UNIVERSITY OF SOUTHAMPTON

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING

School of Electronics and Computer Science

Apply the Linked Data Principles to a Decision Support System for Accessible Travelling

By

Chaohai Ding

Thesis for the degree of Doctor of Philosophy

September 2017

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING

School of Electronics and Computer Science

Thesis for the degree of Doctor of Philosophy

APPLY THE LINKED DATA PRINCINPLES TO A DECISION SUPPORT SYSTEM FOR ACCESSIBLE TRAVELLING

Chaohai Ding

The development of Information Communication Technologies (ICTs) empowers digital inclusion, which can bring benefits to all people. However, according to the literature review of current research related to accessible travelling, most projects are focused on improving assistive technologies, devices, services, and user interfaces regardless of whether they deliver useful or optimised content to satisfy users' special needs. Limitations and challenges are exposed from these projects which are aiming to address the accessible travelling problems faced by people with disabilities, namely the lack of accessibility metadata, data isolation, urgent needs of methods for data integration, and better algorithms for decision making. Therefore, the conceptual model of Linked Data-driven decision support system (DSS) for accessible travelling is proposed in this research to address these problems. Using a Linked Data driven approach, this research explores the areas of open accessibility data, accessibility data integration and interlinking. Moreover, there are three the ontologies proposed to address the needs of standard vocabularies to publish open accessibility data. Furthermore, the research also discusses and demonstrates strategies to apply the decision support methods to Linked Data. As a result, this research would not only benefit people with disabilities or special needs but also contribute to the research of a novel model to address accessibility information barriers and accessible travel planning issues by applying the Linked Data principles to DSSs to provide decision support.

Table of Contents

List of Tables

List of Figures

DECLARATION OF AUTHORSHIP

I, ... [please print name]

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

[title of thesis] ....

....

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. [Delete as appropriate] None of this work has been published before submission [or] Parts of this work have been published as: [please list references below]:

Signed: ....

Date: ....

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisors Professor Mike Wald and Dr Gary Wills for the continuous support of my PhD study and related research, for their patience, motivation, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis.

Besides my advisor, I would like to thank my internal examiner in the ECS, Dr Thanassis Tiropanis for his insightful comments. I also would like to thank my external examiner Dr Silvia Mirri from University of Bologna, for her comments and advices for this thesis.

My sincere thanks also go to the member of the ECS Accessibility Team, Mrs EA Draffan and Dr Abi James, who provided me with the opportunities to work with them and give me the advice for the research on the accessibility. I would like also Mrs Lisa Seaman, who invited me to join the Cognitive and Learning Disabilities Accessibility Task Force (COGA TF) at the Web Accessibility Initiative at the W3C. I thank my fellow colleagues, thanks to the Dr Yunjia Li for his advices on the research of the Linked Data since I am working with him for the Master project. I would also like to thanks, Dr Xin Wang for the discussion of the SPARQL.

Last but not the least, I would like to thank my family. Thanks to my parents to support me to take so many years for the PhD research. In particular, I would like to thank my wife, Mrs Xin Chen, for her understanding and support to let me finish this PhD.

Definitions and Abbreviations

AHP	Analytic Hierarchy Process
AmI	Ambient Intelligence
ANP	Analytic Network Process
BIM	Building Information Modelling
CI	Consistency Index
CR	Consistency Ratio
CWA	Closed World Assumption
DEM	Digital Elevation Models
DL	Description Logic
DSS	Decision support system
ES	Expert Systems
FN	False Negative
FP	False Positive
GA	Genetic algorithm
GQM	Goal Question Metrics
ICT	Information Communication Technologies
LBS	Location Based Service
LOAD	Linked Open Accessibility Data
LOD	Linked Open Data
LOS	Level-of-Service
MCDM	Multiple Criteria Decision Making
ODI	Open Data Institute
OM	Ontology matching
OSM	Open Street Map
OWA	Open World Assumption
PACO	Place Accessibility Ontology
PAM	Personalised accessibility maps
POI	Points of Interest
QA	Question Answering
RDF	Resource Description Framework
SPARQL	SPARQL Protocol and RDF Query Language
SWRL	Semantic Web Rule Language
TACO	Transport Accessibility Ontology
TfL	Transport for London
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TP	True Positive
UI	User Interface
URI	Uniform Resource Identities

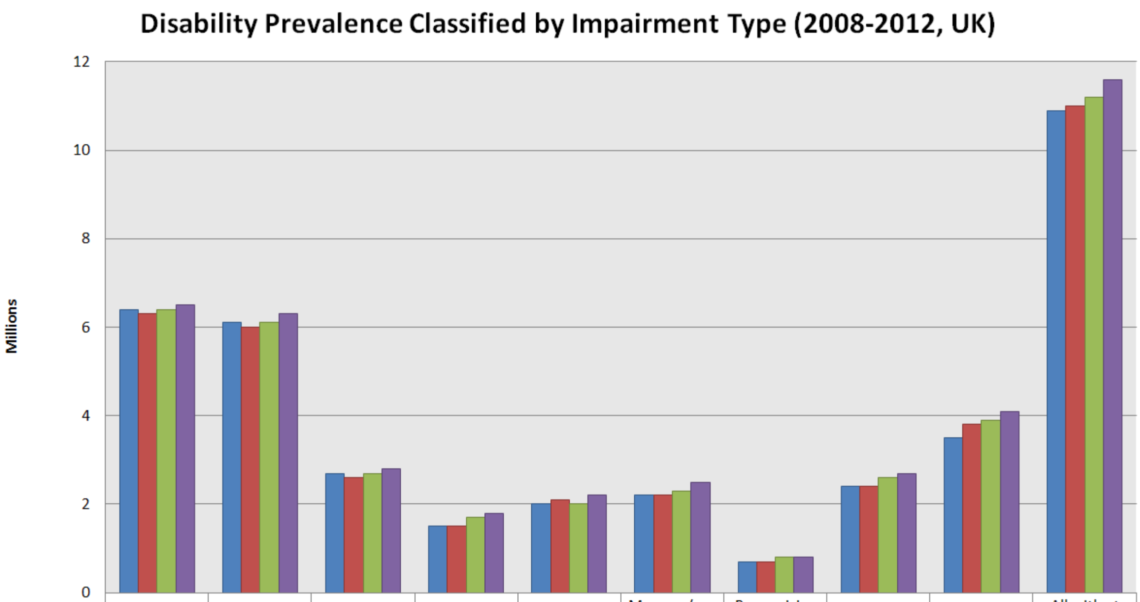
“What the Semantic Web is for me is an indispensable part of what I called ‘The Accessible Planet’ around 1979”

- *William Loughborough*

A pioneer in vision science and web accessibility

Chapter 1: Introduction

According to the United Nations[1], there are approximately 650 million people with disabilities in the world and nearly 2 billion people affected by disabilities. The disability statistics in the Family Resource Survey of 2011/12 stated that there are approximately 11.6 million people with at least one impairment or long and limited term illness in the United Kingdom. Figure 1 demonstrates the disability prevalence in the UK[2] classified by different impairment type, which indicates that the impairment types of mobility, lifting and carrying, and manual dexterity are listed as the top three prevalent disabilities. This figure also demonstrates that the population trend of people with disabilities increased from 10.9 million to 11.6 million during the years from 2008 to 2012 and is estimated to increase to 12.7 million in 2016. In the United State, over half of people with disabilities indicate that transportation is the major problem for their social activities [40]. Although there are many public facilities in urban areas which are built with accessibility in mind, travelling is still challenging for the people with disabilities due to the discordance between the users' expectation and their actual travel experience in the real world [75].



	Mobility	Lifting, carrying	Manual dexterity	Continence	Communication	Memory/concentration/learning	Recognising when in danger	Physical co-ordination	Other	All with at least one impairment
2008/09	6.4	6.1	2.7	1.5	2	2.2	0.7	2.4	3.5	10.9
2009/2010	6.3	6	2.6	1.5	2.1	2.2	0.7	2.4	3.8	11
2010/2011	6.4	6.1	2.7	1.7	2	2.3	0.8	2.6	3.9	11.2
2011/2012	6.5	6.3	2.8	1.8	2.2	2.5	0.8	2.7	4.1	11.6

Figure 1: Disability Prevalence Classified by Impairment Type in the UK (2008-2012)

[1] http://ec.europa.eu/enterprise/sectors/tourism/accessibility/index_en.htm
[2] http://odi.dwp.gov.uk/docs/res/factsheets/disability-prevalence.pdf

1.1 Overview

People with disabilities are facing many problems in their day-to-day social activities, such as moving in or out of their homes without assistance, travelling in personal cars or public transport or visiting an unfamiliar place [85]. One of the main challenges is that it is very difficult and time-consuming to gather the accessibility information of public transport such as buses, taxi, trains, ships, and aeroplanes as well as accessibility information of public places, or facilities before or during their trip. In order to address this problem, the European Commission has proposed the research of accessible tourism to encourage European countries to improve information availability on accessible tourism for disabled people [104]. However, according to the literature review of several projects and research presented in the following chapter, the accessibility information of public places, public transportations and built environment is still mostly absent. Most of the accessibility information providers are isolated from different domains, systems, projects or applications, which means that it is much more costly financially and time-consuming for people with disabilities to prepare their trip in advance or search real-time during the trip.

Another challenge is that there is no open and public space for publishing, consuming and maintaining the accessibility information of these public places, transportations and facilities. Therefore, with the development of Information Communication Technologies (ICTs), the motivation for this research is to investigate how to apply Linked Data principles to publish and interlink accessibility information. Furthermore, based on these linked accessibility datasets, this research also investigates how to use optimised algorithms of the decision support system (DSS) to provide travelling decision support for people with limitations, impairments, and disabilities, especially for people with mobility difficulties. This chapter will mainly give a brief introduction and overview of this research and the proposed research questions as well as the research objectivities.

1.2 Research Statement

In recent years, the development of Information Communication Technologies (ICTs) empowers the digital inclusion, which can bring benefits for all people. However, according to the literature review of current e-Accessibility research, most projects focus on improving assistive technologies, devices and user interfaces regardless of whether the system or services delivered are useful or optimise content to satisfy users' special needs. This leads to the difficulties and makes it time-consuming to gathering the accessibility information of public transportation, public places, or facilities before or during their trips.

With the aim of addressing the gap between users' special needs and complex environmental barriers in real-world travelling scenarios, this thesis explains the research of applying the Linked Data principles to the DSSs to improve accessible travelling in the different phases, such as pre-trip planning, in-trip assistance information and after trip-evaluation. Figure 2 shows a graphical overview of applying the Linked Data principles to integrate open accessibility data from different domains across the Web, such as public transport, hospital, house, education, government, personal finance, shopping, and the internet to benefit the people with disabilities.

Figure 2: Overview of Linked Open Accessibility Data across Different Domains

Open accessibility data is the open data related to the accessibility information, such as step-free access, automatic doors, accessible entrances, accessible toilets, accessible parking or hearing loops etc. Accessibility data also refers to the data that benefits people with special needs, such as baby change facilities, staff help available, customer help, travelling with a baby pushchair or carrying large luggage. In the hypothesis, all this accessibility information from different datasets could be linked together into the Linked Open Data (LOD) Cloud for other people to contribute to, maintain and consume.

Another issue for the lack of accessibility information on the Web is due to there being no standard guideline and spaces to publish the offline accessibility data as online data. Therefore, applying Linked Data principles to publish, interlink and consume accessible travelling data could be a possible solution to promote the transition of offline accessibility data to online and additionally, aggregating it into an open and public space. As the core data layer of the Semantic Web, the advantages of Linked Data like human and machine readable data, well-structured standard data format, semantic linking, knowledge sharing, brings the opportunities to integrate the data from different specified domains into a global space. Furthermore, this opportunity empowers a new conceptual model of the Linked Data-driven DSS for accessible travelling. The conceptual model applies the Linked Data as the traditional data and knowledge base components in the DSS framework.

1.3 Research Questions and Objectives

The aim of the following proposed research questions is to find a novel way for enhancing accessibility by applying the Linked Data principles to DSS:

RQ1: What is an appropriate method for publishing and integrating heterogeneous accessibility related datasets with incomplete information?

RQ2: What decision support algorithms work appropriately with the linked open accessibility data for accessible travelling?

Furthermore, in order to answer these two RQs, three research objectives are defined as follows:

- Appropriate approaches for publishing and integrating and interlinking open accessibility data from heterogeneous sources into Linked Data;
- Appropriate models for the Linked Data-driven decision support system to improve the accessible travelling for people with mobility difficulties;
- Appropriate algorithms for the Linked Data-driven decision support system to improve the accessible travelling for people with mobility difficulties.

Firstly, this research investigates the use of the Linked Data principles to publish, integrate and interlink the open accessibility data from heterogeneous sources, such as transport data, building data, or geographic data to establish a public linked open accessibility data. In this phase, the challenges and problems of publishing open accessibility data as the Linked Data are explored, such as the availability of standard ontologies, the URI naming and referencing for the accessibility information as well as the interlinking methods. Based on this linked data and user preferences for accessible travelling, this research proposes the model of the Linked Data-driven Decision Support System (LD-DSS) for accessible travelling to address the travelling problems faced for people with disabilities or special needs, especially with mobility difficulties. The primary reason for involving users' preferences is due to the complex interactions between the individual with disabilities and public places or services, such as various functional limitations, the various special needs of the individual and the complex service conditions. User preference modelling is widely used in various research projects related to accessibility, such as the research of user modelling in smart homes for people with disabilities [56], user modelling in assistive environments [42] as well as the research of user modelling in context-awareness systems for people with disabilities [50]. Although the user preference modelling helps the definition of the open accessibility data, it is not included in this research. This research explores the area of open accessibility data integration and interlinking, the conceptual model of the Linked Data-driven decision support system for accessible travelling, and appropriate DSS algorithms to address the information barriers of accessible travelling for people with disabilities.

1.4 Contributions of the Thesis

There are a few publications and talks related to this PhD research, which are listed as follows:

- Based on the literature review of ICT technologies and current research projects related to e-Accessibility, several challenges for accessible travelling are identified and propose the novel approach to applying Linked Data principles to decision support systems to enhance accessible travelling. There are two papers [27] and [28] accepted and published in the proceedings of Proceedings of the 11th International Conference e-Society 2013.
- A survey of open accessibility data from the four different open accessibility datasets within the UK was conducted. This survey basically compares the data quality of accessibility information between government published open accessibility data and crowdsourcing accessibility data. The data analysis and lessons learned from this survey were published as a communication paper [29] in the Proceedings of 13th International Web for All Conference - W4A '14, which was co-located with WWW 2014 conference.
- An approach for interlinking open accessibility data to enrich the incomplete open accessibility data is proposed. The detailed explanation of this approach and results were published as a full paper [30] in the Proceedings of the 14th International Conference on Computers Helping People with Special Needs (ICCHP).
- A lightning talk[3] on “Raising the user experience of being on the road” for Open Knowledge Foundation Open Transport Working Group” with the title “Mash up transport data with other datasets to determine accessibility of the location/vehicle[4]”.

There are some contributions related to this PhD research, which are listed as follows:

- Proposed the interlinking algorithm to interlink the different geo-entities from different Linked Datasets.

[3] http://transport.okfn.org/2013/09/13/join-us-at-okcon/
[4] http://www.slideshare.net/ChaohaiDing/presentation-for-okc-by-chaohai-ding

- Proposed the approach to publishing accessibility metadata for physical places into the geo-entities on the Linked Data Cloud.
- Proposed the concept model of Linked Data-driven Decision Support System for accessible travelling.
- Proposed the Mobility Difficulty Ontology to model the people with mobility difficulties.
- Reviewed and listed ontologies related to accessible travelling domain on the Github[5].
- Based on the currently availability of ontologies, this research constructed the ontologies to provide the vocabularies to describe accessibility metadata for physical places and public transportation in the domain of accessible travelling.
- The proposed hybrid strategy to apply the AHP method to query the Linked Open Accessibility Data.

1.5 Thesis Structure

In Chapter 2, the background information on disability, accessibility and accessible tourism is introduced. Then there is a demonstration of the challenges faced by the people with disabilities based on the reviews of several research projects. After that, the literature review of Linked Data principles, Decision Support System, and DSS algorithms are described as well as Linked Data-driven Decision Support Systems. Some approaches or projects are reviewed to analyse the challenges of current research on improving accessibility information, or the research of the DSSs that provide accessible travelling decision support for people with disabilities. The investigation into the research of vocabularies and ontologies for accessible travelling are also explored in this chapter.

In Chapter 3, the main research questions proposed for this research are discussed, as well as the current research gap of accessible travelling. Then this chapter goes on to introduce the research of Linked Data-driven DSSs for accessible travelling. Each model is also demonstrated in detail in this chapter.

In Chapter 4, the metrics for evaluating the datasets generated from data integration and interlinking are presented and discussed. The metrics for evaluating the algorithms of Linked Data-driven decision support system are also conducted for the further research.

[5] https://github.com/chaohaiding/Ontologies-for-Accessible-Travelling

In Chapter 5, the methodologies and experiments for the research of open accessibility data are discussed. In order to conduct the research of open accessibility data used in the real world, the experimental datasets are collected from several online websites or crowdsourcing systems, which are used by the end users with mobility disabilities or limitations. The survey for the open accessibility data is also discussed in this chapter. This chapter also introduces the research of accessibility data integration and the linked open accessibility data interlinking. After that, a crowdsourcing based approach is proposed to evaluate the results.

In Chapter 6, the methodologies and experiments designed for the research of accessible travelling requirements and ontologies for accessible travelling are explained. In order to understand the accessibility requirements and the ontology of mobility difficulties, firstly, there is a study of the mobility difficulty classification. After that, in order to construct the ontology for accessibility metadata and the rules for the ontology reasoning, the online questionnaire to study the accessibility requirements for the people with mobility difficulties is designed. Moreover, this chapter also presents the research of ontologies for accessible travelling, namely the mobility difficulty ontology, place accessibility ontology and transport accessibility ontology.

Chapter 7 mainly presents the research of publishing the Open Accessibility Data as the Linked Data to answer the research question RQ1.3. This chapter will present the challenges and methodologies to publish the user preference data, accessibility data of built environment, and public transport accessibility data.

In Chapter 8, this chapter demonstrates the research of how to applying the decision support algorithms in the Linked Data knowledge base to provide decision support for accessible travelling. In order to explore the research question, this chapter discusses the problems of decision support for accessible travelling. It proposes the approaches of applying question answering and a hybrid strategy to provide accessible travelling decision support with personalised categorisation of difficulties.

The last chapter will conclude the main discussion of this thesis and propose some future works related to this PhD research.

Chapter 2: Literature Review

This chapter describes the background information related to the research of disability, accessibility, accessible tourism/travelling, Semantic Web, Linked Data and Decision Support Systems. Some problems exposed from the literature review are leading to the motivation of this PhD research. The first section in this chapter demonstrates the conceptual models of disability classification. It also describes the concept model of tourism and disabilities and the process sequence of accessible tourism. There are some projects in the field of accessible travelling reviewed in the last part of this section. The second section describes the concept of the Linked Data, which includes Linked Data principles, 5-star Linked Data and the concept of Linked Data-driven web applications. Some standard vocabularies and ontologies related to disabilities and accessible travelling are also presented in this section. In Section 2.3, there is a brief introduction of DSSs and Semantic Web-driven DSSs. It will also review some DSSs algorithms and current research related to the field of accessible travelling. In the last section, it gives a brief summary of this chapter.

2.1 Disability and Accessible Travelling

The International Classification of Functioning, Disability and Health (ICF) is the framework to describe and organise the information on functioning and disability. It provides the standard language for the definition of health and disability as well as the conceptual basis for measuring health and disability. In the ICF framework, disability is multidimensional and interactive. As indicated in Figure 3, there are four main components in this framework, namely body function, body structure, activities and participation, and environmental factors. The body function component includes mental functions, sensory functions and pain, voice and speech functions etc. The body structure component includes the structure of the nervous system, the eye, ear and related structure etc. The activities and participation component include the learning and applying knowledge, communication, and mobility etc. And the environmental factors include the products and technology, services, systems and policies etc. [107]. In the ICF framework, the activity refers to the execution of a task or action by an individual, and participation means the engagement in the social life. The activity limitations will occur through the discordance between environmental factors and personal factors, which leads to participation restrictions. The following sections will demonstrate the research of disability classification based on ICF framework, the introduction of disability model applied in this research, the research of accessible travelling and accessibility measurement.

