré que l'utilisation de la classification traditionnelle de l'environnement en catégories sociales et physiques a été remise en question (division socio-physique) et complique le processus de développement d'ontologies pour la mobilité des PMR, en particulier pour définir les relations entre les parties sociales et physiques de l'environnement; un problème fondamental pour la modélisation des interactions entre les humains et les environnements sociaux et physiques. Pour résoudre ce problème, une nouvelle approche basée sur une perspective « Nature-Développement » a été présentée. Nous avons montré que cette perspective facilitait l'intégration de l'environnement social et physique en définissant les propriétés sociales de telle sorte qu'elles soient locales à chaque entité.

Au chapitre 4, l'objectif était d'évaluer le niveau d'accessibilité des segments du réseau piétonnier pour les PMR. Pour illustrer l'utilité de l'approche proposée, nous avons cartographié l'accessibilité du réseau piétonnier pour deux utilisateurs avec des profils et niveaux de confiance différents à l'aide de données du quartier Saint-Roch à Québec. L'accessibilité des segments de réseau a été démontrée pour un utilisateur spécifique par rapport à un utilisateur de fauteuil roulant manuel moyen (confiance moyenne de 127 utilisateurs).

Au chapitre 5, dans le but d'intégrer plus concrètement les facteurs sociaux dans l'évaluation de l'accessibilité du réseau piétonnier, l'accent a été mis sur l'investigation de l'efficacité des actions politiques sur l'évaluation de l'accessibilité du réseau piétonnier. Nous avons enquêté sur l'influence de la mise en œuvre des tests de politiques sur l'accessibilité du réseau piétonnier, notamment les trottoirs et les bateaux pavés. Parmi les diverses politiques, nous avons testé l'impact de trois politiques différentes, soit 1) améliorer la qualité des bateaux pavés existants (largeur, pente et qualité de surface), 2) enlever la neige des intersections et 3) relocaliser la ligne existante de poteaux électriques sur les trottoirs. L'influence de ces politiques a été quantifiée et visualisée sur la carte d'accessibilité générée pour le secteur Saint-Roch à Québec. Les résultats ont démontré l'impact des différents tests de politiques sur l'accessibilité des bateaux pavés pour les PMR. Nous avons vu que l'impact de l'amélioration de la qualité de surface des bateaux pavés est presque négligeable par rapport aux facteurs précédents. De plus, nous avons remarqué que la mise en place de la relocalisation de la ligne existante de poteaux électriques sur les trottoirs a permis une amélioration significative du niveau d'accessibilité des trottoirs dans le secteur visé.

Dans le dernier chapitre, nous avons proposé une approche multicritère pour planifier des itinéraires personnalisés pour les personnes à mobilité réduite. Les principaux besoins et les mandats correspondants ont été déterminés dans le calcul de la route pour les PMR où l'accessibilité a été soulignée comme le besoin fondamental de calculer les routes optimales pour les PMR. Ensuite, nous avons proposé une approche de routage basée sur les niveaux d'accessibilité des segments du réseau. Nous avons étudié les critères d'accessibilité à partir des perceptions des utilisateurs, généré des réseaux de routage sur la base des critères déterminés, quantifié l'indice d'accessibilité (IA) et enfin calculé les itinéraires personnalisés. L'approche Fuzzy-TOPSIS a été étendue pour agréger les valeurs des critères et l'algorithme de Dijkstra a été modifié pour calculer les routes optimales. Pour valider la méthode proposée pour le calcul des IA, ceux-ci ont été recalculés en utilisant une autre approche qui applique les «If-Then Rules». Ensuite, pour évaluer la similarité entre deux résultats obtenus, l'erreur quadratique moyenne (EQM) entre deux vecteurs de IA_FT (Fuzzy-TOPSIS) et IA_FL (Fuzzy Logic) a été calculée (c'est-à-dire 0,09) et a montré un désaccord très subtil entre deux vecteurs. Le processus d'acheminement a été mis en place dans la région de Saint-Roch à Québec par la participation de trois utilisateurs de fauteuil roulant manuel. Les résultats de routage ont été visualisés sur l'application de la technologie d'assistance mobile multimodale (MobiliSIG).