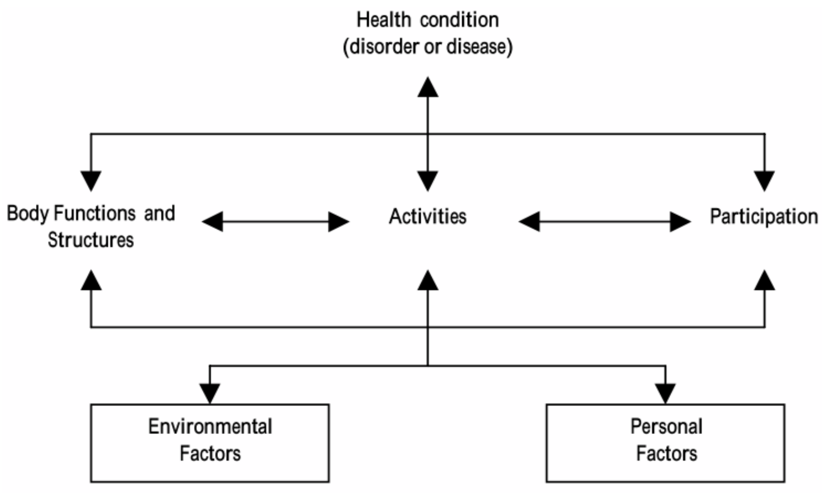


Figure 3: Interactions between the Components of ICF [107]

2.1.1 Disability Classification

There are two most widely used models of disabilities, namely the medical model and social model. The medical model is focus on the disability diagnosis and illness. Compared with the medical model, the social model of disability is developed to help disabled people to explain their personal experience of disability in the social activities rather than disability itself. The social model of disability is introduced by Oliver M. et al. [73] in the early 1980s, which is widely used in the research related to disability. According to the survey exposed by G. Shaw et al. [86], they argued that the research on the disabled tourist should be part of wider studies of disability that encompass the social model of disability. Therefore, in this research, disability is considered as the complex social gap between the individual and their social environmental factors.

In general, disabilities can be classified as follows, namely visual disability, hearing disability, physical disability, speech disability, or cognitive and neurological disabilities. For the classification of impairments in the social model, Wiethoff et al. [105] proposed the approach of using ontology to describe the travelling limitations based on ICF framework and the Activity Theory. The user groups are classified on the basis of functional limitations. In their research, they applied ICF code, and the user groups could be defined in two stages: the main group classification, and the sub-group classification. The main groups include lower limb impairment, wheelchair users, upper limb impairment, upper body impairment, physiological impairment, psychological impairment, cognitive impairment, vision impairment, hearing impairment, and communication production/receiving impairment. The sub-group classification will be two different levels in each main group: light and severe.

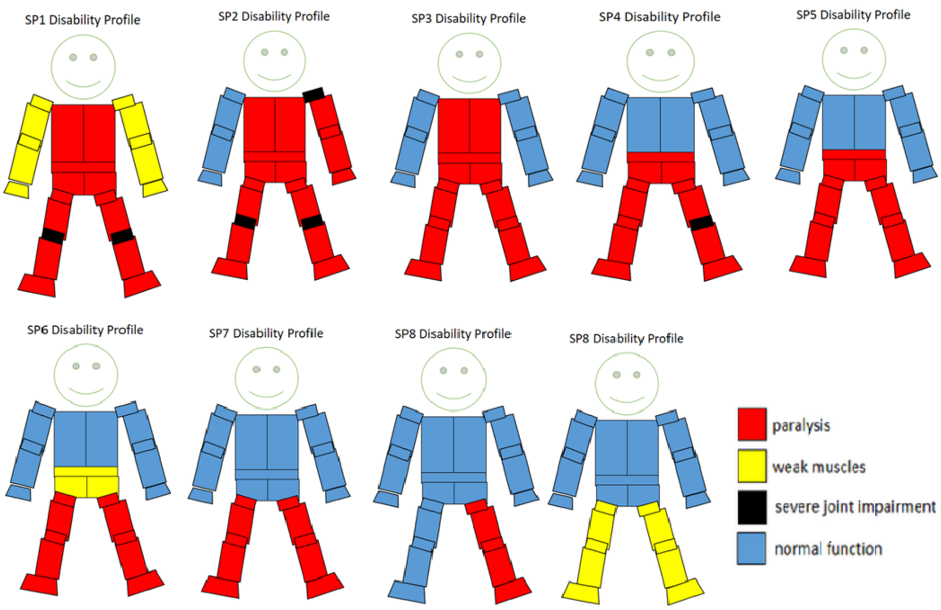


Figure 4: Wheelchair Sports Classification for Paralympics Games[6]

However, for the user groups, this research is only focused on the people with mobility disabilities. There is a standard classification of wheelchair sports athletes in Paralympics Games

[6] https://en.wikipedia.org/wiki/Wheelchair_sport_classification

stated in Figure 4. Initially, the classification of wheelchair sport should also combine with the spinal injury locations to provide fair competition for the Paralympics Games, which is not presented in this figure. However, this figure demonstrates how the standard organisation classified the people with mobility disabilities based on three different parts of the body and functional abilities, namely upper limb, upper body and lower limb, as well as four different functional abilities, namely paralysis, weak muscles, severe joint impairment and normal function.

The classification can be also based on the special needs of people with disabilities. For example, based on the report of National Disability Authority (NDA) of Ireland, Pühretmair [80] classified people with disabilities into physical access disability (people with mobility impairment), sensory access disability (people with hearing or visual impairment), and communication access disability (people who have difficulties with writing, vision, speech, and language). However, the term of accessibility is not only restricted to people with disabilities but also increases the flexibility and usability of services for other people. G. Vanderheiden listed the same functional requirements between temporary constraints and each disability demonstrated in Table 1 [99].

Table 1: Functionality Required by Disability and Constrains [99]

Operable Functionality	Required by Disabilities	Required by Constraints
Operable without Vision	Blind	Eyes are busy or who are in darkness
Operable with Low Vision	Visual Impairment	Using a small display or in a smoky place
Operable with No Hearing	Deaf	Loud environments or whose ears are busy or are in forced silence
Operable with Limited Hearing	Hard of Hearing	People in noisy environments
Operable with Limited Manual Dexterity	Physical Disability	People in a space suit or chemical suit or who are in a bouncing vehicle
Operable with Limited Cognition	Cognitive Disability	People who are distracted or panicked or under the influence of alcohol
Operable without Reading	Cognitive Disability	People who just haven't learned to read this language, people who are visitors, people who left reading glasses behind

Therefore, there are some research and projects considering the term of accessibility as the solutions to address the gap between the needs of user activities and constrains of body functionalities. For example, in terms of the special needs required by people with disabilities, accessible travelling information can also include the information and services such as financial cost or time constraints. The term of accessibility refers to people’s ability to achieve their desired goods, services, activities, and destinations [68]. If an individual’s disability is classified without personal needs or preference, the complex environment factors could lead to a gap between their initial desire and actual experience.

2.1.2 Accessible Travelling

As stated in the first chapter, travelling is listed as one of the top challenges for people with disabilities or older people. According to the consumer behaviour models, tourist is considered as a problem-solving task for those people who initially feel motivated to go on the vacation. With this motivation, they will firstly search the information related to the trip. Then they can make decisions based on their search results. Finally, after returning from the holiday, they can evaluate the holiday experience in several aspects [14]. For the travelling process, Pühretmair and Miesenberger [81] summarised three stages of travelling for people with disabilities:

- Travel planning and decision making, which takes place weeks or months before travelling;
- Arrival and departure with different means of transport;
- The stay including all activities during the stay.

There are also four key areas into which the supply side of accessible tourism can be conveniently conceptualised, namely accessible infrastructure and facilities, accessible transport, accessible services, and accessible Information [16]. For these four key areas, accessible infrastrcure and facilities are related to the physical places or facilities in the real world, where the tourism system should be accessible for people with disabilities. Accessible transportation is the connection between an individual and their target destinations. Accessible services provide universal designed services, which are easy to use for all people. The term of accessible information refers to the information that is available in a variety of formats, such as standard text, content on the Web or the Internet, digital formats, large print, Braille, etc. In order to satisfy users' requirements, involving user preferences in the system is one of the significant factors in the research of user sensitive inclusive design and accessibility [59] [93].

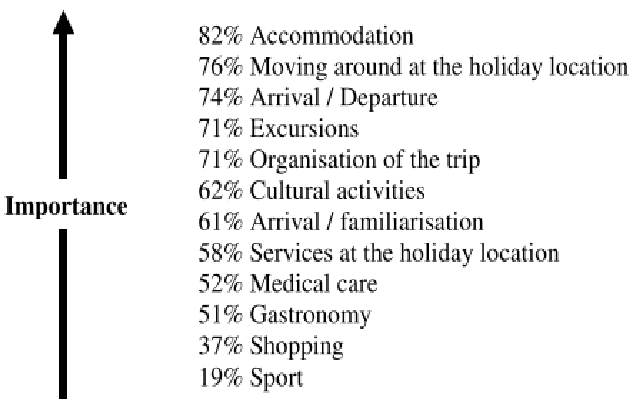


Figure 5: Importance Ranking of Tourisms Facilities [78]

The importance ranking of facilities for people with disabilities is carried out by a study in Germany presented in Figure 5 [78]. The accommodation is the highest priority for the accessible tourism. The term of mobility and public transportation is the following important requirements accounted for nearly 76%. However, accessible travelling is a complex issue due to the unique and different challenges faced by the people with disabilities, such as the complex built environment, different transportation patterns and other constraints or limitations of travelling routes.

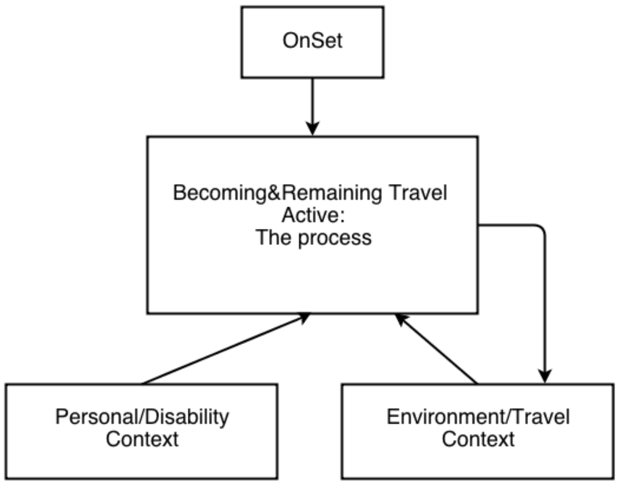


Figure 6: A model of Tourism and Disability [75]

Based on the ICF framework, Packer et al. [75] presented a modified model of tourism and disability described in Figure 6. In this model, they summarised the process of becoming and remaining travel active as a six-step process:

- Journey of acceptance;
- Reintegration and exploration;
- Evaluation;
- Planning the trip;
- Managing the trip;
- Reflection.

The first four steps include the search of journey information, integration of exploration choice, evaluation and make the decision. In the same scenario, the time cost for the people with disabilities will increase dramatically due to the information and accessibility challenge. Bekiaris et al. also proposed the special needs of three steps travel process sequences for adapted information systems, namely pre-trip phase, on-trip phase and end-trip phase, which are corresponding to the planning task, tracking task and assessment task [9]. This three-step travel process is quite similar to the three-stage travelling process summarised by Pühretmair and Miesenberger [81]. One of the major differences is that Bekiaris et al. add the end-trip phase to evaluate the trip experience, which is also following the consumer behaviour model.

2.1.3 Accessibility Measurement

The measurement for accessibility is relatively difficult because accessibility can be affected by too many factors and is highly related to the individual's activities and abilities. Therefore, activity-based travel models and integrated transportation/land use models are most suitable for quantifying accessibility [67]. Accessibility can be evaluated based on the time, money, discomfort and risk required to research opportunities. There are some measurements proposed for evaluating or measuring accessibility. Gravity-based measures for accessibility is the most common and general measurement, which is often used to measure accessibility in a traffic analysis [12].The equation below describes the accessibility degree of zone i:

$$Accessibility_i = \sum_j Opportunities_j \times f(C_{ij})$$

, where:

i = index of origin zones, j = index of destination zones, $f(C_{ij})$ = function of generalised travel cost (so that nearer or less expensive places are weighted more than farther or more expensive places). However, the theoretical origin of the gravity measure comes from physics. Geurs and van Wee produced a checklist of recommendations of how any accessibility measure should behave, regardless of its perspective [41]:

- Accessibility should relate to changes in travel opportunities, their quality and impediment.
- Accessibility should relate to changes in land use.
- Accessibility should relate to changes in constraints on demand for activities.
- Accessibility should relate to personal capabilities and constraints.
- Accessibility should relate to personal access to travel and land use opportunities.

They also identified the four types of components for measuring accessibility, namely the land-use component, the transportation component, the temporal component and the individual component [41]. In **Error! Not a valid bookmark self-reference.**, there are four basic perspectives identified on measuring accessibility by taking all these four components into account. Moreover, with the development of ICTs, Kwan argued that the measurements of individual accessibility should not ignore the complexities and opportunities brought by these new technologies. He presented the possible methods for modelling individual accessibility and implications for geographical analysis [63]. Transport for London (TfL) also proposed the Public Transport Accessibility Level (PTAL) to provide a detailed and accurate measurement of the accessibility of a point of interest to the public transport network in the area of Greater London, by taking into account walk access time and service availability [96]. However, this PTAL measurement does not consider the speed or utility of accessible services, crowding, ability to board services or ease of interchange, which are important factors for people with disabilities to access the public transportation network.

Table 2: Four Basic Perspectives on Measuring Accessibility.

Measure	Component			
	Transport component	Land-use component	Temporal component	Individual component
Infrastructure based measures	Travelling speed; vehicle-hours lost in congestion		Peak-hour period; 24h period	Trip-based stratification
Location based measures	Travel time and or costs between locations of activities	Amount and spatial distribution of the demand for and/or supply of opportunities	Travel time and costs may differ,	Stratification of the population
Person based measures	Travel time between locations of activities	Amount and spatial distribution of supplied opportunities	Temporal constraints for activities and time available for activities	Accessibility is analysed at individual level
Utility based measures	Travel costs between locations of activities	Amount and spatial distribution of supplied opportunities	Travel time and costs may differ	Utility is derived from the individual or homogeneous population group level

2.2 Semantic Web and Linked Data

The dramatic development of the World Wide Web brings the advantages of knowledge sharing from local spaces into a global information space. However, in recent years, the revolution of the Semantic Web proposes the new principles of data sharing, instead of document sharing on the traditional Web, which is known as the Linked Data. As the core data layer in the Semantic Web, the basic idea of Linked Data provides the principles to create and publish structured and machine-readable data with additional semantic linking to other resources on the Web. The data can be linked to other resources from external datasets. In the traditional Web, the linking between different hypertext documents is implicit and without meaning. Therefore, the basis of Linked Data is to use the Uniform Resource Identities (URIs) to identify all the entities either in the real world or on the Web. Moreover, the Linked Data still relies on the Hypertext Transfer Protocol (HTTP), which provides the protocol for data traversing and data querying. Resource Description Framework (RDF) is the standard data model for the Linked Data to provide useful metadata for the resource. SPARQL Protocol and RDF Query Language (SPARQL) is the standard querying language for RDF datasets. When applying the linking to other URIs, Linked Data exposes the significant advantages compared with the traditional Web, namely human and machine readable data, well-structured standard data format, domain specified, semantic linking, openness, and real-time reasoning [13]. The following sub-sections will introduce the concept of the linked open data, open accessibility data, the principles of linked data, ontology and linked data driven web applications.

2.2.1 Linked Open Data

The simple concept of open data defined by Open Data Institute[7] (ODI) is the data that anyone can access, use or share. The definition of open in the Open Definition is also simply "A piece of data is open if anyone is free to use, reuse, and redistribute it – subject only, at most, to the requirement to attribute and/or share-alike". According to the Shakespeare Review[8], the benefit of open data would be identified £6.8bn of total value in UK public sector data. With the development of the Semantic Web technologies and the motivation of open data, the datasets in the Linked Open Data Cloud (LODC) have shown a dramatic increase since the year 2009, which cover various major domains[9]. All these domains are various form government, publications, life science, media, geographic, social web and other user-generated content as well as cross-domain datasets.

Table 3: Datasets by topical domain

Topic	Datasets	Percentage %
Government	183	18.05%
Publications	96	9.47%
Life sciences	83	8.19%
User-generated content	48	4.73%
Cross-domain	41	4.04%
Media	22	2.17%
Geographic	21	2.07%
Social web	520	51.28%
Total	1014	

Table 3 above gives an overview of the topical domains of the 1014 datasets that were discovered by the crawler created by the researchers from University of Mannheim[10]. With the advantages of

[7] https://theodi.org
[8] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/198752/13-744-shakespeare-review-of-public-sector-information.pdf
[9] http://lod-cloud.net/
[10] http://linkeddatacatalog.dws.informatik.uni-mannheim.de/state/

Semantic Web and dramatic increased datasets In the LODC, it empowers the research of question answering (QA) systems to query the Semantic Web. And the key challenge in this area is to translate the users' information need expressed in natural language into the standard semantic web query processing and inferencing techniques, which is related to the research of Information retrieval and natural language processing [97]. This research would only focus on research of applying the QA systems over the Linked Data in the accessible travelling domain rather than addressing any research challenge related to QA systems.

2.2.2 Open Accessibility Data

There is no standard definition of open accessibility data. However, the term of open data is the idea that some data should be freely available for everyone to use and republish as they wish, without restrictions from copyright, patents or other mechanisms of control [3]. In this research, open accessibility data is the open data related to the accessibility information for people with disabilities, such as data about step-free access for public transport stations, accessible entrances, accessible toilets, accessible parking or the availability of hearing loops in the built environment.

There are also other different terms to refer to the same or similar concept of open accessibility data. The smart data mentioned by Prandi, C. [79] is also one kind of open accessibility data, while smart data is the information representation for urban environment accessibility. Open accessibility data is not only the accessibility data for people with disabilities, but also refers to the data like the availability of baby change facilities, staff help and customer help, which could benefit people with special needs, such as travelling with a baby pushchair or large luggage etc. The data source of open accessibility data includes heterogeneous data resources, such as the open transport data (public transport timetable, station facilities etc.), building data (accessible facilities, step-free access, accessible parking etc.), geographic data (latitude/longitude etc.) and some other real-time data (crowdsourced data, sensors or events etc.).

2.2.3 Linked Data Principles

In order to make all published data useful for other datasets, Tim Berners-Lee proposed the following four rules as the Linked Data principles to publish data [95]:

- Use URIs as names for things.
- Use HTTP URIs so that people can look up those names.
- When someone looks up a URI, provide useful information, using the standards (RDF, SPARQL).
- Include links to other URIs. So that they can discover more things.

However, not all the datasets in Linked Data are publically open. Some datasets in Linked Data are for internal usage or some particular group of users only. Therefore, in order to encourage people, especially government data owners to open their datasets, the Open Data is launched under Open Government Licence to publish certain public data with free access for everyone. These datasets are published by government sectors, departments or statistics organisations, which are structured in standard formats (XML, Eexcel, CSV, or JSON etc.). Some of these datasets are also published in text, HTML, and PDF, which need to be converted into a standard format (RDF). Open data includes a wide range of data including the transport data, hospital data and other public data, such as the National Public Transport Access Nodes (NaPTAN), Accessibility Statistics, and National Travel Survey in UK Open Government Data. There is a 5-star data rating schema suggested by Tim Berners-Lee to publishing the Linked Open Data in Table 4.

Table 4: 5-Star Linked Open Data [95]

★	Available on the web (whatever format) but with an open licence, to be Open Data
★★	Available as machine-readable structured data (e.g. excel instead of image scan of a table)
★★★	as (2) plus non-proprietary format (e.g. CSV instead of Excel)
★★★★	All the above plus, use open standards from W3C (RDF and SPARQL) to identify things, so that people can point at your stuff
★★★★★	All the above, plus: Link your data to other people's data to provide context

2.2.4 Ontology Based Data Integration

In the Semantic Web, ontology is the formal, explicit specification of a shared conceptualization [45]. The Web Ontology Language (OWL) is the standard language for authoring the ontologies. Using ontology for accessibility requirement specification process is proposed by Van Heijst [47] and applied in several projects, such as AccessOnTo [106], Masuwa-Morgan et al. [71] and the WTO-ICF Ontology proposed by the World Health Organisation. Wiethoff et al. also proposed ASK-IT Ontology based the ICF limitation ontology for travelling and disability. The limitation includes cognitive limitation, hearing limitation, lower limb limitation, physiological limitation, psychological limitation, upper body limitation, upper limb limitation, vision limitation, and walking limitation. Each limitation includes several sub-limitations [105].

There are three different ways to integrate data based on ontology, namely the single ontology approaches, multi-ontology approaches and hybrid approaches [103]. The single ontology approaches are used as a global ontology providing a shared vocabulary for the specification of semantics. However, due to the nature of the changes in the information source, or mapping of data sources afterwards, the single approaches will need to change rapidly to address the incompatibility issues. In order to address these problems, there is the development of multi-ontology approaches, where each data source is described by its own ontology. Therefore, there is no one global ontology needed. However, the multiple ontology approaches are very costly for implementation effort and will also face ontology matching challenges between low dimensional data and high dimensional data.

With the existence of a shared conceptualization, the ontology should be widely reused and merged. Therefore, ontology matching is the key interoperability of the Semantic Web. The general solutions to address the problems of semantic heterogeneity can be divided into automatic, semiautomatic, and manual mapping. There are several approaches and tools available for ontology matching. One of the major approaches is the rule-based approach combined with machine learning algorithms to improve the quality of matching result [38]. Halevy et al. proposed a data sharing and management infrastructure to address the challenges of data interoperability between RDF and XML sources [48]. This Piazza system mainly provides the matching between entities in RDF format and XML format. Doan and Madhavan proposed a GLUE system that employs machine learning techniques to find the mappings between different ontologies [32]. Basically, they applied the Jaccard coefficient to measure the similarity between the given concepts. They also applied the multi-strategy learning approach for context mapping between database schemas [33]. Aumueller et al. demonstrated a schema and ontology matching tool called COMA++ based on the combination of different match algorithms [4]. Jain et al. proposed the BLOOMS system based on the idea of bootstrapping information that already exists on the Linked Open Data cloud and demonstrates a competitive performance for ontology alignment [55].

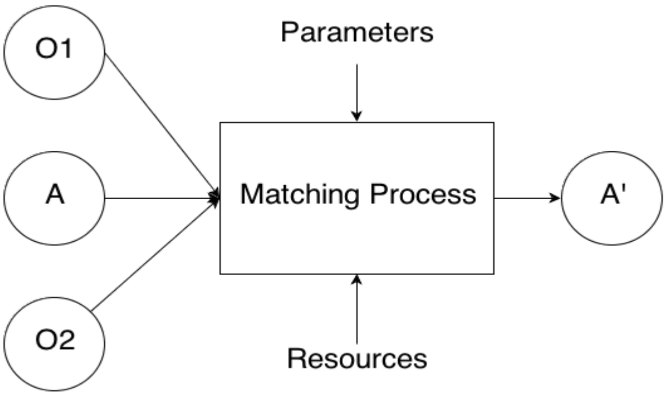


Figure 7: Ontology Matching Operation [89]

A general process of ontology matching is demonstrated in Figure 7. The target alignment A' is decided by the two ontologies, O1 and O2, with an input alignment A, as well as matching parameters and external resources [89]. There are also several challenges for ontology matching methods, such as several ontologies matching, increased heterogeneity, time constraints, relation, and instance mapping [69]. For the evaluation of matching methods, the Ontology Alignment Evaluation Initiative provides the general evaluation methodologies and results for testing the increase ontology matching systems [1].

2.2.5 Ontology Reasoning

One of major features in the Semantic Web is the ability to provide definitions for objects. Types of objects are accessible and can be manipulated [54]. In the semantic Web, the Description Logic (DL) is a formal foundation for ontology languages and tools. Description Logic is decidable fragments of First Order Logics and a family of logic based knowledge representation formalisms, which describes the domain in terms of concepts, roles, and individuals. The Web Ontology Language (OWL) is the W3C recommendation ontology in the Semantic Web. There are three different version of OWL, namely OWL Full, OWL DL and OWL Lite. OWL Full is the union of OWL syntax and RDF, OWL DL restricted to Frist Order Fragment and OWL Lit is a subset of OWL DL. Description logics are created with the focus on the tractable reasoning. There are following key tasks required for the reasoner[11]:

- Satisfiability of a concept: determine whether a description of the concept is not contradictory, i.e., whether an individual can exist that would be the instance of the concept.
- Subsumption of a concept: determine whether concept C subsumes concept D, i.e., whether description of C is more general than the description of D.
- Consistency of ABox with respect to TBox: determine whether individuals in ABox do not violate descriptions and axioms described by TBox.
- Check an individual: check whether the individual is an instance of a concept.
- Retrieval of individuals: find all individuals that are instances of a concept.
- Realisation of an individual: find all concepts which the individual belongs to, especially the most specific ones.

The main reason for the ontology as the formal, explicit specification of a shared conceptualization is because of the reasoning in ontologies. The reasoning means deriving facts

[11] http://www.obitko.com/tutorials/ontologies-semantic-web/reasoning.html

that are not expressed in ontologies explicitly. In the Semantic Web, it follows the Open World Assumption (OWA). The OWA is the assumption that what is not known to be true is simply unknown. The OWA assumes incomplete information by default, which could intentionally be underspecified and allow others to reuse and extend. The benefit of the OWA makes the knowledge base easily reusable and extendable, good for knowledge level and schema mapping, dealing with incomplete information and inference. In the opposite, the Closed World Assumption (CWA) is the assumption that what is not known to be true must be false, which is widely used in the traditional database. CWA is good at dealing with schema data mapping, constraining and validating data[12].

2.2.6 Linked Data-driven Web Applications

The concept of the Linked Data-driven Web application is presented in Figure 8. There are two main differences between Linked Data-driven Web applications and traditional Web applications, namely the data integration and republishing component. These two components are mainly fetching data from the LOD cloud and republishing data back to the LOD cloud. There are also some other external entities that Linked Data-driven Web application will interact with, such as the semantic indexer and user agent.

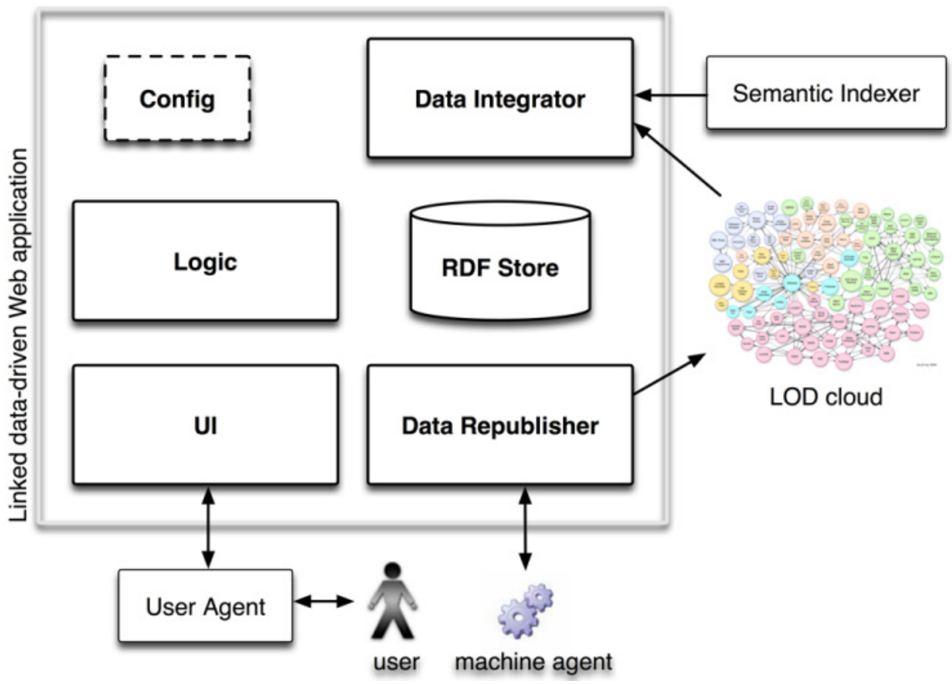


Figure 8: Concept of A Linked Data-driven Web Application [49]

[12] http://www.cs.man.ac.uk/~drummond/presentations/OWA.pdf

There are also four common components for the Linked Data-driven Web application proposed by Hausenblas [49], which could be conceptually defined as follows:

- A local RDF store, which is able to cache results and act as a permanent storage device to track users, etc.
- Some logic and UI modules implementing the business logic, the User Interface (UI) and the interaction parts of the application.
- A data integration component, focusing on gathering linked data from the Web of Data.
- A republishing component that eventually exposes parts of the application's (interlinked) data on the Web of Data.

With the increasing amount of datasets published on the Linked Open Data Could, there are also a few projects focus on the research of other non-data components. For example, the Semantic Web interface research conducted by A. Kahallili et al. aims to address the Semantic Web technologies barriers for data publishers to publish data as the Linked Data [60]. And the LDcache project presented by H. Eber et al. is a caching service for the Linked Data-driven Web applications [36]. All the projects described above can help to reduce the technical barriers to build the Linked-Data driven Web applications.

2.3 Decision Support and Semantic Web

Due to the complex relationship between people and environmental factors in accessible travelling scenario, this section will explain the concept of different type DSSs, the Linked Data-driven DSSs and the review of methods and algorithms of DSSs with multiple criteria problems and uncertainties. The Decision Support System (DSS) is a computer-based solution system, which is used to support decision making and addressing problems, such as management, operation, and planning. The research of this area is typically focused on the efficiency. Initially, there are two most widely implemented approaches for a DSS, namely data-driven and model-driven DSS. The other three approaches are becoming more popular and widely spread because of Web technologies, namely communication-driven, knowledge-driven and document-driven DSSs [11]. The major reasons for the need of DSSs by human decision makers are: cognitive limits, economic limits, time limits and competitive demands [22]. Therefore, DSSs could provide appropriate support for people with disabilities, such as user alerts, problem recognition and solve, or even facilitating a user's ability to process knowledge.

2.3.1 Decision Support System

The research DSSs could be divided into decisions making and improvement of decision effectiveness, which can be traced back to the early 1960s. In the mid-1990s, the dramatic growth of the World Wide Web made DSSs widely used to process more effective decisions. As shown in Table 5, there are five major types of decision support systems, namely data-driven DSS, model-driven DSS, communications-driven DSS, knowledge-driven DSS and document-driven DSS [88].

Table 5: DSS Types [10]

DSS Type	Purpose	Examples
Data-driven DSS	Focus on the access and manipulation of large amounts of data.	Data warehousing systems Elementary systems
Model-driven DSS	Operates on some models of reality, in order to optimise or simulate outcomes of decisions based on data provided.	Finance Systems
Communication-driven DSS	Focus on the interaction and collaboration aspects of decision-making.	Groupware and video-conferencing system that allow distributed and networked decision-making.
Knowledge-driven DSS	Actually recommend or suggest actions to the users, rather than just retrieve information relevant to a certain decision	These systems try to perform some parts of the actual decision making for the user through special-purpose problem-solving capabilities.
Document-driven DSS	Use text or multimedia document collections as their basis of decision information	Document analysis and IR systems

Data-driven DSSs are focused on the access and manipulation of large amounts of data, like data warehouse systems and elementary systems. It is deployed via the mainframe system with client/ server link or via the Web. Model-driven DSSs are operated on some models of reality, in order to optimise or simulate outcomes of decisions based on data provided. They are also used for customers and suppliers in the aspect of scheduling and decision analysis. These DSSs are deployed on standalone workstations. Communication-driven DSSs are used for the interaction and collaboration in the field of decision-making. This type of DSSs is mainly developed via the client/server architecture or the Web.

Knowledge-driven DSSs are used for actually recommending or suggesting actions to the users, rather than just retrieving information relevant to a certain decision. These systems try to perform some parts of the actual decision making for the user through special-purpose problem-solving capabilities. Document driven DSSs mainly use text or multimedia document collections as their basis of decision information. This type of DSSs has a broad base of user groups and they are used for searching the Web page to find documents related to the keywords or items based on the client/server or the Web [10]. The most successful document driven DSS is the Web page search engine. Bhargava et al. demonstrated an association between the advantages of Web-based technologies and current research for DSSs, which is the Web driven DSSs [11].

The concept of DSSs includes strategic planning, management control, and operational control. And the problem tasks in DSS could be divided into structured, unstructured, and semi-structured. In order to handle a high volume of unstructured information, Courtney [24] proposed a new decision paradigm for DSSs based on the evaluation of classic decision making processes demonstrated in Figure 9. In addition, many applications have shown the advantages of the approach to involve the agent computing in DSSs [64] [108]. An intelligent agent is an autonomous entity that has the ability to act in an environment and interact with other agents. Moreover, agent-based DSSs can be built on the fuzzy inference engine to improve efficiency and conduct effective decisions [7], [23].

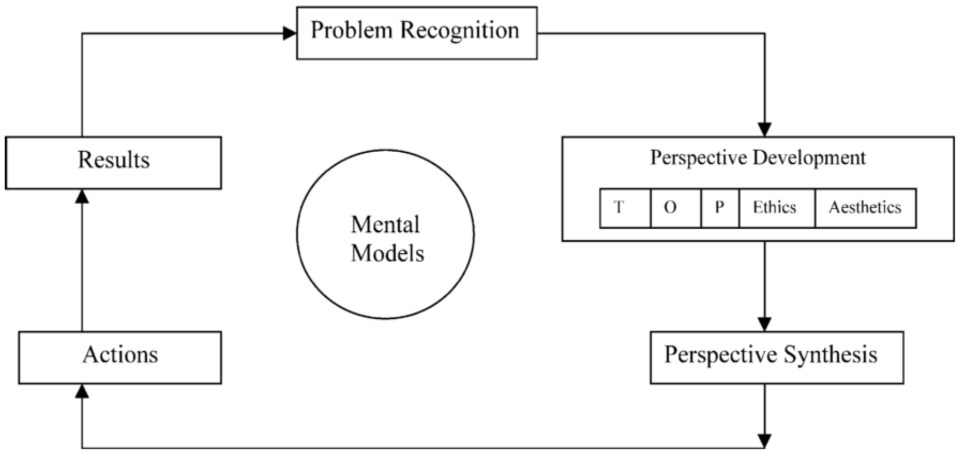


Figure 9: A New Decision Paradigm for DSSs [24]

2.3.2 DSS Algorithms

There are various existing multiple criteria decision making (MCDM) methods, such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR method, Analytic Network Process (ANP), Mathematical programming, and Genetic Algorithm (GA) [51].

The AHP method converts the decision problem into a hierarchy of sub-problems and establishes priorities among its elements by evaluating their importance. The AHP is one of most commonly used MCDM methods to evaluate several alternatives to achieve a certain goal [20]. In order to address the uncertainty issues, the fuzzy set theory is applied for DSSs [77]. There are some applications combining the fuzzy set with AHP called Fuzzy AHP for assigning weights of the criteria for option selection [11], [21], [70]. The Fuzzy TOPSIS is also applied in some applications to rank and select the alternative decisions [74].

The VIKOR method was developed for multi-criteria optimisation in the complex situation, which is focussed on ranking and selecting alternatives, and determining optimised solutions for a problem with conflicting criteria [84]. An effective DSS would be considered as the contribution to a decision maker's task by supporting them to reach either or both a more accurate solution and a faster solution [25]. Because of the complex multi-criteria, there are many algorithms trying to improve the accuracy and decrease the time cost by reducing the data dimensions.

Principal Component Analysis (PCA) is one of the most widely used dimensionality reduction methods for data analysis and compression. It is based on transforming the data to a new coordinate system such that the direction with the greatest variance lies on the first coordinate and the second greatest variance on the second coordinate.

Independent Component Analysis (ICA) is a statistical and computational technique for revealing hidden factors that underlie sets of random variables, measurements, or signals. Both these two algorithms are popularly used in image feature extraction systems. Based on systematically testing of PCA and ICA employed in face recognition system (Draper, Baek, Bartlett, & Beveridge 2003), the result showed the most important factor of performance is the nature of the task and it is difficult to predict the best technique for a novel domain.

Algorithm optimisation is also widely used in DSSs to speed up the progress of decision making and improve the provided solutions accuracy. Particle Swarm optimisation (PSO) is an evolutionary computational algorithm inspired by the natural system, which is the bird flocking behaviour to reach the destination that is not completely known. A set of solutions called particles move around the search space from one iteration to another following the rules that depend on: inertia (previously moved), memory (best solution based on previous experience) and cooperation (global best solution) [6]. The empirical study of PSO [87] indicated that the PSO could converge very quickly towards the optimal positions but may slow its convergence speed when it is near a minimum. This empirical study also proposed an approach by using an adaptive inertia weight to improve PSO's performance.

Genetic Algorithm (GA) [52] is appropriate for large size data set, nonlinear problems with unpredictable solutions. GA applies three types of rules, namely selection rules, crossover rules and mutation rules for creating the next generation from its current population. It is mainly used to address optimisation problems and also apply in many decision support systems for clustering and searching. A hybrid approach which combined GA and PSO for optimising order clustering has been proposed [62].

The hybrid approach obtains faster convergence and higher clustering accuracy. Based on the literature review, the performance of methods or algorithms is dependent on various factors, such as the nature of the task, complexity of the data structure or scheme, and the scale range of knowledge base. Therefore, the main task of this research is to find the appropriate algorithms for the decision support system based on the travel accessibility knowledge base (linked open accessibility data), which is integrated from heterogeneous datasets. This proposed Linked Data-driven DDS framework could not only provide people with disabilities appropriate accessibility information for accessible travelling but also address the information barriers.

2.3.3 Linked Data-driven DSSs

With the emergence of the Semantic Web, Linked Data provides a set of new features and technologies for DSS. There are many common goals shared by the semantic web and DSSs. For example, in order to deliver relevant, reliable and accurate information to the users based on their preferences, both Semantic Web and DSSs could be able to precisely interpret information. However, DSSs have much more specific goals and domain-specific, such as making a plan or reacting to a certain situation. The fact that DSSs are often domain-specific and potentially even organisation-internal also affects the data filtering and selection methods that should be used.

Since 2005, there are some projects that have been trying to build DSSs to address different tasks based on the ontology and Semantic Web technologies, such as information integration and sharing, web service annotation and discovery, as well as knowledge representation and reasoning [15]. Based on the survey of using Semantic Web technologies for DSSs, the most research into the Semantic Web and DSSs in recent years is the personal DSS, which supports decision-making for individual. Many DSSs applied the Semantic Web technologies in the medical and healthcare domains, which could be classified as the Expert Systems (ES) due to its transitionally applying ontology and rule-based methods [15]. For instances, El-Hachem et al. proposed an ontology based knowledge platform combining the social web and the Semantic Web for an ambient childhood obesity prevention system [37]. Moreover, Gray et al. applied the semantic sensor web for environmental decision support applications [44], and an ontology-driven framework for spatial decision support is also proposed by Li et al. [65].

Furthermore, according to the summary by Blomqvist [15], the intersection between the Semantic Web and DSSs is focused on contextualizing data, utilizing social annotation, and providing better decision support through advanced user modelling. There are some challenges summarised from the interview conducted by a group of technique developers and experts in the area of Semantic Web and DSSs. One of the major challenges is the need for better methodologies of data integration, such as data aggradation methodologies, data abstraction and data analysis. Another major challenge is the need for better models, including the model evaluation and decision sharing models. Moreover, the need of the better user interface for data access with special-purpose is also very urgent [15]. Researchers also emphasised that the data reusing and integrating with other data resources would empower various domain-specific decision support applications. There have also been some research projects involving DSSs in tourism and travelling. For example, Sabou et al. proposed the method to use Linked Data to support tourism decision making. They also emphasised the advantages and benefits of this method by linking application data to other resources on the Web of Data [83]. Besides this, some recently proposed frameworks also inspire the research of using Semantic Web technologies for decision support. For instance, Crowley et al. proposed the linked sensor framework for integrating and linking heterogeneous data from various senor sources. This framework could bring the opportunities for data integration between the Linked Data and sensor data to provide a better decision support [26]. As a result, all these studies described above could help to bring opportunities and evidence for the research of Linked Data-driven DSSs for the accessible travelling domain.