7.2 Contribution de la thèse

Dans cette étude, l'objectif global visait l’utilisation des capacités du SIG (système d'information géospatiale) pour l’évaluation et la représentation spatio-temporelle de l’accessibilité des réseaux piétonniers et la planification d'itinéraires pour les PMR en tenant compte de leurs perceptions, de leurs préférences ainsi que de leur confiance. Grâce aux différentes phases de cette recherche, l'objectif général et les objectifs spécifiques de cette thèse ont également été atteints et sont résumés comme suit.

1. Une ontologie spécifique à la mobilité des PMR, prenant en compte les aspects sociaux et physiques de l'environnement ainsi que les facteurs personnels, et des objectifs liés à

cette mobilité ont été développées. Pour développer cette ontologie, une nouvelle approche basée sur une perspective « nature-développement » a été présentée, ce qui a conduit à développer une ontologie considérant les relations entre les parties sociales et physiques de l'environnement. Il convient de noter que la perspective « nature-développement » peut, en réalité, avoir des intérêts beaucoup plus larges; c'est-à-dire, d'aller au-delà de la question du handicap. Cette approche sera utile dans la conception d'outils visant à évaluer l'interaction « humain-environnement » dans un contexte plus large. Il permettra aux spécialistes du handicap de cartographier la complexité d'une situation donnée en identifiant directement les relations entre les aspects physiques et sociaux d'une entité.

2. Une approche fondée sur la confiance pour l'évaluation de l'accessibilité des réseaux piétonniers pour les PMR a été développée. À notre connaissance, c'est la première fois qu'une approche basée sur la confiance est utilisée pour évaluer l'accessibilité du réseau piétonnier dans une zone urbaine. En évaluant le niveau d'accessibilité de chaque segment, la carte d'accessibilité du réseau piétonnier a ensuite été générée. Cette carte peut être utilisée par les autorités municipales comme un outil de prise de décision pour localiser les segments inaccessibles ou peu accessibles et proposer un plan d'amélioration de l'accessibilité dans la zone.

3. Un cadre pour explorer, évaluer et quantifier l'impact des facteurs sociaux sur l'accessibilité des zones urbaines a été développé. Pour atteindre cet objectif, nous nous sommes concentrés sur la façon dont les politiques en tant que facteur social sont prises en compte dans l'évaluation de l'accessibilité du réseau piétonnier. L'influence de certaines politiques potentielles a été analysée, quantifiée et visualisée sur une carte d'accessibilité générée. L'approche proposée pourrait être utile aux autorités de la Ville pour explorer les meilleures options politiques pour s'adapter et voir leurs impacts. Les décideurs peuvent comparer les impacts de différentes politiques et décider quelles politiques seraient les plus efficaces.

4. Enfin, nous avons développé une approche pour calculer des itinéraires personnalisés pour les PMR en tenant compte des perceptions, des préférences et de la confiance des

utilisateurs. Cette approche peut offrir un cadre beaucoup plus utilisable pour les fournisseurs de systèmes de navigation.

7.3 Discussion et Conclusions

Dans cette recherche, nous avons proposé une nouvelle méthode pour évaluer et représenter l'accessibilité du réseau piétonnier et calculer des itinéraires personnalisés pour les PMR. Tout d'abord, pour exécuter les concepts les plus pertinents liés à la mobilité des PMR, leurs propriétés et leurs relations ont été identifiées et une ontologie spécifique de mobilité pour les PMR a été conçue. L'ontologie proposée spécifie les facteurs personnels et environnementaux nécessaires au développement de technologies d'assistance plus adaptées à la mobilité des PMR. En outre, l’ontologie proposée intègre plus particulièrement la dimension sociale de l’environnement et permet de prendre en compte son impact sur l’évaluation de l’accessibilité des réseaux piétonniers pour les PMR. Celle-ci n'est pas exhaustive, et il est possible de la développer pour prendre en compte des concepts plus détaillés liés à la mobilité des PMR. Bien que nous ayons pris en compte les concepts les plus pertinents basés sur le modèle PPH ainsi que d'autres documents appropriés, des recherches supplémentaires sont toutefois nécessaires pour évaluer la validité de l'ontologie.

Ensuite, l'ontologie proposée a été utilisée pour développer un cadre d'évaluation de l'accessibilité. Dans ce but, nous avons proposé une méthode fondée sur la confiance des utilisateurs de fauteuils roulants manuels pour évaluer le niveau d'accessibilité d'un réseau piétonnier. L'approche proposée utilisait un système Fuzzy-Logic pour calculer le niveau d'accessibilité de chaque segment en intégrant les facteurs personnels et environnementaux les plus significatifs. La fondation du système Fuzzy-Logic proposé est plus adaptée au raisonnement humain. La comparaison des résultats de cette approche avec d'autres approches, notamment la méthode Fuzzy-TOPSIS, a montré la validité du système Fuzzy-Logic. Cependant, la définition des fonctions d'appartenance et des règles If-Then de cette méthode a limité son intégration automatique pour l'évaluation de l'accessibilité par l'outil de navigation proposé. Pour pallier à ce problème, nous avons proposé une nouvelle méthode basée sur la méthode de Fuzzy-TOPSIS pour évaluer le niveau d'accessibilité d'un réseau piétonnier.

Poussant plus loin notre enquête, nous avons étudié des moyens d'intégrer plus efficacement les facteurs sociaux dans l'évaluation de l'accessibilité d'un réseau piétonnier. Pour ce faire, une méthode basée sur des scénarios a été proposée pour la simulation de l'accessibilité des réseaux piétonniers. Parmi divers facteurs sociaux, nous avons étudié l'influence de la mise en œuvre d'un changement de la politique sur l'accessibilité des intersections et des trottoirs au moyen de la simulation. Cette analyse d'évaluation de l'accessibilité, basée sur des scénarios pourrait constituer un cadre adéquat pour étudier l'impact de différents facteurs sociaux sur l'accessibilité des zones urbaines. Les autorités de la Ville peuvent se servir cet outil en tant qu'outil décisionnel pour l'amélioration de l'accessibilité des réseaux piétonniers. Ici, nous avons considéré plus spécifiquement l'impact des facteurs sociaux qui ont une influence directe sur la dimension physique de l'environnement. Des investigations supplémentaires sont nécessaires pour aller au-delà de ces facteurs sociaux et envisager des scénarios plus complexe impliquant un ensemble de facteurs sociaux et leurs interactions dans l'évaluation de l'accessibilité des réseaux piétonniers.

Le routage personnalisé était la dernière étape du processus de développement de l'outil de navigation adapté pour les PMR. L'approche Fuzzy-TOPSIS a été modifiée pour permettre l'agrégation de différents critères pour chaque segment et l'algorithme de Dijkstra a été modifié pour calculer les routes optimales. L'un des principaux points forts de l'approche proposée était de la consideration des perceptions, des préférences, et des niveaux de confiance des PMR dans la planification de leurs itinéraires. Nous avons montré comment les préférences et les niveaux de confiance de l'individu affectaient le calcul des itinéraires optimaux. Différents tests et efforts d'évaluation avec les PMR nous ont permis de valider notre méthode. Cependant, ces tests ont également révélé d'autres complexités dans la capture des profils des utilisateurs et de leurs préférences, ce qui nécessite par conséquent des investigations supplémentaires.

7.4 Perspectives de la recherche

Une nouvelle approche pour l'évaluation de l'accessibilité des réseaux piétonniers et la planification d'itinéraires pour les PMR compte tenu de leurs préférences et des capacités perçues est fournie dans cette thèse, mais il reste encore des lacunes de recherche et des défis d'application qui doivent être étudiés en tant que travaux futurs. Ici, en passant en revue les limites de cette thèse, nous discutons d'abord comment notre méthodologie proposée peut être étendue pour répondre à plus de besoins des PMR en plus de l'accessibilité. Ensuite, nous discutons des approches potentielles pour résoudre les défis restants et les lacunes de cette thèse.