2.4 Related Works

In this section, there are some projects reviewed that are attempting to address the accessibility challenges of day-to-day activities for people with disabilities. Some of these projects are using the ontology driven approaches to enhance the accessibility for people with disabilities shown in Table 6, which includes the project ASK-IT, AEGIS, OASIS, GPII and RailGB.

The ASK-IT project is exposed the specification of information needs, which is used for the development of a mobile communication platform for people with mobility difficulties. This research combines the activity theory with content modelling to improve the travelling experience. The ASK-IT project classified the users group as follows: lower limb impairment, wheelchair users, upper limb impairment, upper body impairment, physiological impairment, psychological impairment, cognitive impairment, vision impairment, hearing impairment, and communication production/receiving impairment [9] [105].

AEGIS [61] is an ontology based project that is investigating the use of ontology for modelling and integrating the information between users with disabilities and different assistive tools. AEGIS project classified users into several user groups based on needs and interaction models, namely users with visual, hearing, motion, speech and cognitive impairments as well as application developers. This project also develops open source-based generalised accessibility support framework into mainstream ICT.

OASIS [100] is a European project that is trying to establish an open architecture for integrating and standardising accessible services. This project is ontology driven and benefits the quality of life for aged people. This project proposes a hyper-ontology to provide the ontology matching for other different ontologies.

Table 6: Ontology-driven Projects to enhance Accessibility

Projects	Aims	Approaches	Focus	Problem
ASK-IT [105]	An Ambient Intelligence (AmI) in semantic web enabled services, to support and promote the mobility of Mobility Impaired people.	Ontology driven, agent computing and semantic web service	People with mobility difficulties and elder people	No accessibility data sharing.
AEGIS [61]	Using the 3rd generation access techniques to provide a more accessible, exploitable and deeply embeddable approach in mainstream ICT.	Ontology driven and Open Accessibility Framework	People with disabilities and ICT developers	ICTs accessibility only; No accessibility data sharing.
OASIS [100]	Open reference architecture for integrating and standardising accessible services.	Ontology driven and semantic services	Elder people	ICTs accessibility only; No accessibility data sharing.
GPII [101]	A global inclusive infrastructure to make information accessible for everyone with limitations, barriers, or disabilities	Ontology driven, agent computing and semantic services	People with disabilities and ICT developers	ICTs accessibility only; No accessibility data sharing.
RailGB [66]	Using the linked data approach to help people with disabilities to gather accessible information within the London Tube.	Ontology driven and Linked Data	People with mobility difficulties and special needs	Accessibility data sharing; No data integration; Tube information only.

GPII [101] is an international project aiming to establish a global inclusive infrastructure to make information accessible for everyone with limitations, barriers, and disabilities. The GPII concept is based on three functions: providing an easy to learn and use way to store personal information; providing a way to use this preference information to configure assistive tools and accessibility features; providing the tools and infrastructures for vendor and developers to create new solutions for the problems faced by the people with disabilities.

RailGB is a mobile prototyping application that applied the Linked Data approach to help people with disabilities to gather accessible information within the London tube stations [66]. This project is proposed by the University of Southampton and exposes some limitations for using the open data and accessibility data. For example, one of the challenges is the difficulties to find the accessibility data, which is publicly-available, high quality and well structured. And another challenge is the difficulties to link the requirements of disabilities with the facilities via ontology reasoning and inference.

In addition, there are some other projects involving the Location Based Service (LBS) and sensor technologies, to monitor the environment [42], [44], [94]. Some projects also applied the end-user evaluation and crowdsourcing method to improve service accuracy and quality [2], [43], [72]. However, most of these projects are facing following challenges, such as various data modelling methods to represent the accessibility information, no additional annotation or metadata to describe the accessibility information and no linking among different metadata resources. Thereby it leads to the problem that accessibility metadata isolated from one application or system to others. Therefore, one of the main purposes for this research is to investigate how to apply the Linked Data principles to address this data sharing and reuse problem in the accessible travelling domain.

2.5 Summary

In summary, this chapter reviewed the literature related to this PhD research. In the first section, it reviewed the model of disabilities proposed by WHO-ICF and the concept of disability and accessibility. The theory and models for accessible travelling is also demonstrated in the first section. In the following section, there is a brief introduction to the Linked Data and Semantic Web technologies, such as the concept of the Linked Open Data, the Linked Data principles, ontology, ontology reasoning and the Linked Data-driven Web applications. As a conclusion, the term of accessibility refers to easy access to the facilities or information for people with disabilities. Complex interactions and barriers can restrict the accessible trip planning, such as the lack information of the public facilities and services, searching for accessibility information during the trip, and people’s special needs and abilities. Therefore, in order to address the problem of information barriers and data isolation described above, the next chapter would mainly discuss the research challenges and questions.

Chapter 3: Research Challenges and Methodologies

As described in the previous chapter, complex interactions and barriers can restrict the accessible travelling for people with disabilities. This chapter will mainly discuss the research challenges and propose the research questions to address the problem of information isolation and barriers for accessible travelling.

In the first section, it demonstrates the gap analysis by reviewing some research projects related to fields of the accessible travelling, such as the accessible journey planning, route planning and wayfinding for people with disabilities. This section exposes the research problems in the latest research of accessible travelling.

In the second section, there are two main research questions proposed based on the research problems and challenges which are exposed in the first section. There are also some research objectives illustrated in this section to answer these two research questions. The main research objective is how to apply the Linked Data principles to the DSSs in the accessible travelling domain. Therefore, the conceptual model of Linked Data-driven DSS for accessible travelling is proposed to illustrate the methods to reach this objective. This section discusses the main research questions and demonstrates the research methodologies as well.

The third section will mainly discuss the proposed conceptual model of Linked Data-driven DSS for accessible travelling. At first, this section will give a detailed discussion of the proposed conceptual model. In order to design the experiments to study proposed conceptual model, there is a reference architecture based on this conceptual model, which is used for building the Linked Data-driven Web applications for accessible travelling decision support. This section also gives detail introduction of each model. And the last section will give a brief conclusion of this chapter.

3.1 Research Problems

As presented in the previous chapter, there are some projects that are attempting to address the accessibility challenges of day-to-day activities for people with disabilities or special needs. Route planning for people with disabilities is one of the major research subjects to improve urban mobility and accessibility. There is a list of projects presented in Table 7. These projects proposed different approaches or methods to address the routeing and navigation problems faced by the people with mobility difficulties.

MAGUS project proposed a comprehensive Level-of-Service (LOS) model for wheelchair users based on a few research methods, such as questionnaires, interviews, observations and physical measurement. This project emphasised that the type of wheelchair is strongly influenced that which barriers hindered access [8].

U-Access is a Web based decision support systems for assisting pedestrians of differing abilities to navigate through urban environments. This project proposed the simplified models of both LOS and users' preference [91]. RouteCheckr is a personalised multi-criteria navigation system for mobility impaired pedestrians proposed by Völkel et al. [102]. They also described the approach that how to use equally weighted and normalized criteria based on predefined user group profiles and users' ratings. However, the problem for this system is that there are no algorithms for reducing malicious rating, which is also a major challenge for the most crowdsourcing systems. Mobility-for-All project presented the socio-technical architecture for supporting people with cognitive disabilities and special needs to use public transportation based on the distributed cognition framework [19]. PAMs project, the Personalised Accessibility Maps [58] also exposed the challenges for their current work, which is no standards with respect to accessibility data quality. Therefore, there is the emergent need for them to develop the automatic validation tools to address the data quality of accessibility information.

Another significant challenge to plan trips for people with disabilities is the lack of accessibility information. Therefore, there are several projects applied crowdsourcing or citizen sensing approaches to collect useful accessibility data. The OurWay project presented the approach to combine accessibility maps and route planning for people with mobility difficulties based on the crowdsourcing. The proposed system allows users to annotate the accessibility information of their surroundings [53]. One of their findings is that the lack of standard accessibility models. There are also some other issues exposed from this project, such as no accessibility information for the Points of Interest, no personalization and no information sharing across different user groups as well as external systems. Another citizen sensing approach to collect related data to improve public transportation is proposed by Steinfeld et al. [92].

Table 7: List of Projects for People with Mobility Difficulties (PwMDs)

Projects	Aims	Approaches	Focus	Problem
Mobility-for-All [19]	A socio-technical architecture for supporting people with cognitive disabilities and special needs	Distributed Cognition Framework	People with cognitive disabilities and special needs	Public transport only; No accessibility data sharing.
MAGUS [8]	A comprehensive Level-of-Service (LOS) model for wheelchair users based on questionnaires, interviews, observations and physical measurement.	Using Digital Elevation Models (DEMs) to measure barriers	People with mobility difficulties	Outdoor navigation only; No accessibility data sharing; No personalization.
U-Access [91]	A web based DSS for assisting pedestrians of differing abilities to navigate through urban environments.	DSS, graph theory and shortest path algorithms	People with mobility difficulties	Outdoor navigation only; No accessibility data sharing.
OurWay [53]	A prototype with the combination of accessibility maps and route planning for people with mobility problems.	Annotation, shortest path algorithms, rating and feedback feeding system	People with mobility difficulties	No data of POIs; No and user modelling; No accessibility data sharing.
RouteCheckr [102]	Personalised multi-criteria routeing for mobility impaired pedestrians' navigation.	Weight based personalization, crowdsourcing rating system	People with mobility difficulties	No algorithm for reducing malicious rating; No accessibility data sharing.
Path 2.0 [76]	A participatory system for collecting GPS data to generate accessible routes for people with mobility difficulties.	Crowdsourcing, social computing	People with mobility difficulties	No accessibility data of POIs; No personalization; No accessibility data sharing.
Accessibility Maps [18]	A collaborative creation of accessibility map provides the means for data integration, collected automatically or with user intervention, to augment standard maps with accessibility information.	A prototype to build the Accessibility Maps based on the citizen sensing	People with mobility difficulties	Highly depends on crowdsourcing data; No accessibility data sharing; No method for data conflict or repetition.
PAMs [58]	A concept of the personalised accessibility maps	prototype	People with special needs	No accessibility data sharing.
mPass [79]	The smart data associated with the accessibility generated from social network	Crowdsourcing, citizen sensing	People with mobility difficulties	No accessibility data sharing.

Cardonha, C. et al. [18] proposed a prototype to build the Accessibility Maps based on the citizen sensing. This prototype provides the means for different data integration to augment the standard maps with accessibility information, such as flooding, potholes, defective sidewalks and other issues, which can create the barriers for outdoor navigation of people with disabilities. However, the major issue of this platform is that it highly depends on the crowdsourcing data, and it does not provide the solutions to address the issues of data conflict or duplication. The mPass project [79] presents the concept of smart data and extracts the accessibility information from various of social networking sources. All these projects are trying to address the major challenges for current research of accessible routeing or wayfinding, namely the lack of accessibility data, more personalised models and methodologies to integrate accessibility data.

However, one of the main problems for these projects is that they are mainly driven by crowdsourcing accessibility data, which leads to data quality and data conflict issues if there are no effective data quality control methods involved. There is a survey of open accessibility data presented in Chapter 5, which summarizes the problems of crowdsourcing accessibility data and lessons learned from the open accessibility data. Another issue is that most accessibility data used in these projects are isolated and independent from other projects. Therefore, there is no data sharing and linking feature among these projects, which leads to the large effort of research on the accessibility information integration.

In the aspect of using the Semantic Web technologies for DSSs, there are also some challenges exposed by Blomqvist [15]. One emergent challenge is the need for better data aggregation, data abstraction, and data analysis. Although there are few DSSs for accessible navigation or routeing applied the Semantic Web technologies, the better solutions to address the data integration challenges could bring the opportunities of better decision support for accessible travelling. There are also some other challenges, such as the need of models due to most developers having problems with changing information schema, exchanging data sources, and incorporating external information. And most these problems lead to the money cost and it is also time-consuming for people with disabilities to find such accessibility information to prepare their trip, or search real-time information of surroundings during the trip. Therefore, next following sections will discuss main research questions and methodologies.

3.2 Research Questions and Methodologies

The motivation of this research is to address the gap between users with disabilities or special needs and accessibility information, and thereby help them to reduce the barriers and time cost to find such accessibility information to prepare their trip. As described in Chapter 2, achieving and integrating a large amount of accessibility data is the primary challenge for many projects in the field of either accessible routeing or Semantic Web driven DSSs. Therefore, with the advantages of the Semantic Web technologies and the Linked Data, the motivation of this research is proposed the novel approach to apply the Linked Data principles to DSSs in the domain of accessible travelling in order to address these problems and challenges of accessible travelling exposed in previous section. As a result, it could bring the opportunities to interlink isolated accessibility data from various systems and domains into the global space, thereby to address one of the major research problems in the field of accessible travelling. Therefore, the conceptual model of Linked Data-driven DSSs for accessible travelling is firstly proposed to illustrate the overview of the proposed approach.

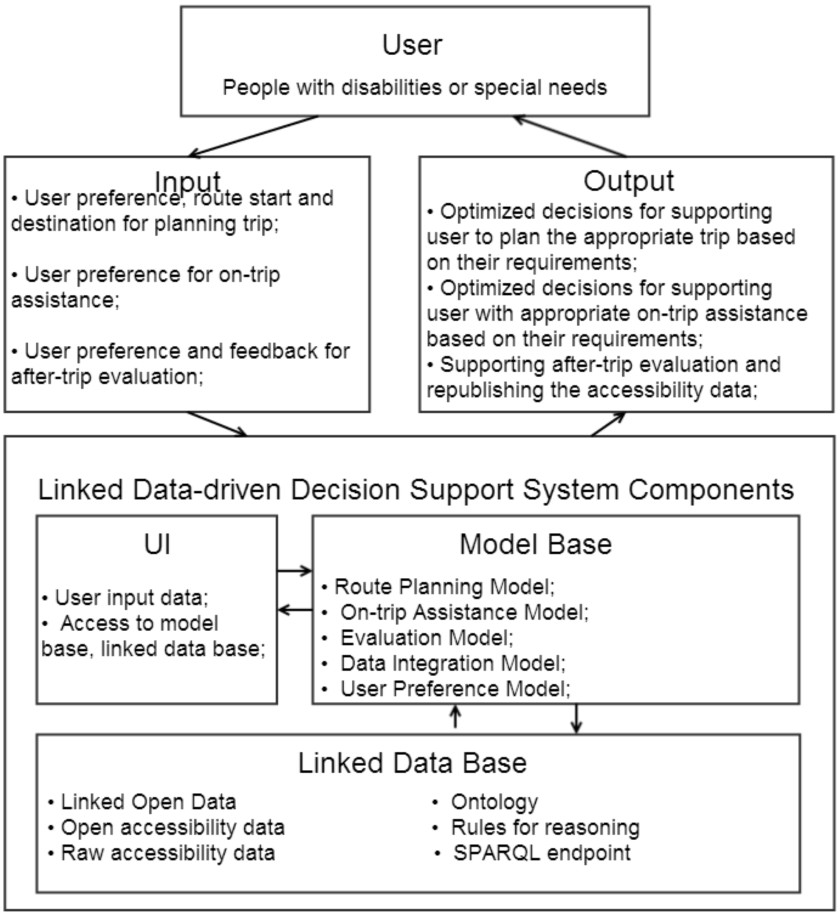


Figure 10: Conceptual Model of Linked Data-driven DSS for Accessible Travelling

As presented in Figure 10, this conceptual model is applied the standard DSS framework with the additional advantages of the Linked Data principles and domain knowledge of accessible travelling. For example, in the accessible travelling domain, the traditional database and knowledge base is replaced with the Linked Data Knowledge Base. Moreover, there are three main models proposed for accessible travelling based on the three types of problems for accessible travelling presented in Section 2.1, namely pre-trip planning, on-trip assistance and after-trip evaluation. There are significant amount of data required for accessible route planning model, which includes the Level-of-Service (LOS) of public transportation patterns, Points of Interests (POIs) and complex situations on the road or street. The on-trip assistance model is used for the situation where users seek help or real-time accessibility information of the surrounding area based on their special needs and real-time location. The functionalities of the on-trip model are more likely to exist in the context-aware pervasive systems. The after-trip model is used for users to review, evaluate, thereby verify the accessibility data and improve the data quality based on their travelling experience and personal preference. Based on these proposed models, the approach would conduct better accessible travelling decision support for people with disabilities, especially with mobility difficulties. However, some models are not within current research scope, such as the after-trip model and on-trip assistance model, which would be discussed in the further work. Therefore, in this research, there are mainly two research questions (RQs) that need to be explored within the proposed model, which are described as follows:

RQ1: What is an appropriate method for publishing and integrating heterogeneous accessibility related datasets with incomplete information?

RQ2: What decision support algorithms work appropriately with the linked open accessibility data for accessible travelling?

In order to answering the first research question RQ1, there are two sub-questions that need to be explored:

- RQ1.1: How to integrate and enrich heterogeneous open accessibility data?
- RQ1.2: How to use URI naming and referencing to publish the open accessibility data as the Linked Data in accessible travelling domain?

As stated previously, the motivation of this research is to apply the Linked Data principles to DSSs for accessible travelling decision support. In order to carry out the answers to these two sub-questions, this research begins with a pilot study of the open accessibility data. The pilot study of open accessibility data is mainly carried out as the early phase of this research. Firstly, this research designed the experiment to collect the accessibility datasets from several existing systems and projects in the real world. Although the target datasets collected in the experiments are a small sample of the open accessibility datasets, they are still following these four features: various data formats, various data providers, and various data licence. After that, this research applied the quantitative research method (survey and data observation) to process the study of the open accessibility data. Both data collection and the survey of the open accessibility data is demonstrated more detail in Chapter 5.

The answers to the RQ1.1 are mainly explored by comparative study of different ontology-based data integration methods. The comparative study is carried out by theoretical discussion of each ontology-based data integration method and the experiments by applying data integration methods to the open accessibility data. The result of the experiments is compared by the metrics demonstrated in Chapter 4. The comparative study of the open accessibility data is presented more detail in the third section of Chapter 5. The study result of the RQ1.1 is demonstrated in Chapter 7.

The research to the RQ1.2 is based on the literature review of ontology related to the domain of accessible travelling and the study of the requirements for people with mobility difficulties. In order to carry out the answers to RQ1.2, this research explores the some core ontologies and other ontologies related to accessible travelling to study the URI naming and referencing the open accessibility data. The study of applying the Linked Data principles to publish the open accessibility data as the Linked Data is presented in Chapter 6 and the result is demonstrated more detail in Chapter 7.

In order to answer the second research question RQ2, there are also two sub-questions that need to be explored in this research:

- RQ2.1: What kinds of accessibility data does a user need for accessible travelling?
- RQ2.2: How to apply the decision support algorithms in the Linked Data knowledge base to provide decision support for accessible travelling?

The research of the RQ2 is mainly carried out based on the experimental result of RQ1. The experimental result of RQ1 is the Linked Open Accessibility Data integrated and generated from several open accessibility dataset. The research for the RQ2.1 is applying quantitative research method (interview and questionnaire) to study the accessibility data requirements for the people with mobility difficulties in the domain of accessible travelling decision support. The closed questions designed for study are mainly summarised from previous studies described in Chapter 2. The result of the study is using the statistical analysis to test the validation of the hypothesis. The study process and result is demonstrated more detail in Chapter 6.

The research of the RQ2.2 is applying the empirical method to study the methods to apply the decision support algorithms into the Linked Data for accessible travelling decision support. This study is firstly carried out by the experiment designed to apply QA system into the Linked Data for accessible travelling decision support. The second experiment is applying the decision support algorithms to the Linked Data for accessible travelling decision support. Both experiments process and result are presented more detail in Chapter 8. The next section will present the more detail of the mode of the Linked Data-driven DSS for accessible travelling.