1. Les itinéraires calculés peuvent être adaptés en fonction des itinéraires souhaités par les PMR, mais ces itinéraires peuvent ne pas être conformes à des exigences différentes qui n'ont même pas été prises en compte. En plus de l'accessibilité, les besoins des PMR imposent des exigences supplémentaires sur le calcul des itinéraires optimaux. Par conséquent, si la PMR n'est pas satisfaite selon ses besoins, par exemple en ce qui concerne la sécurité de l'itinéraire proposé, elle peut ignorer l'activité souhaitée. Par conséquent, une fois que le besoin d'accessibilité est satisfait, alors les critères importants suivants, y compris la sécurité, la conformabilité et la plaisance, peuvent être pris en compte dans le calcul de l'itinéraire optimal. Ces trois critères sont discutés ci-après.

I. La sécurité est définie comme se sentir à l'abri des différentes menaces. Le niveau de sécurité d'une personne peut être influencé, par exemple, par la forme urbaine et la présence de certains groupes ou individus (Alfonzo, 2005). Divers indicateurs peuvent être déterminés pour refléter la sécurité d'un itinéraire à partir de la perception des PMR (Jonietz, 2016). Indicateurs tels que la sécurité routière (Brown, Werner, Amburgey et Szalay, 2007 et Weinstein Agrawal, Schlossberg, & Irvin, 2008), la faible vitesse du trafic et le volume (Borst, Miedema, de Vries, Graham et van an Dongen, 2008 et Samarasekara, Fukahori et Kubota, 2011), la sécurité contre le crime comme le vandalisme, le mauvais entretien des logements, la présence de bars, les magasins d'alcool (Clifton et Livi, 2005), les conditions d'éclairage appropriées (Kaufmann, Papaioannou, Blaszczyk et Marques

Almeida, 2010 et Sanches et Ferreria, 2000) et le nombre d'intersections (Beale, Field, Briggs, Picton et Matthews, 2006 et McCormack et Shiell, 2011).

II. Selon la hiérarchie de marche, la conformabilité des itinéraires se positionne comme le troisième niveau de critère important, qui désigne le niveau de facilité, de commodité et de satisfaction de la personne en matière de mobilité. Pour évaluer le confort d'une route, différents indicateurs pourraient être pris en compte tels que les qualités environnementales. Ces indicateurs comprennent l'état du réseau piétonnier (par ex. : la largeur des trottoirs et l'entretien des trottoirs), les caractéristiques qui offrent des commodités (par ex.: les toilettes urbaines conçues pour les PMR) et les conditions météorologiques (par ex.: la lumière du soleil et la direction du vent). En outre, les concepts liés à la circulation routière, tels que les éléments d'apaisement de la circulation et les limites de vitesse, peuvent également affecter le confort des routes pour les PMR.

III. Le plaisir, en tant que dernier critère significatif, réfère à la façon comment une zone est agréable et intéressante pour la mobilité à partir de la perception des PMR. La diversité, la vivacité, l'harmonie architecturale et les attractions esthétiques peuvent toutes affecter le niveau de satisfaction d'une personne à l'égard du plaisir. La présence d'un espace vert, d'un point d'intérêt (par exemple, lieux historiques, architecture attrayante ou intéressante, magasins de détail) ou d'une ligne d'intérêt (par exemple, rue commerçante et restaurants en plein air) pourrait également améliorer ces qualités.

2. Calculer les routes optimales en tenant compte des critères susmentionnés est une tâche compliquée, car la route accessible pourrait ne pas être la plus sure et la plus confortable. Pour résoudre ce problème, une approche devrait être développée pour déterminer un itinéraire, qui considère tous les critères requis avec une compensation d'un critère par un autre. Ainsi, la fonction de cout employée devrait être adaptée en considérant un équilibre entre tous ces critères comme:

$$Index\ de\ routage(IR) = W_A * AI + W_S * SI + W_C * CI + W_P * PI$$

Où W_A, W_S, W_C et W_P indiquent les poids pour l'accessibilité, la sécurité, le confort et le plaisir, respectivement. Pour calculer l'équation ci-dessus, nous devons d'abord quantifier les indices de chaque critère, y compris l'indice d'accessibilité (IA), l'indice de sécurité (IS), l'indice de la conforte (IC) et l'indice de plaisir (IP). Ensuite, l'indice de routage est déterminé en pondérant chaque critère (c'est-à-dire W_A, W_S, W_C et W_P) en fonction de leur importance à partir de la perception de la PMR. L'indicateur d'accessibilité (IA) était le seul indice examiné dans cette thèse.