3.3 Linked Data-driven DSS for Accessible Travelling

In order to validate the conceptual model of the Linked Data-driven DSSs for accessible travelling, the reference architecture is proposed by following this conceptual model, which is presented in Figure 11.

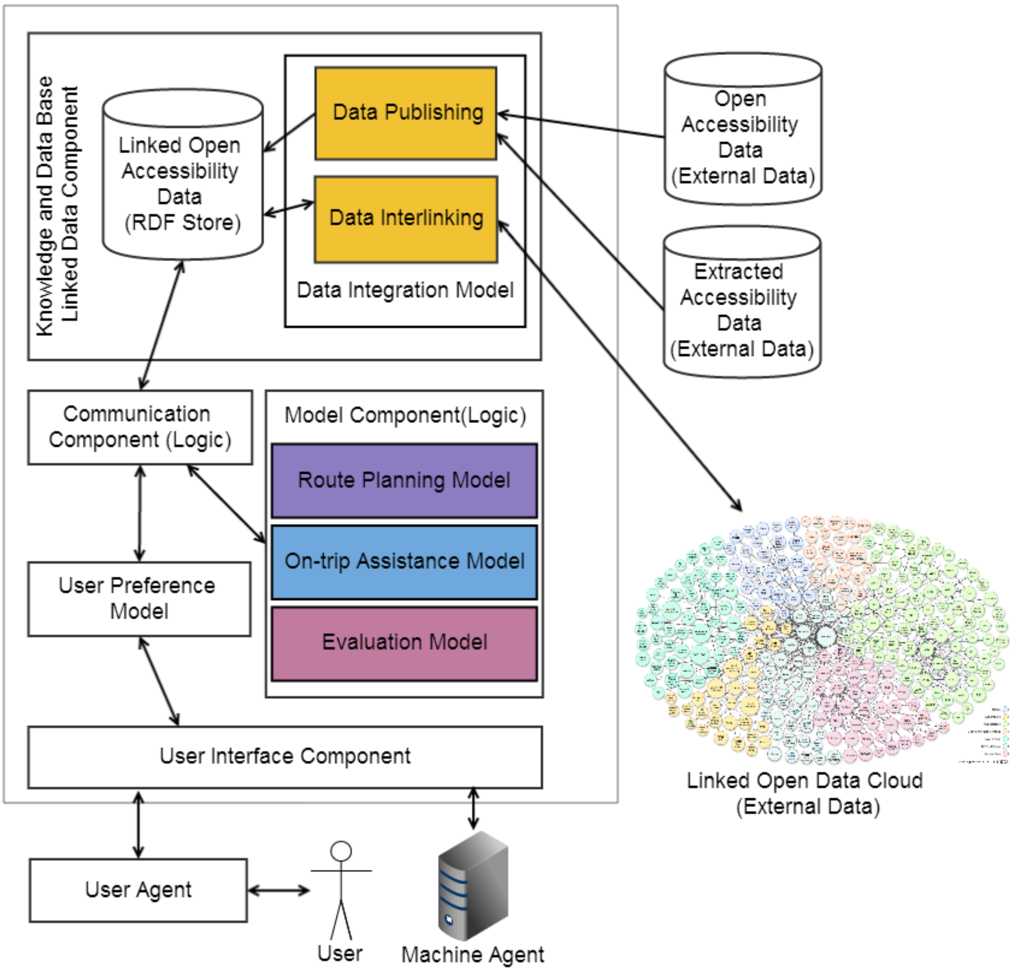


Figure 11: The Reference Architecture of Linked Data-driven DSSs for Accessible Travelling

This reference architecture is driven by the combination of components in traditional DSSs framework, accessible travelling theories and the architecture of the Linked Data-driven Web applications. There are three main models in this reference architecture: the open accessibility data integration model, decision supporting model (including route planning model and on-trip assistance model), and evaluation model. The functionalities overview of these three models has already been briefly explained in the section above. Moreover, there are also some other models or components, which are not included in the research. For example, the User Interface component is a significant component in DSSs, but it is beyond the focus of this research. The detail functionalities of each model will be demonstrated in the following sub-sections. Each model is corresponding to the two main research questions. And some sub-research questions are also proposed in each model, which need to be explored and answered with the research methodologies.

3.3.1 Open Accessibility Data Integration Model

In the proposed conceptual model, the data integration model is the model proposed to address the problems and challenges described in Section 3.1, namely the lack of accessibility data, accessibility data not shared or isolated across different systems and the low quality of crowdsourced accessibility data. Therefore, the first stage of this research is applying the Linked Data principles to publish, integrate and enrich the accessibility data extracted from different projects and systems. As stated previously, the open accessibility data is the data that describes the accessibility information of facilities or service in the real world, which could benefit people with disabilities. As described in previous chapter, there are various data formats of open accessibility data existing on the Web. There are three primary types of accessibility related dataset extracted in this research, namely open data, extracted data (unstructured data) and the Linked Data. The open data is published by the authorities or organisations with standard formats and is free to access by everyone. The extracted data is the data extracted from traditional Web documents, like the web page. The Linked Data is the dataset published on the Linked Data Cloud with semantic annotation and linked to other resources.

For the open accessibility data integration, as presented in Figure 12, there are two main steps defined in this model: data publishing phase and data interlinking phase. The purpose to integrate these three types of data is to address the challenges of accessibility data achievement, which can provide the Linked Data basis as the knowledge base for the decision support model of Linked Data-driven DSS for accessible travelling.

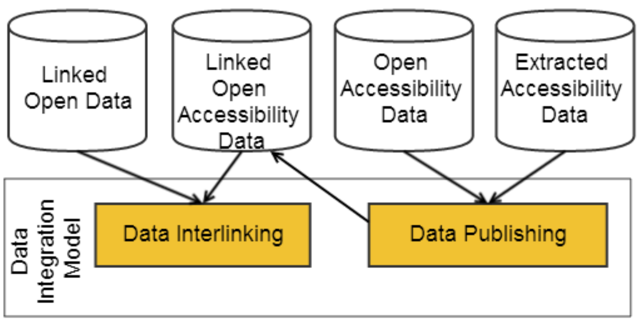


Figure 12: Data Integration Model

The research of data publishing phase explores the questions like the needs of accessibility data, URI naming or referencing, and using the 5-star Linked Data rules to publish the high quality open accessibility data. This step is focused on the research of the approaches to publish and integrate heterogeneous open accessibility data into linked open accessibility data.

The interlinking phase in this model focuses on the research of the approaches to link the same entities in linked open accessibility data to other resources on the Linked Open Data cloud. The process of data publishing includes the data archiving, cleaning, processing, integration and publishing. According to the literature review in the Chapter 2, there is not much accessibility information available in the datasets of the Linked Open Data Cloud. However, there are still some datasets provided limited accessibility information, such as DBpedia[13] and LinkedGeoData[14]. In the DBpedia, there are 247 stations in the UK annotated with the object property (dbo:isHandicappedAccessible). As demonstrated in Figure 13, the triples are representing the railway station entity in the DBpedia (London Waterloo Railway Station[15]). It only provides the data property (dbo:isHandicappedAccessible) to represent the accessibility levels of the train station.

Entity	Attribute	Value	+ New
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/route	West of England Main Line	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/interchange	Waterloo tube station	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/ontology/isHandicappedAccessible	true	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/portsmouthDirect	y	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/interchange	Waterloo East	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/swmlLocal	y	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/railexits	98.44299999999999784	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/windsor	y	✖
http://dbpedia.org/resource/London_Waterloo_station	http://www.w3.org/1999/02/22-rdf-syntax-ns#type	http://schema.org/Place	✖
http://dbpedia.org/resource/London_Waterloo_station	http://dbpedia.org/property/woking	y	✖

Figure 13: The Entity of London Waterloo Railway Station in DBpedia

Compared with the entity in DBpedia, the same entity (London Waterloo Railway Station[16]) in LinkedGeoData provides the data properties (ldgo:wheelchair and ldgo:wheelchair_toilet) to represent the accessibility information of this railway station entity demonstrated in Figure 14.

---

13 http://wiki.dbpedia.org/
14 http://linkedgeodata.org/About
15 http://linkeddata.uriburner.com/rdf-editor/#/editor?uri=http:%2F%2Fdbpedia.org%2Fresource%2FLondon_Waterloo_station&view=statements&pageNo=1
16 http://linkedgeodata.org/page/triplify/node3638795617

There are also some other datasets providing the geographic information, such as Freebase[17] and Ordnance Survey Linked Open Data[18]. All these datasets are published in the Linked Open Data Cloud with standard formats in RDF.

Property	Value
lgdo:changeset	40568103 (xsd:int)
dcterms:contributor	lgd:user351324
lgdo:gadmSameAs	<http://gadm.geovocab.org/services/withinRegion?lat=51.502838&long=-0.112801#point>
geom:geometry	lgdg:node3638795617
lgdo:historicalName	Waterloo Bridge
rdfs:isDefinedBy	lgd:meta/node3638795617
rdfs:label	London Waterloo Waterloo metroojaam (et) Ватерлоо (uk) Ватерлоо (ru)
geo:lat	5.15028379E1 (xsd:double)
geo:long	-1.12801E-1 (xsd:double)
dcterms:modified	2016-07-08T15:17:48 (xsd:dateTime)
lgdo:network	National Rail
lgdo:operator	Network Rail
lgdo:railway%3Aref%3ADB	XKLW
lgdo:ref	WAT
lgdo:toilets%3Awheelchair	yes
rdf:type	spatial:Feature lgdm:Node lgdo:RailwayStation lgdo:RailwayThing
lgdo:version	6 (xsd:int)
lgdo:wheelchair	true (xsd:boolean)
lgdo:wheelchair_toilet	yes
lgdo:wikipedia	en:London Waterloo station

Figure 14: The Entity of London Waterloo Railway Station in LinkedGeoData

Therefore, in the second phase, the interlinking phase exposes the research of approaches to link the entities in the linked open accessibility data to other resources in the LODC. This research will explore the interlinking methods for open accessibility data demonstrated in Chapter 5. The evaluation metrics for the performance of the integration method is presented in Chapter 4. As a result, this data integration model could contribute to the accessibility data with improved quality for the proposed conceptual model of Linked Data-driven DSS for accessible travelling.

3.3.2 Decision Support for Accessible Travel Model

The decision support model is designed to provide accessible travel planning and accessible information management based on the linked open accessibility data. Combined with user preference model, the role of this model in the proposed conceptual model is presented in Figure 15, which includes the pre-trip route planning model and the on-trip assistance model.

This model follows the decision paradigm described in Figure 9, namely problem recognition, perspective development, perspective synthesis, action, and results. The pre-trip route planning model is focused on the decision support for accessible route planning based on some complex

[17] https://developers.google.com/freebase/
[18] http://data.ordnancesurvey.co.uk/

environmental situations. The on-trip assistance model is trying to provide appropriate decision support when users are looking for accessibility related information or some real-time data such as location, sensor data and accessibility facilities of the surrounding area based on their real-time needs. In order to make better and effective decisions support, the research of this model aims to find algorithms to provide optimised accessible travelling decisions for users based on the linked open accessibility database and user preference model. Both questions of user preference and definition of needs are the primary challenges of the user preference model. However, this thesis only explored the research of the pre-trip route planning model as the on-trip assistance required real-time accessibility information. Although the user modelling research is not within the research objectivities, the research of user preference for accessible travelling is still one of research experiments to conduct the appropriate algorithms for decision support. The research of decision support model is explored in Chapter 8.

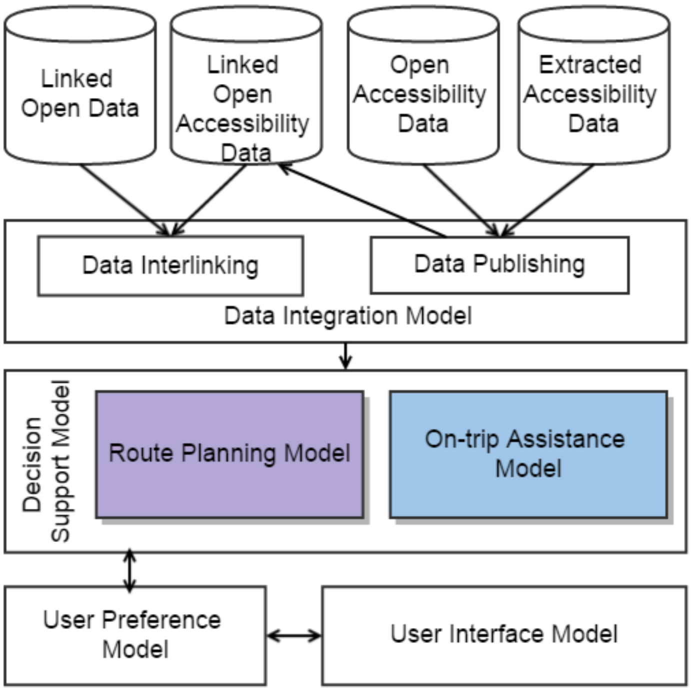


Figure 15: Decision Support for Accessible Travelling Model

The Linked Data-driven approach provides some advantages, such as the specified accessible travelling domain, semantic annotation, and machine-readable data, which could be used to empower the intelligent DSS to provide effective decision support. However, it also expose some other challenges, such as the need of reasoning rules for people's disability, metadata of accessible services and accessible facilities, the methods of accessibility data publishing, interlinking and data querying in accessible travelling specified domain. These challenges would be explored in Chapter 7 and Chapter 8.

3.3.3 Evaluation Model

The evaluation model is an important component in the concept model of the Linked Data-driven DSS for accessible travelling. The evaluation model described in this section is presenting the concept of this evaluation model and its role played in the proposed main concept model, which is present in Figure 16.

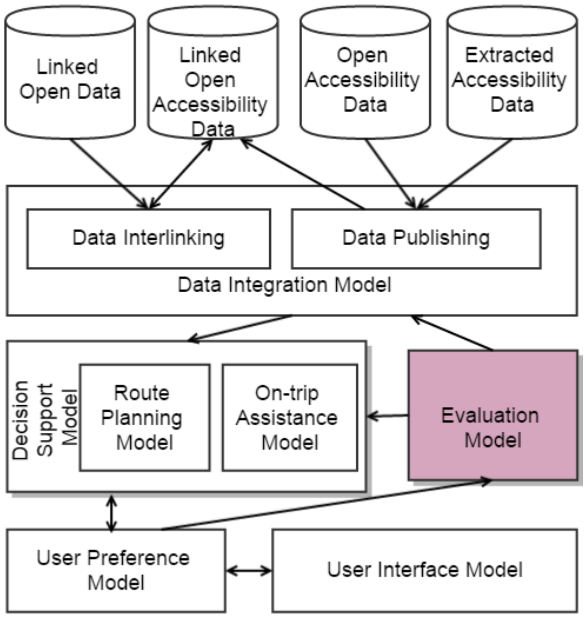


Figure 16: Evaluation Model

This evaluation model needs to explore the methodologies for analysing the feedback to generate real-time accessibility information of the target services or facilities. For example, if the decisions generated from the decision support model do not satisfy users' expectation, or users find that some accessibility information is out of the date, this evaluation model could allow the end users to contribute their feedback or new accessibility data.

However, due to the fact presented in Chapter 2 that accessibility is the degree of services or facilities for people to access, there are some special issues related to the accessibility data generation. Each individual with disabilities is faced with their unique challenges. Therefore, how to associate the feedback from each individual and user preference is another challenge for the evaluation model. In this research, the research of evaluation model is presented in Chapter 5. It will mainly explore how to apply crowdsourcing method to enrich and evaluate the Linked Open Accessibility Data. The user interface model is the presentation component in the concept model of Linked Data-driven DSS for accessible travelling. It is an important component in either the reference architecture or implemented systems. However, the research of the user interface model is out of the scope for current research, which would be discussed in the future work.

3.4 Summary

In summary, this chapter exposed the research problems and challenges in the research fields of accessible travelling based on the literature reviewed from previous research projects. Therefore, this thesis proposed the research of applying the Linked Data principles to the decision support systems for accessible travelling. Firstly, this chapter proposed research questions based on the problems and challenges exposed from previous research projects. It also gives the detailed description of the concept model of the Linked Data-driven DSS for accessible travelling. This proposed model aims to address the problems and challenges exposed from current accessible travelling research, namely the lack of accessibility data, accessibility isolation, the needs for more personalised models and methodologies to integrate accessibility data.

In order to investigate the use of linked open data for accessible travelling decision support, there some component models proposed in this chapter. The data integration model is focussed on the data processing, accessibility data integration, publishing and semantic linking to other resources on the Linked Open Data cloud. This model provides the linked accessibility data for the DSS model. The decision support model proposes effective decision support for accessible trip planning. The evaluation model provides the functionalities to review and evaluate the performance of the algorithms and models. Both user interface model and user preference model are significant components in the proposed model. The user interface model is the user interface of this Linked Data-driven system, which could provide universal design and accessible interface for all users. However, these two models are currently out of the scope of this research and could be discussed in the future works. Moreover, one of the primary issues of current research is that there are many projects for accessible route planning highly dependent on crowdsourced accessibility data. If there is no effective data quality control methods involved, it would lead to other issues like poor data quality and data conflict. In the next chapter, software metrics are presented, which will be used in this research to evaluate the accessibility data generated from the data integration model and, algorithms and the quality of the Linked Open Accessibility Data.

Chapter 4: Evaluation Metrics

In previous chapters, there has been a discussion of the research questions challenges proposed for the conceptual model of Linked Data-driven DSSs for accessible travelling. In this chapter, the software metrics are presented to evaluate the accessibility data generated from the data integration model, and there are also some metrics proposed to evaluate the algorithms. Firstly, there is a brief introduction of the existing accessibility measurements, which are the methods to weight the accessibility level of different barriers for people with disabilities. In the second section, the software metric is proposed to evaluate quality of the Linked Open Accessibility Data based on Goal Question Metrics approach (GQM). The third section provides the approach and benchmark for evaluating the algorithms in both data integration and the decision support systems. The last section briefly concludes the discussion of this chapter.

4.1 Accessibility Measurements

As described in section 2.1, in this research, disability is considered as a complex social issue between the individual and their social environment factors, which would be classified as activities and participations. In the ICF model (presented in Figure 3), the activity refers to the execution of a task or action by an individual, and participation means the engagement in the social life. The activity limitations would occur through the discordance between environmental factors and personal factors, which leads to participation restrictions.

Travelling involves both the task execution and the social engagement, such as planning a journey for a holiday, going to a place of employment by public transport, or travelling for engaging in social activities. Therefore, accessible travelling plays a significant part for people with disabilities or limitations in improving their social activities and engagement. In this research, the measurement for accessibility is much more focused on the person-based measurements, which involves the travel time, land-use opportunities, temporal constraints, time available for activities, and accessibility analysis based on the individual level. For travelling by multi-model transport, researchers should also consider walking, assisted walking or wheelchair use by taking account into some additional travel cost factors, such as safety or gradient. However, the measurements presented in Section 2.1.3, are mainly used for city planning or land-use analysis, which would not satisfy the requirement of the proposed model. In this research, the term of accessibility is related to the relationship between personal capabilities and constraints as well as the relationship between personal access to travel and land use opportunities. Moreover, the accessible travelling is considered as an activity-based model. Therefore, the proposed method for accessibility measurements will measure the accessibility based on the accessible facilities and services as well as the users' preference to determine whether the service or facilities are accessible for people's special needs. The study of the importance of accessibility facilities and service is exposed in Chapter 6.

4.2 Evaluation Metrics for Data Integration

In this section, the software metrics are proposed for evaluating the open accessibility data integration, which is designed to meet the requirements proposed by the research question RQ1. Firstly, based on the survey of the open accessibility data from heterogeneous sources, three minimum requirements for the attributes of the open accessibility data are defined, which is presented in Figure 17, namely attributes related to accessibility, attributes related to the geographic and attributes related to the time constraint.