3. Définir les " If-Then rules" précises tout en développant des Fuzzy Systems est une étape très importante dans le routage et plus spécifiquement dans le processus d'évaluation de l'accessibilité. Les règles peuvent être extraites de diverses méthodes, y compris les experts du domaine, le regroupement de données et les algorithmes d'apprentissage automatique. Dans cette thèse, nous avons extrait les "If-Then rules" du point de vue d'un expert qui utilise un fauteuil roulant manuel. Cependant, plusieurs questions restaient sans réponse. Voici quelques exemples : les développeurs peuvent-ils définir eux-mêmes les règles? Les développeurs peuvent-ils comprendre assez bien les experts pour transcrire des règles précises? Les experts comprennent-ils la Fuzzy Logic? Les experts peuvent-ils définir les règles directement? Les experts peuvent-ils vérifier les règles créées par le développeur? Une étude plus approfondie est nécessaire pour une validation plus rigoureuse des If-Then rules proposés dans cette thèse. Un processus de validation supplémentaire avec des experts et des utilisateurs de fauteuils roulants dans des scénarios d'application plus réalistes peut également être réalisé.

4. Un autre défi important en lien avec ce travail de recherche était de collecter des données précises et détaillées sur le réseau piétonnier, car il s'agit généralement d'une tâche très longue et couteuse. Pour effectuer notre analyse, nous avons donc limité la zone d'étude. De plus, les caractéristiques environnementales sont temporelles: elles changent dans le temps. La temporalité des caractéristiques de l'environnement augmente la complexité du processus d'évaluation de l'accessibilité et, par conséquent, peut entraver le processus de trouver des itinéraires adéquats pour les PMR. Ainsi, un travail futur potentiel consiste à proposer une approche efficace pour générer des données détaillées relativement rapides et peu couteuses (y compris des données temporelles). User-Generated Content (UGC) (Anderson, 2007) et en particulier Volunteered Geographic Information (VGI) (Goodchild, 2007) sont deux exemples de ces ensembles de données désirés qui sont devenus des

méthodes largement populaires et généralement acceptables au cours des dernières années. Un projet VGI réussi est le projet OSM (Open Street Map) basé sur des données collectées collectivement et librement disponibles depuis 2004 (Goetz, 2012; Mooney, Corcoran et Winstanley, 2010; Neis, Goetz et Zipf, 2012). Le VGI utilisé dans OSM est également proposé et présenté pour être utilisé dans des applications de routage dans le cas spécifique d'assistance à la mobilité pour les utilisateurs de fauteuils roulants (Holone et al., 2008; Rashid et al., 2010 et Menkens et al., 2011).

5. Nous avons démontré comment les préférences et les confiances de l'individu affectent le calcul des routes optimales. Cependant, l'un des défis dans ce contexte est la temporalité des capacités des PMR. Le niveau de capacité de l'individu peut varier d'un moment à l'autre (par exemple, le matin et le soir) et, si on le considère, cela compliquerait le processus de calcul. Par conséquent, nous recommandons que d'autres recherches soient entreprises pour étendre l'approche proposée pour deux états corporels de frais et de fatigue. Un profil d'utilisateur peut également être affecté par la familiarité du chemin de routage, de sorte que la confiance de l'individu soit influencée par l'anxiété des lieux inconnus.

6. Dans notre travail, les contraintes de temps liées aux sous-tâches ne sont pas intégrées dans le calcul des routes personnalisées. La méthodologie de routage devrait être révisée et modifiée, en incluant la théorie spatiotemporelle dans les scénarios de navigation. Par exemple, quand un PMR veut atteindre un point à un moment précis et effectuer également des tâches spécifiques avant / après ce moment, alors les services basés sur la localisation doivent correspondre à plusieurs activités dans une période de temps spécifique. Raubal, Miller et Bridwell (2004) proposent un cadre général pour la théorie spatiotemporelle qui combine les idées de la géographie du temps classique avec une théorie étendue des affordances.

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