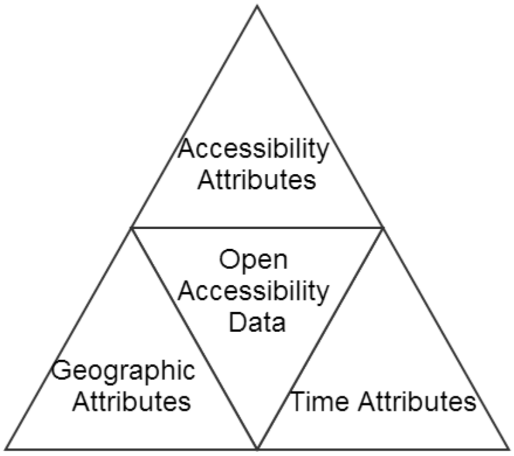


Figure 17: Open Accessibility Data Attributes

Accessibility related attributes could include accessibility information of services or facilities in target places or built environment, such as step-free access, accessible toilet, accessible parking, lifts, automatic doors etc. Geographic attributes include geographical location identifiers such as the latitude/longitude or others. Time attributes stand for the time the information was gathered or created, which lead to validation of the data reliability. All these three types of attributes are the minimum requirements. There are also some additional attributes, such as the globally unique identifiers related to other applications or systems regardless the geographic attributes, and the special needs related attributes, such as special meal types in the restaurant, baby changing facilities, Wi-Fi or public toilets.

Table 8: Important Factors for Open Accessibility Data Metrics

Factor	Description
Accuracy	Accuracy refers to the difference between the data and actual value.
Correctness	Correctness means that the data were collected according to the exact rules of the definition of the metrics.
Sensitivity	Data should be time-stamped so that we know exactly when they were collected the same way each time, so that the resulting measures are comparable.
Reliability	Data should be consistent from one measuring person to another, without large differences in value.
Complexity	Depending on the different data sources, the attributes of accessibility data should not be too complex due to the difficulties of data integration and algorithms for decision support.
Validity	This attribute is related to the annotation of accessibility related information for open accessibility data, such as wheelchair-accessible, accessible-parking.

Based on the metrics rule for data collection proposed by Fenton and Pfleeger [39] and Web Accessibility Metrics[19], some important factors are proposed for open accessibility data evaluation metrics, which are shown in Table 8. The accuracy refers to the difference between the

[19] http://www.w3.org/TR/accessibility-metrics-report/

accessibility data and its actual value in the real world. Correctness means that the data were collected according to the exact rules of the definition of the metrics, which is defined as the minimum requirements for the open accessibility data. Sensitivity refers to up-to-date accessibility information, which should be time-stamped.

Reliability refers to how consistent the data is when measuring one person to another. For example, a place annotated as wheelchair accessibility should be accessible for all types of wheelchairs users, such as manual wheelchairs, powered wheelchairs, or even pushchairs. Otherwise, the data should be annotated as specified accessibility. Complexity refers to the attributes of target accessibility not being too complex, which would lead to the complexity of algorithms. There is a validity factor to measure that the target dataset includes the accessibility related information.

The Goal Question Metrics approach (GQM) is a generic approach to software metrics. There are three steps in GQM as following [17]:

- Conceptual level (Goal): A goal is defined for an object, for a variety of reasons, with respect to various models of quality, from various points of view, relative to a particular environment.
- Operational level (Question): A set of questions is used to characterize the way the assessment/achievement of a specific goal is going to be performed based on some characterizing model. Questions try to characterize the object of measurement (product, process, resource) with respect to a selected quality issue and to determine its quality from the selected viewpoint.
- Quantitative level (Metric): A set of data is associated with every question in order to answer it in a quantitative way. The data can be objective and subjective.

Based on the rules described above, the evaluation metrics proposed for open accessibility data integration are stated in Table 9, which define the purpose, issue, object and viewpoint for the data integration task. There are four questions proposed to characterize the object of measurement. In order for datasets to be comparable, the first question is to identify the data quality of current datasets. The second question is to evaluate the process of data integration, and the third question is to measure the result of the process. The last measurement is to evaluate the algorithms applied in the integration process. The main purpose of data integration model is to generate the Linked Open Accessibility Data (LOAD) that could provide the knowledge base for the proposed model of Linked Data-driven DSS for accessible travelling decision support. There are also some discussions about the assessments or guidelines of the data quality measurements of linked datasets by other researchers.

Table 9: Evaluation Metrics for Open Accessibility Data Integration

Goal	**Purpose Issue Object Viewpoint**	**Improve and Enrich the quality of open accessibility data from the viewpoint of accessibility data experts.**
Question	Q1	What is the quality of current accessibility datasets?
Metrics	M1	Percentage of entities with minimum requirement attributes (accessibility, geographic and time property)
	M2	Percentage of entities with incomplete information
	M3	Percentage of entities without accessibility property or no accessibility metadata
	M4	Percentage of duplicated entities
Question	Q2	Is the integration process actually performed?
Metrics	M5	Percentage of matched entities identified during the reviews
	M6	Percentage of mismatched entities identified during the reviews
Question	Q3	Is the performance of the integration process improving or enriching data quality?
Metrics	M7	$\frac{Entities\ with\ improve\ or\ enrichment}{All\ matched\ entities}$ *100%
	M8	$\frac{Entities\ without\ improvement\ or\ enrichment}{All\ matched\ entities}$ *100%
	M9	$\frac{Entities\ with\ conflict\ information}{All\ matched\ entities}$ *100%
Question	Q4	How is the performance of the integration approach?
Metrics	M10	Precision
	M11	Recall
	M12	F1 Score

Table 10: Data Quality for Linked Open Accessibility Data

Measure	**Factor**	**Questions**
M1	Accuracy	Are facts actually correct?
M2	Intelligibility	Are there human-readable labels on things?
M3	Completeness	Do you have all the data you expect?
M4	Referential correspondence	Is there one and only one point per referent that represents some set of real-world referents?
M5	Boundedness	Do you have just the data you expect or is it polluted with irrelevant data?
M6	Typing	Are nodes properly typed as resources or just string literals?
M7	Modelling correctness	Is the logical structure of the data correct?
M8	Modelling granularity	Does the modelling capture enough information to be useful?
M9	Connectedness	Do combined datasets join at the right points?
M10	Isomorphism	Are combined datasets modelled in a compatible way?
M11	Currency	Is the data up to date?
M12	Sustainable	Is there a credible basis for believing the data will be maintained?

Based on the assessment checklist proposed by Glenn Mcdonald[20], there is a modified data quality checklist proposed for the LOAD, which is presented in Table 10. M1-M6 refers the publishing of generated accessibility data as the Linked Data. M7-M10 refers the correctness of accessibility related ontology modelling and data mapping. Especially, M8 presents the quality measurements of modelling accessibility related data. M10 measures the interlinking quality between different linked datasets. M11 is related to time, which is important for accessibility related data due to its sensitivity. M12 is focused on the maintenance of these datasets. As a result, this checklist could provide the guideline for measuring the quality of linked open accessibility data integrated from different sources.

4.3 Evaluation Metrics for Algorithms

In order to evaluate algorithms applied in the decision support model, the evaluation metrics are proposed for measuring the performance of algorithms to provide more optimised and effective decision support for accessible travelling. In Table 11, there are five factors proposed, namely computation complexity, scalability, quality, feasibility, and accuracy. The computation complexity refers to the computational performance of the decision support algorithms. Scalability presents the performance of algorithms when the size of datasets is enlarged. Feasibility means the options calculated by the algorithm should satisfy the requirement of people with disabilities or special needs.

Table 11: Evaluation Metrics for Algorithms Applied in Decision Support Model

Factor Name	Description
Complexity	This metric is related to the computational performance of a given algorithm.
Scalability	This metric is related to the performance of algorithm when the size of open accessibility datasets gets larger or the scope of route planning gets broader.
Feasibility	This metrics is related to the options proposed by algorithms whether are feasible for people with disabilities or special needs based on their preference.
Quality	This metric is used to compare the different proposed routes calculated based on the same preference in order to measure the better algorithm.
Accuracy	This metric is used to measure the accuracy of decision support algorithms.

For accuracy, there are several standard evaluation metrics for measuring the accuracy of algorithms applied in the decision support systems, namely statistical accuracy metrics and decision support accuracy metrics [46]. Statistical accuracy metric is mainly measuring the accuracy of a recommender system by comparing the recommendation scores and user’s rating. *Mean Absolute Error* (MAE) is a widely used statistical accuracy metric. The formula is formally defined as follow:

[20] http://lists.w3.org/Archives/Public/public-lod/2011Apr/0140.html

$$\text{MAE} = \frac{\sum_{i=1}^{N}|p_i - q_i|}{N}$$

, where:

$|p_i - q_i|$ is the absolute error between ratings-prediction pair$< p_i, q_i >$.

N is the natural number of corresponding ratings-prediction pairs.

The lower the MAE score presents the more accurate, which is the recommendation predication. In this research, the ratings-prediction is based on the decisions generated by the model and ratings generated by the end users. There are some other metrics widely used as statistical accuracy metrics, such as Root Mean Squared Error (RMSE), and Correlation. For decision support accuracy metrics, there are also some that are widely used, such as reversal rate, weighted errors and ROC sensitivity. Despite the most common algorithm evaluation metrics described above, it is very common to use the *Precision*, *Recall* and *F1* metrics, which are defined as following formulas [31]:

$$Precision = \frac{|true\_positive|}{|ture\_positive| \cup |false\_positive|}$$

$$Recall = \frac{|true\_positive|}{|ture\_positive| \cup |false\_negative|}$$

$$F1\ Score = \frac{2 * Precision * Recall}{Precision + Recall}$$

4.4 Summary

In this chapter, some software metrics are described to evaluate the linked open accessibility data generated from the data integration model, the data integration approaches, and the algorithms for the decision support model. Based on research objectivities, accessible travelling is considered as an activity-based model, and it would measure the accessibility based on the availability of accessible facilities or services and users' preferences. According to a review of some standard accessibility measurements, they do not currently satisfy the requirements of the accessible travelling defined in this research. Therefore, evaluation metrics are proposed for measuring the open accessibility data, the approach of the data integration process, the linked open accessibility data, and the algorithms for accessible travelling decision support. The measurement metric for open accessibility data is based on the guidelines of metrics for web accessibility. The evaluation metrics of data integration is based on the GQM approach. The measurements of linked open accessibility data follow criteria in the assessment of data quality for linked datasets. In order to evaluate decision support algorithms in the further work, the algorithm evaluation metrics for measuring the performance of algorithms are also defined to provide optimised and effective decision support for accessible travelling. The following three chapters will present designed experiments and methodologies for achieving the research goals.

Chapter 5: Open Accessibility Data

In this chapter, we mainly demonstrate the methodologies and experiments used to conduct research of the open accessibility data. In order to conduct the research of the open accessibility data used in the real world, experimental datasets are collected, mostly from online websites or systems used by end users with mobility disabilities or limitations. This chapter explores the following two research questions:

- RQ1.1: How to integrate and enrich heterogeneous open accessibility data?
- RQ2.1: What kinds of accessibility data does a user need for accessible travelling?

In the first section, a survey of open accessibility data is conducted based on the data sources within the UK. The survey basically demonstrates the current stage of open accessibility data within the UK and the result of the survey is analysed as well. The lessons learned from this open accessibility survey are also presented in this section. In the following section, the data schema observation approach for each dataset is applied in the experiment, which is aiming to inspect the potential interlinking relationship between each dataset. The fourth section presents the research of the open accessibility data integration by exploring the entity matching methods. The fifth section primarily presents the Linked Data-driven Web application proposed to crowdsource the Linked Open Accessibility Data. This section demonstrates the reference architecture of the application and the prototype. The limitation of the application is also discussed for the reference of future research work. The last section reviews the research of open accessibility data discussed in this chapter. Lastly, there is a brief introduction of the next chapter.

5.1 A Survey of Open Accessibility Data in the UK

In this section, the survey of open accessibility data within is presented. All the experimental datasets collected in this survey are from within the UK. The datasets are extracted from several open online systems or applications based on different data formats (CSV, Excel, JSON, and HTML), data sources (Open Data, Commercial Data, and the Extracted Data) and data availability. These datasets are namely the Wheelmap dataset, Factual restaurant dataset, Step-free Access Guide Feed (Transport for London Open Data), National Rail Data and AccessTogether.

At the time of the experiment, Wheelmap is one of the most popular mobile applications, which aims to improve wheelchair accessibility information for physical places based on the crowdsourcing. The Wheelmap website provides the open API for 3rd party access for free and the data format is JSON. The Factual restaurant dataset is provided by Factual, which is an open data platform developed to maximise data accuracy, transparency, and accessibility. For the purpose of this research, Factual provides the dataset in CSV format. The dataset of Step-free Access Guide Feed is provided by the Transport for London Open Data Team. At the time of experiment in 2014, the dataset is in XML format and currently, the team provides an open data API for developers to access the real-time data. National Rail Data is based on data extracted from the National Rail website, and the code of crawler is published on GitHub[21]. All the data published on the national rail website is managed by the government department. AccessTogether is also a research project focusing on the crowdsourcing complex accessibility facility in the built environment. The dataset is shared in Google Docs and can be downloaded in CSV or Excel format. The more detail of the how survey data collected and what methodologies applied in the analysis will be introduced in following sub-sections.

5.1.1 Wheel map

Wheelmap[22] is an online map service for searching, finding and marking wheelchair accessible places by crowdsourcing. The project is mainly based on Open Street Map (OSM)[23] project, an open source, collaborative, free and editable online map service. There are three fundamental geographic entities in OSM, namely Nodes, Ways and Relations. Nodes are the most primitive entities using WGS84 reference system to represent geographic information with latitude and longitude. For data gathering, Wheelmap provides the RESTful API that is open for developers to query data. Table 12 indicates the accessibility data available in the UK, which was extracted from

[21] https://github.com/chaohaiding/nationalrail-access-crawler
[22] http://wheelmap.org/en/
[23] http://www.openstreetmap.org

the Wheelmap API on 29/11/2013. There are totally 421666 nodes within the UK with their own unique and valid OSM Node ID in Wheelmap. 4687 of these nodes are annotated with wheelchair accessible, while 1001 nodes are not wheelchair accessible. There are 898 nodes annotated as limited wheelchair accessible. 98.44% of these nodes are annotated as unknown for wheelchair accessible information. The nodes are classified into 12 categories and 130 types. Each category is associated with several types. There are 12 core attributes for each entity, which will be explained in the data schema observation section (Section 5.3). Places with categories transfer, food and shopping are listed as top three categories with accessible information.

Table 12: Wheelchair Accessible in Wheelmap Dataset

Categories	Yes	No	Limited	Unknown
Transfer	1445 (0.59%)	272 (0.11%)	158 (0.06%)	244094 (99.24%)
Food	1038 (1.82%)	367 (0.64%)	430 (0.75%)	55135 (96.78%)
Leisure	100	13	27	5744
Bank	351	43	33	15204
Education	132	15	32	11597
Shopping	767	118	123	33552
Sport	19	0	13	1851
Tourism	88	45	15	11459
Accommodation	66	35	13	6940
Misc	484	78	35	20648
Government	26	3	2	1910
Health	171	12	17	6946
Total	**4687 (1.11%)**	**1001 (0.24%)**	**898 (0.21%)**	**415080 (98.44%)**

5.1.2 Factual

Factual[24] is a commercial location platform that provides over 65 million local businesses and points of interest across 50 countries. There are three extended attributes datasets, namely restaurant, doctors and hotels. Both restaurant and hotel datasets provide an accessibility related attribute, called “Wheelchair Accessible”. However, the dataset Restaurant-UK is the only the dataset that provides the accessibility information within the UK. Table 13 indicates that there are the 210613 restaurant entities extracted from Factual API on 10/01/2014, 8904 entities are annotated as wheelchair accessible while 1786 entities are indicated not accessible. However, there are 199923 (94.92%) restaurants that are unknown for wheelchair accessibility. Besides the

[24] http://www.factual.com/

"Wheelchair Accessible" attribute, each restaurant contains 13 core business attributes including name, address, phone, category, lat/long, and URL as well as 43 restaurant specific attributes, such as cuisine types, meal types, price range, rating, hours of operation, payment options, and Wi-Fi, which would also be of benefit for people with special needs.

Table 13: Wheelchair Accessible in Factual Dataset

Wheelchair Accessible	Yes	No	Unknown
Restaurant (UK)	8904 (4.23%)	1786 (0.85%)	199923 (94.92%)

5.1.3 Transport for London Open Data

Transport for London (TfL) provides a series of Open Data for developers, which includes step-free tube guide data[25], station facilities data and some other real-time datasets. The step-free tube guide data contains step-free access information of London tube stations, DLR and Overground as well as information on the step heights and gaps between the platform and the train for people with limited mobility. According to the XML-based dataset downloaded on 10/01/2014, the step-free access tube data is published by TfL and updated to 16/08/2013. There are 362 tube station entities with 5 core attributes, such as Station Name, National Public Transport Access Nodes (NaPTAN)[26], Links, Accessibility Interchanges and Accessibility.

Table 14: Accessibility Information in Step-free Guide Dataset

Items	Yes	No	Unknown
Blue Badge Car Park Spaces	147 (40.61%)	35 (9.67%)	180 (49.72%)
Taxi Ranks Outside Station	13 (3.59%)	169 (46.69%)	180 (49.72%)
Specific Entrance	16 (4.42%)	141 (38.95%)	205 (56.63%)
Accessible Toilet	54 (14.92%)	128 (35.36%)	180 (49.72%)
Access Via Lift	98 (27.07%)	84 (23.20%)	180 (49.72%)
Limited Capacity Lift	8 (2.21%)	174 (48.07%)	180 (49.72%)

Table 14 states the 6 sub-attributes in the attribute named as Accessibility including accessible car parking spaces, taxis outside stations, specific entrances, accessible toilets, lift access and access

[25] www.tfl.gov.uk/syndication/feeds/step-free-tube-guide.xml
[26] http://data.gov.uk/dataset/naptan

type. Approximately 50% of all the sub-attributes are annotated as either accessible or not, while the rest of the entities are displayed as unknown.

5.1.4 National Rail Dataset

As there are no open APIs or open datasets related to UK National Rail stations accessibility data, we extracted the data from the national rail website[27] and converted the unstructured data into well-structured data. Based on the data crawled on 14/01/2014, there are 2601 railway stations that have data associated with accessibility, such as the ramp for train access, step-free access, wheelchair availability, accessible toilets, accessible ticket machines and accessible car parking for people with disabilities. There are some other attributes for the people with special needs, such as toilets, public Wi-Fi and baby changing facilities.

Table 15: Accessibility Information in National Rail Dataset

Items	Yes	No	Unknown
Ramp for train access	1726 (66.36%)	842 (32.37%)	33 (1.27%)
Staff help available	1199 (46.10%)	1370 (52.67%)	32 (1.23%)
Step-free access coverage	1347 (51.79%)	1220 (46.91%)	34 (1.31%)
Wheelchairs available	374 (14.38%)	2195 (84.39%)	32 (1.23%)
Toilets	792 (30.45%)	1778 (68.36%)	31 (1.19%)
Baby changing facilities	365 (14.03%)	426 (16.38%)	1810 (69.59%)
National key toilets	168 (6.46%)	623 (23.95%)	1810 (69.59%)
Accessible public telephones	152 (5.84%)	320 (12.30%)	2129 (81.85%)
Customer help points	1726 (66.36%)	843 (32.41%)	32 (1.23%)
Accessible ticket machines	995 (38.25%)	285 (10.96%)	1321 (50.79%)
Car Park	1548 (59.52%)	910 (34.99%)	143 (5.50%)
Accessible car park equipment	392 (15.07%)	1210* (46.52%)	999 (38.41%)
Public Wi-Fi	200 (7.69%)	0 (0%)	2401 (92.31%)

[27] http://www.nationalrail.co.uk/

* Wheelchair users may require assistance in this car park.

Table 15 states the data annotation for each accessibility related attribute. The percentage of entities without annotation for most attributes is approximately 1%. Some attributes, such as baby changing, national key toilets (accessible toilets), accessible phones and accessible ticket machines have more than 50% unknown annotations. Moreover, there is no geographic data in the extracted data. Therefore, we combined the extracted data with rail references data downloaded from NaPTAN to generate a Nation Rail dataset with 9 core attributes, namely Station Name, AtcoCode, TiplocCode, Easting, Northing, and 13 accessibility related attributes as well as more than 40 other attributes.

5.1.5 AccessTogether

AccessTogether[28] is another crowdsourcing platform to provide additional accessibility data for geographical data. According to its schema, there are approximately more than 58 attributes related to accessibility, which could be divided into three main categories of disabilities, namely the mobility disability, hearing disability and visual disability. Some attributes are very useful for people with disabilities, such as audio-descriptions, background-noise, doorways, FM-audio-system, and sign-language-tours. However, these attributes are too complex and specific for data integration, reuse and crowdsourcing. Moreover, there are some external ids, such as Factual ID and Foursquare ID for each entity to reference to the entities in social networking applications, which means the data could be easily linked to other datasets. Based on the dataset extracted on 10/01/2014, there are only 4827 entities across 43 countries and 3788 entities annotated with 'none' for Factual ID. There are only 46 entities in the UK. Due to the lack of accessibility information and few entities in the dataset, therefore, this dataset currently will not be involved in the further research of open accessibility data depends on the data quantity and quality of AccessTogether Project.

5.1.6 Lessons Learned

Based on the survey of open accessibility data described above, there are several lessons that have been learned:

- There are some datasets related to accessibility available online, which could refer to real world places.
- Open accessibility data is from multiple heterogeneous resources. Some applications, such as Wheelmap, Accesstogether, Step-free guide feed and Factual, expose the

[28] http://www.accesstogether.org

accessibility data in standard formats (XML, JSON and CSV etc.). Some data sources like National Rail dataset are mainly extracted from web pages, which need to be converted to the stand formats.

- There are various attributes related to accessibility in the open accessibility datasets, but there is no standard guideline to specify attributes for accessibility due to the differences between various applications. For example, there is only one wheelchair accessibility attribute related to the railway station in Wheelmap rather than a list of accessibility attributes in National Rail dataset.

- The classification of accessibility data could be divided into four types to satisfy the needs of people with disabilities, namely people with mobility disabilities (wheelchair users), people with hearing disability, people with visual disabilities and people with cognitive disabilities. However, it will be more complex if it refers to people with special needs. Therefore, some datasets are restricted to one specific need, such as Wheelmap and Factual. However, a discussion is still needed about what kind of attributes of places should be annotated for people with disabilities.

- Crowdsourcing is not enough due to too much incomplete information. For example, 98.44% of the entities in the Wheelmap dataset are annotated as unknown for wheelchair accessible and 20% of the entities are annotated with blank name. 94.92% restaurant entities in Factual are named with blank for wheelchair access. However, there are more than 50% of all entities annotated with accessibility attributes in both National Rail and step-free access guide datasets, which are primarily published by the government. This means that the accessibility related datasets published by the government or organisations have the better quality than crowdsourced datasets.

One major motivation of this research is to address the challenges of accessibility data gathering and sharing barriers existing in current projects, and thereby to enhance accessible travelling or routeing for the people with disabilities. As discussed above, crowdsourcing is not enough to address the problem of information issues. However, it is still a powerful approach to combine with the open data to improve the accessibility data completeness and accuracy, which is the accessibility information for further data processing, integration and publishing.

5.2 Open Accessibility Data Schema

In the previous section, we described the data quality of each open accessibility dataset in the experiment. In this section, we will demonstrate the data schema of each dataset presented in the previous section, namely the Wheelmap dataset, National Rail, TfL step-free access guide and Factual. According to the introduction in Section 4.2, the minimum attributes for open accessibility data related to accessible travelling are as follows: geographic related attributes, time-related attributes and accessibility related attributes. The geographic attributes are the attributes related to geographic locations, such as the Latitude/Longitude. The time-related attributes are the attributes that indicate the creation date, modified date and deleted date. The accessibility attributes are the attributes used to describe the accessibility information, such as wheelchair accessibility, description, etc. There are also some additional attributes for the data schema, such as the unique identification number or universal identification number for each entity or record in each dataset, data source provider, the category of entities and contact information.

Table 16: Data Schema of Wheelmap Dataset

Attribute Type	Attribute Name	Sub-Attribute Name
Name	Name	
IDs	Open Street Map Node ID	
	ID	
Geographic Related Attributes	Address	Postcode, House Number, Street, City, Country, State District, State, Country Name, Country Code
	Latitude/ Longitude	
Time Related Attributes	Creation Date	
Provenance	Data Provider	
Accessibility Related Attributes	Accessibility	Wheelchair accessibility
		Wheelchair accessibility description
Others	Category	Type
		Category
	Contact	Website
		Phone

Firstly, as one of most popular wheelchair accessibility crowdsourcing applications, the data schema of the place entity in the Wheelmap dataset is almost followed the data schema of Open Street Map. As we can see in Table 16, the place entity is called the node entity in the Wheelmap dataset, which is the same as the entity in Open Street Map. There are two different identifier numbers in the dataset, namely the OSM node ID and the Wheelmap ID. Therefore, the dataset provides a potential external interlink to the entities in the other Linked Datasets based on the Open Street Map, such as the LinkedGeoData. There are 7 different attribute types in the dataset.

The name attribute provides human-readable information for the target entity, which is also an important attribute for entity matching. The geographic attributes are used for both entity matching and human readability. The time-related attribute in the Wheelmap dataset is the only creation date. For the attributes related to accessibility information, there are only two attributes, namely wheelchair accessibility and the description for wheelchair accessibility. The option values for wheelchair accessibility could be divided into yes, no, limited, unknown. There are also two types of attributes that provide additional information for entity matching, namely category attribute and contact attribute. The category attribute in this dataset is reused in OSM. The data provider in the provenance attribute is created by us and is used as the source of the open data.

Compared with the Wheelmap dataset, the National Rail dataset is much more complex in accessibility information. As there is no open API or open data for the National Rail station dataset at the moment of the data collection experiment, the railway station dataset is mainly extracted from the web page of national rail. Therefore, the data schema presented in Table 17 mainly follows the data structure that is published on the web page.

Table 17: Data Schema of National Rail Station Dataset

Attribute Type	Attribute Name	Sub-Attribute Name
Name	Station Name	
IDs	Atco Code/ Tiploc Code/ Crs Code	
	ID	
Geographic Related Attributes	Easting/ Northing	
	Latitude/ Longitude	
Time Related Attributes	Creation Date, Modification Date,	
Provenance	Data provider, Revision Number	
Accessibility Related Attributes	Accessibility and mobility access	Helpline contact
		Staff help available
		Ramp for train access
		Step-free access coverage
		Step-free access note
		Wheelchairs available
	Ticket buying and collection	Accessible ticket machine
	Getting to and from the station	Accessible Parking
	Facilities	Accessible Toilet
	Staffing and general services	Customer help point
Other Attributes	Facilities, Staffing and general services, Ticket buying and collection, Getting to and from the station	13 attributes

There are three basic types of attributes. The geographic related attributes initially include the easting and northing to identify the geolocation. For effective data integration, we calculated the latitude and longitude identifier for each entity in this dataset based on the easting and northing geographic reference. The accessibility related attributes in the National Rail dataset include various items, such as helpline, staff help, ramps for train access, step-free access coverage and notes, wheelchair availability, accessible ticket machines, accessible parking, and accessible toilets. Both the step-free access coverage and ramp for train access attributes provide the reference for the minimum requirements of wheelchair accessibility. The time-related attributes provide time sensitive information, such as the creation time of the data and the last modification time. The attribute of revision times is classified as one attribute in the provenance attribute with the data provider. There are other attributes related to rail services for the national rail stations, such as the station facilities, staffing and general services and ticket services.

Table 18: Data Schema of TfL Tube Station Dataset

Attribute Type	Attribute Name	Sub-Attribute Name
Name	Station Name	
IDs	NAPTANS ID	
	ID	
Geographic Related Attributes	Latitude/ Longitude	
Time Related Attributes	Creation Date Time	
Provenance	Data provider	
Accessibility Related Attributes	Accessibility	Accessible Interchange
		Blue Badge Car Park Spaces
		Taxi Ranks Outside Station
		Access Type
	Specific Entrance	Specific Entrance Required
	Toilets	Accessible Toilet
	Lifts	Access Via Lift
		Limited Capacity Lift
Other Attributes	Lines	Maximum Steps
		Maximum Gap

Based on the data structure provided by TfL step-free access guide, we summarised some necessary attributes related to our research, which is presented in Table 18. As we can see, these three minimum requirements for attributes are contained in this dataset. It also provides the NaPTAN (National Public Transport Access Nodes) ID, which is the national system for uniquely identifying points of access to public transport in England, Scotland and Wales. There are several attributes related to accessibility, which include the accessible interchange, accessible parking, access type, accessible toilets, and access via lifts. Due to the fact that this dataset is published by TfL statistically at the moment of data collection, some information might be out of date, such as the working status of the accessible toilets and lifts. However, currently, TfL provides real-time access to their new open data service for developers.

The Factual dataset is more focused on restaurant information. The data schema of restaurants in the Factual UK dataset is presented in Table 19, the dataset includes three minimum attribute types. There is only one accessibility related attribute, which indicates the wheelchair accessibility for the restaurant. However, the dataset provides some additional attributes for people with special needs in the restaurant service, such as the cash only payments, open times and meal types. The meal types include gluten free, vegetarian and children meals.

Table 19: Data Schema of Factual Restaurant Dataset

Attribute Type	Attribute Name	Attribute Name
Name	Name	
IDs	factual_id	
	ID	
Geographic Related Attributes	Address	address, address_extended, region, locality, post_town, admin_region, postcode, country
	Latitude/ Longitude	
Time Related Attributes	Creation Date Time	
Provenance	Data provider	
Accessibility Related Attributes	accessible_wheelchair	
Other Attributes	Contact	Telephone, fax, website, email
	Payment	payment_cashonly
	Parking	parking_garage, parking_street, parking_validated, parking_free
	Open times	open_24hrs

Based on the data schema observation above, there are some common schemas in each dataset, such as the name of the place, IDs, three minimum attributes, and provenance. As a core dataset, there are some differences between the Wheelmap dataset and other datasets, especially the accessibility attributes. In order to demonstrate the schema difference of accessibility data between different datasets, there is an example of two equivalent entities in Wheelmap and National Rail datasets presented in Figure 18.

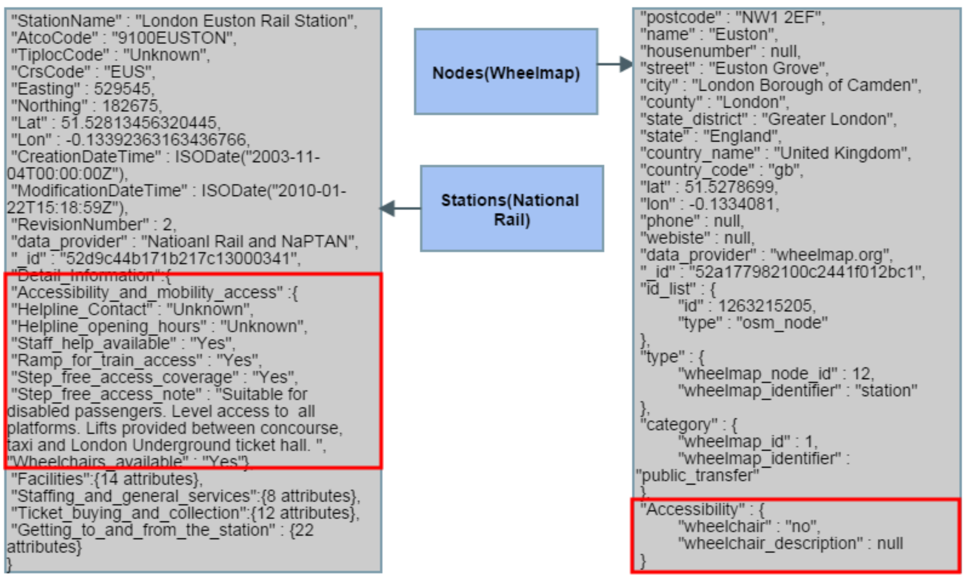


Figure 18: Same Entities in National Rail and Wheelmap Dataset

Firstly, there are some common attributes to describe the basic information of places, such as name, geographic data, phone, and address. For example, the name of the train station in the National Rail dataset is London Euston Rail Station compared with Euston in Wheelmap. Although the names in each dataset are slightly different, they are semantically the same, which point to the same entity in the real world. Also, the latitude and longitude of the entity in two datasets are slightly different. For the accessibility related attributes, as we can see in Figure 18, there are only two attributes related to accessibility in the Wheelmap dataset. By contrast, the National Rail dataset provides more than eight attributes to describe accessibility information. However, the most difficult issue is how to enrich the accessibility data by semantically integrating and interlinking the entities in separated datasets. The challenges in this example will be the answers of the following questions based on the accessibility metadata provided by the datasets: whether the station is wheelchair accessible, which information is correct, how accessible the station is for me, and which facility is available. Therefore, the next section will explore the research of accessibility data integration and interlinking based on open accessibility data in the accessible travelling domain collected and observed in this experiment.

5.3 Open Accessibility Data Integration

Based on the survey of open accessibility data and data schema observation in the previous sections, this section explains the methodologies and experiments for open accessibility data integration and interlinking. As a core data layer of the Semantic Web, the Linked Data exposes the advanced characteristics for knowledge sharing, such as human and machine readable data, well-structured data, standard data format, ontology-based reasoning and domain specified. Ontology is the formal, explicit specification of a shared conceptualization. The role of ontologies in the data integration can be used to describe the semantics of the information sources and to make contents explicit.

As stated in Chapter 2, there are three different ways to integrate data based on ontology, namely the single ontology approaches, multi-ontology approaches and hybrid approaches. However, the multiple ontology approaches are very costly for implementation effort and will also face mapping challenges between low dimensional data and high dimensional data, such as mapping between the entity with only one wheelchair accessible attribute in the Wheelmap dataset and the same entity with multiple attributes presenting wheelchair accessibility in the National Rail dataset. The multiple ontology approaches are also faced with the problem of finding common vocabularies to compare different data sources. Moreover, the mapping between the multi-ontologies is still a research challenge, which involved a large number of research efforts into this research area. The hybrid approaches are developed to address both the issues occurring in the single and multiple approaches. The hybrid approaches combine the advantages of multiple approaches to develop ontology for each data source and the advantages of single approaches of building the global ontology to be used as shared vocabularies.

There are the several facts existing in this research experiment, such as the multiple heterogeneous schemas among the datasets, the effort cost to implement ontology for each data source with multi-ontology approaches, and the degree of reusability of the ontologies. Therefore, we only applied two approaches of ontology-driven data integration, namely the hybrid ontology approach and single ontology approach to integrate the open accessibility datasets in the experiment. The detail of each approach will be described and discussed in following sub-sections.

5.3.1 Hybrid Ontology Approaches

Firstly, we introduce the most advantageous approach, namely the hybrid ontology approaches, which are used to overcome the drawbacks of the single or multi-ontology approaches. The main principles of the hybrid ontology approaches could be divided into two parts: (a) Similar to multi-ontology approaches, developing the individual ontology for each data source; (b) Similar to single ontology approaches, developing one global ontology of shared vocabularies to make the source ontology comparable.

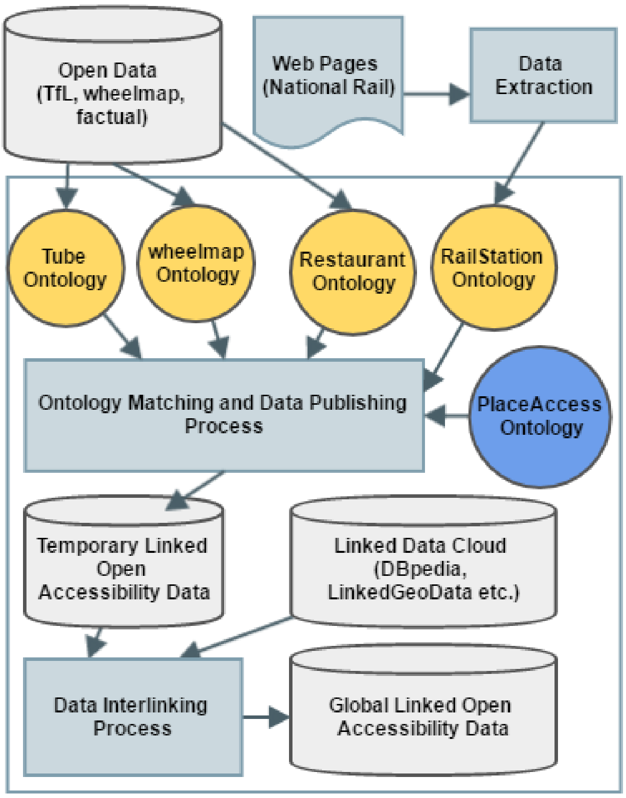


Figure 19: Hybrid Ontology Approaches for Open Accessibility Data Integration

The architecture of hybrid ontology approaches designed for the open accessibility datasets integration is presented in Figure 19, which is also used as the data integration model in the Linked Data-driven DSS for accessible travelling demonstrated in Chapter 3. In this architecture, there are four ontologies designed for the datasets including the tube station ontology, Wheelmap ontology, restaurant ontology and railway station ontology. The ontology of each data source is built based on their own data schema, which is presented in previous sections. As we discussed previously, the greatest disadvantage of multi-ontology approaches is the effort cost and difficulties of implementing multi-ontologies. Due to the uncertainty of data schema developed for each data source in the future, the multiple ontology approaches may not be scalable or reusable for future integration. Therefore, in the hybrid ontology approaches, a top-level and global ontology is implemented to define the shared accessibility terms in the accessible place domain, which could reduce the difficulties and complexities of multi-ontologies mapping. The global ontology is called PlaceAccess ontology[29], which reuses some existing standards ontologies including the DBpedia ontology, Freebase ontology, LinkedGeoData ontology and Schema org ontology etc.

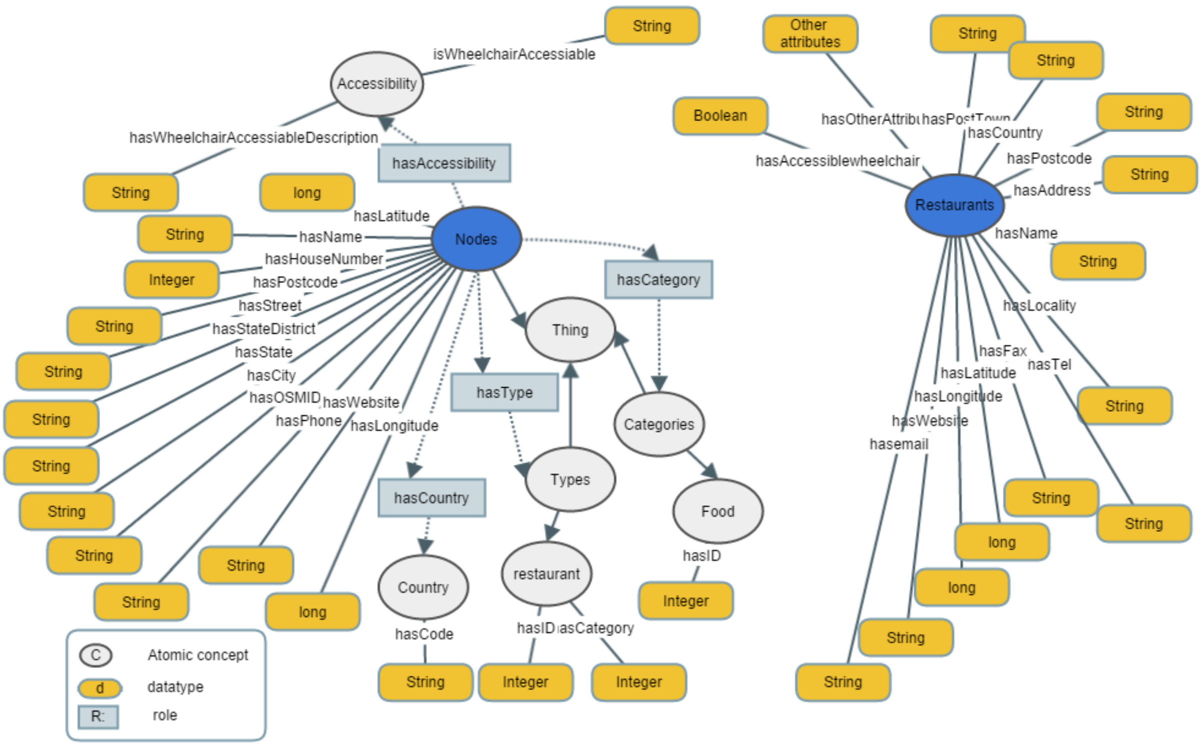


Figure 20: Wheelmap Ontology and Factual Ontology

The PlaceAccess ontology defines the common and shared vocabularies among the data sources collected in the experiment. For example, Figure 20 illustrates the graph of the Wheelmap

[29] http://waisvm-cd8e10.ecs.soton.ac.uk/2014/2/ontology/placeaccess.owl

ontology and Factual restaurant ontology. The Wheelmap ontology is on the left side of this figure while the Factual restaurant ontology is on the right. Due to the fact that the Wheelmap dataset is the largest dataset with many different types and categories for the POIs, in this figure, the restaurant type is the only type of Wheelmap node class displayed to indicate the shared the vocabularies between the Factual restaurant ontology.

In order to explain the process of data publishing and interlinking in the hybrid ontology approaches, the diagram in Figure 21 demonstrates the experimental process. Firstly, all extracted data and open data are stored locally in MongoDB based on the Ubuntu System in the remote Visual Machine without changing the schemes. MongoDB is a document-based, scheme less NoSQL database. In the data publishing phase, we use the pre-designed schema based ontologies to publish each dataset and use the global ontology PlaceAccess ontology to interlink each Linked Dataset. The next step is to dump the whole database into JSON-LD[30], a W3C standard format for Linked Data. In our experiment, the reason to use the JSON-LD is due to the data stored on the MongoDB is JSON-based and perfect to publish the data in JSON-LD format. In the ontology matching process, we use the equivalent assertion (owl:sameAs) to interlink the same concept or instance in different ontologies. The equivalent assertion is also used to interlink the same entities in the Linked Open Accessibility Data to other external datasets in the Linked Open Data Cloud, such as DBpedia, Freebase and LinkedGeoData by applying some existing standard approaches, such as the Named Entities Recognition or Semantic Similarity approaches.

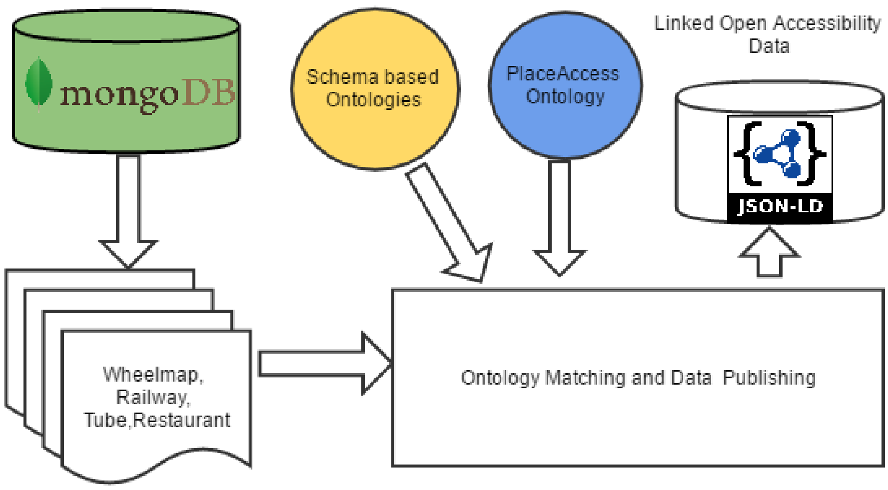


Figure 21: Process of Hybrid Ontology Approaches

Although the development of the hybrid ontology approaches is to address the issues of single ontology approaches and multiple ontology approaches, there are still some challenges for this

[30] http://www.w3.org/TR/json-ld/

approach at the current stage of the experiment. Firstly, due to the fact that the ontology should be the formal, explicit specification of a shared conceptualization rather than the specific data schema in different applications, there is much more effort needed for developing the ontology for each data source. Moreover, the approaches of building ontologies for each dataset based on its data schema make it very difficult to maintain the ontologies, which would lead to difficulties in publishing the Linked Open Accessibility Data as well as further data republishing and interlinking. For example, if the data provider changes the data schema into a different structure, then the related schema based ontology needs to be redesigned to match the change of data schema or a programme must be used to transform the structure of the new data schema into the old data schema. Therefore, the experiment of applying single ontology approaches is presented in the next section, which demonstrated the most straightforward way to integrate and publish open accessibility data as Linked Data.

5.3.2 Single Ontology Approaches

The single ontology approach is a straight forward, quick-and-dirty approach, which is applied in the first stage of this ontology-based data integration experiment. The architecture of single ontology approaches is presented in Figure 22.

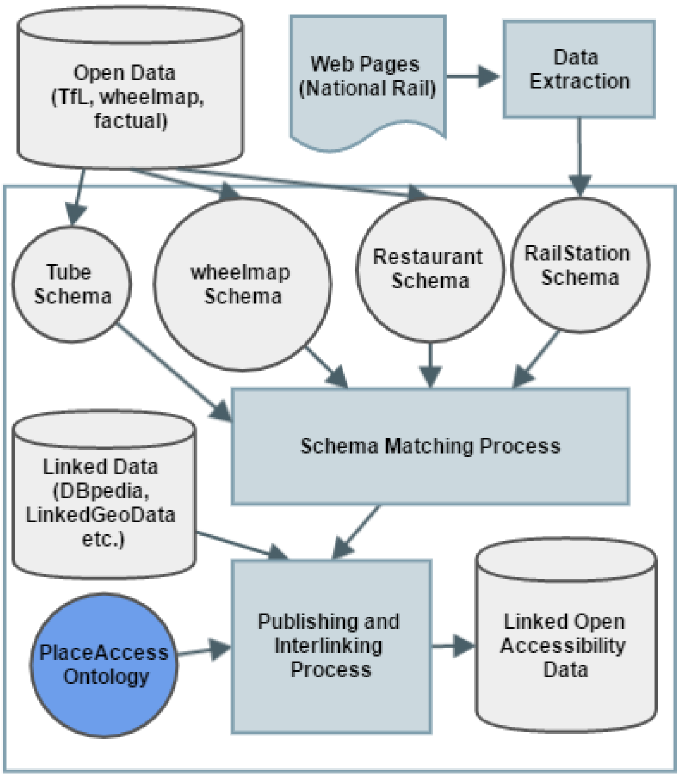


Figure 22: Single Approach for Open Accessibility Data Integration

Compared with multiple ontology approaches, single ontology approaches provide a schema matching process to match the schema of the different data sources. Due to the difficulties of mapping between low dimensional data and high dimensional data, a simple schema matching rule is developed to match the same entities in different datasets through the data schema observation in previous sections. The matching rule is explained in the following sub-sections.

After the schema matching process, and the global ontology, the PlaceAccess Ontology is designed to describe the common concepts and semantic relationships for the accessibility facilities and information of real world places across the data sources. In the publishing and interlinking process, the integrated data is published as Linked Data with the PlaceAccess ontology. The place class in PlaceAccess Ontology also refers to the place class in schema.org ontology[31] and node class in LinkedGeoData ontology[32]. There are 12 primary categories and 130 different types of places in Wheelmap dataset, which is same as the categories in the LinkedGeoData ontology. There are 50 different categories and 120 types in schema ontology and some existing properties describe the place class, such as name, geographic information (latitude and longitude), address, telephone or the URL to present the place from the real world on the Web. However, there is no existing standard ontology to describe the accessibility facilities or services for the buildings or places. Therefore, we need to construct the classes for accessibility related facilities and services, such as Braille, Large Print, Sign Language, Automatic Doors, Hearing Systems, Help Points, Lifts, Accessible Parking, Accessible Toilets, Step-free and Accessible Changing Rooms as well as some object attributes and data attributes to define the relationships, constraints and the reasoning rules.

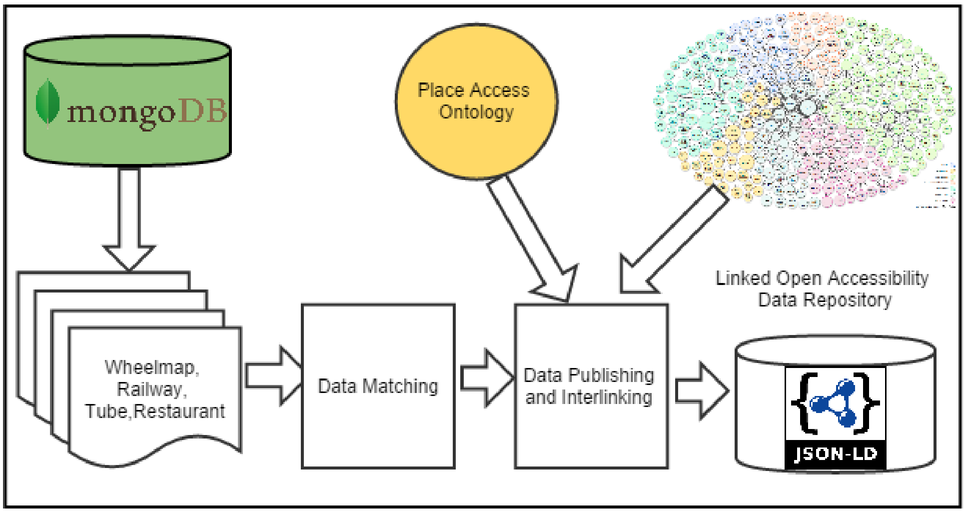


Figure 23: Single Ontology Approaches Process

As described previously, the datasets in this experiment are extracted from either open APIs or web pages, which are all stored in MongoDB. The MongoDB database provides the effective

[31] http://schema.org/docs/schemaorg.owl
[32] http://lov.okfn.org/dataset/lov/details/vocabulary_lgdo.html

compatibility features for storing these documents as JSON-LD. The diagram in Figure 23 presents the single ontology approaches process, which firstly provides data matching based on their own data schema. Then the process applies the PlaceAccess Ontology to annotate the semantic metadata to each entity in each database and dump all datasets into JSON-LD. After that, there is an interlinking process to use equivalent assertions (owl:sameAs) to interlink the same entity from linked open accessibility data and other resources in the Linked Open Data Cloud, such as DBpedia, Freebase and LinkedGeoData. Compared with the hybrid ontology approaches, the single ontology approaches could address the problems of schema based ontology designing, multi-ontologies maintenance, and ontologies matching. The following sub-section will present the rules for schema-based entity matching applied in this experiment.

5.3.3 Entity Matching Rules and Result

The entity-matching rule described in this section is primarily used for matching the same entities from different datasets in the experiment. Due to the fact that there is geographical data available for each entity in these four datasets, this simple mapping rule includes geographic distance matching, entity name matching and other information matching, such as address, postcode, phone number and other specified identifiers. The matching rules for each entity are described as follows:

- Step One: The Entity Type Matching. There are 12 primary categories and 130 different types of places in the Wheelmap dataset, such as train station, tube station, platform and restaurant. Therefore, it is easier to map other datasets to the Wheelmap dataset based on the entity categories and types.

- Step Two: The Name Similarity Matching. This step is mainly for both entities with the name. If not, then go to step three. In this step, it applied the Regular Expression Matching and Jaro-Winkler Distance algorithm to get the name similarity score between two entities. Firstly, the Jaro Distance $\mathrm{d_j}$ of two given strings $\mathrm{s_1}$ and $\mathrm{s_2}$ is:

$$\mathrm{d}_j = \begin{cases} 0 & \text{if m} = 0 \\ \frac{1}{3}\left(\frac{m}{|\mathrm{s_1}|} + \frac{m}{|\mathrm{s_2}|} + \frac{m-t}{m}\right) & otherwise \end{cases}$$

, where:

- m is the number of matching characters
- t is the number of transpositions (transposition is a permutation which exchanges two characters and keeps all others fixed)

Two characters from s_1 and s_2 respectively, are considered matching only if they are the same and the distance of position is not farther than $\left\lfloor \frac{\max(|s_1|,|s_2|)}{2} \right\rfloor - 1$. The Jaro-Winkler Distance d_w of two given strings s_1 and s_2 is:

$$d_w = d_j + (\ell p(1 - d_j))$$

- d_j is Jaro Distance of two given strings
- ℓ is length of common prefix at the start of the string up to a maximum of 4 characters
- p is a constant scaling factor for how much the score is adjusted upwards for having common prefixes. p should not be exceed 0.25 and the standard value is $p = 0.1$.

- Step Three: Calculating the Geographic Distance. Calculating the geographic distance based on latitude and longitude of each entity.

- Step Four: Additional Information Matching. Matching any additional information available for both entities, such as telephone, postcode, website or identifiers.

- Step Five. Based on the scores calculated in previous matching steps, the candidate matched entities should be satisfied with following metrics: the Geographic Distance and the Name Similarity Score (if there is a name similarity score). If there is more than one pair of entities in the candidate list, the entities with smallest geo distance should be considered as a pair of matched entities.

Based on the experimental designs described above, the following part of this section will present and discuss the experimental result. According to the entity matching rules proposed in the previous section, there are two independent variables that affect the matching results, namely geographic distance and name similarity. In order to provide an effective and accurate data integration approach, experiments are designed based on these two factors with different values to investigate the relationship between these two factors and entity matching result. In the first entity matching experiment, there are three groups of results based on the following matching conditions:

- Group 1: geographic distance <= 100 meters and name similarity score >=0.95
- Group 2: geographic distance <= 200 meters and name similarity score >= 0.85
- Group 3: geographic distance <= 300 meters and name similarity score >= 0.7

Table 20: Entity Matching Evaluation (Experiment 1)

	Matched	True	False	TP	FP	FN	Precision	Recall	F1 Score
Group1	**Geo distance<=100m and Name similarity>=0.95**								
Restaurant	1616	1610	6	1610	6	1009	0.996287	0.614738	0.760331
Tube	42	42	0	42	0	15	1	0.736842	0.848485
Railway	2121	2121	0	2121	0	295	1	0.877897	0.934979
Group2	**Geo distance<=200m and Name similarity>=0.85**								
Restaurant	2641	2485	156	2485	156	16	0.940931	0.993603	0.96655
Tube	50	49	1	49	1	7	0.98	0.875	0.924528
Railway	2370	2370	0	2370	0	46	1	0.98096	0.990389
Group3	**Geo distance<=300m and Name similarity >=0.7**								
Restaurant	8125	2493	5632	2493	5632	5500	0.306831	0.311898	0.309344
Tube	62	57	5	57	5	5	0.919355	0.919355	0.919355
Railway	2421	2416	5	2416	5	5	0.997935	0.997935	0.997935

Table 20 demonstrates the matching result based on the match rule combined with the matching condition of the first experiment, different name similarity score and different geographic distance. In order to evaluate the matching result, all the matched data is voted by the 14 users on the line system from 18th August 2014 to 1st September 2014. Table 20 also demonstrates the evaluation result, such as True Positive (TP), False Positive (FP), False Negative (FN), Precision, Recall and F1 score. For the second entity matching experiment, there are three groups of results based on the following different matching conditions:

- Group 1: geographic distance <= 100 meters and name similarity score >=0.85
- Group 2: geographic distance <= 100 meters and name similarity score >= 0.7
- Group 3: geographic distance <= 100 meters and name similarity score >= 0.5

Table 21: Entity Matching Evaluation (Experiment 2)

	Matched	True	False	TP	FP	FN	Precision	Recall	F1 Score
Group1	**Geo distance<=100m and Name similarity>=0.85**								
Restaurant	2408	2322	86	2322	86	217	0.964286	0.914533	0.938751
Tube	46	46	0	46	0	11	1	0.807018	0.893204
Railway	2316	2316	0	2316	0	100	1	0.958609	0.978867
Group2	**Geo distance<=100m and Name similarity>=0.7**								
Restaurant	3484	2625	859	2625	859	859	0.753444	0.753444	0.753444
Tube	47	47	0	47	0	10	1	0.824561	0.903846
Railway	2342	2342	0	2342	0	74	1	0.969371	0.984447
Group3	**Geo distance<=100m and Name similarity>=0.5**								
Restaurant	6239	2343	3896	2343	3896	3614	0.375541	0.393319	0.384224
Tube	53	53	0	53	0	4	1	0.929825	0.963636
Railway	2349	2348	1	2348	1	67	0.999574	0.972257	0.985726

Table 21 presents the data matching rules combined with these matching conditions. The result and all the matched data is also voted by 14 users from 18th August 2014 to 1st September 2014. In order to demonstrate the evaluation of the entity matching rules, Figure 24 indicates the best accuracy and cut-off point of geographic distance. Figure 24 (a) is the data analysis result of restaurant entity matching between Wheelmap and Factual, which indicates that the best accuracy is 53.35% based on low geographic distance. Figure 24 (b) is the railway station entity matching result between Wheelmap and National Rail datasets, which provides very high accuracy based on low geographic distance. Figure 24 (c) is the tube station entity matching result between Wheelmap and TfL tube station datasets, which also demonstrates high accuracy based on the low geographic distance. Figure 24 (d) presents the overall best accuracy (69.18%) with low geographic distance. Figure 25 indicates the relationship of the best accuracy and the cut-off point of name similarity. Figure 25 (a) is the restaurant entity matching indicated that the best accuracy is 91.94% and the cut-off point similarity score equals to 0.8346. Figure 25 (b) is the railway station entity matching. The best accuracy is 99.99% and the similarity score equals 0.5025. Figure 25 (c) is the tube station entity matching, which demonstrates the best accuracy of 94.67% at the point of 0.3132. Figure 25 (d) presents the overall best accuracy (94.28%) with the cut-off point (0.8311).

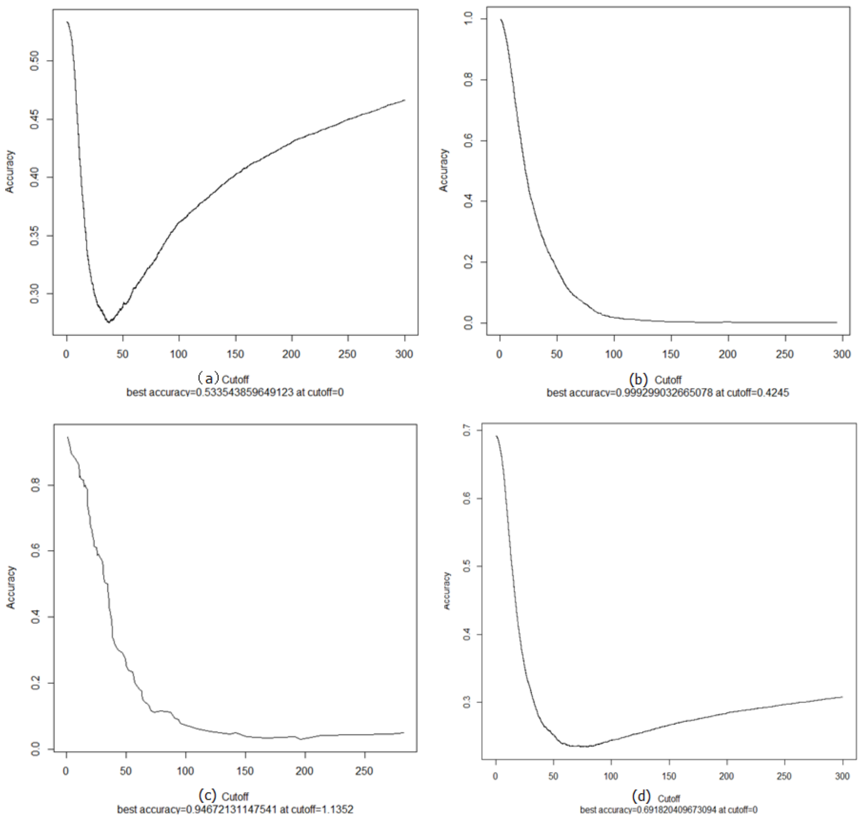


Figure 24: Accuracy and Geographic Distance

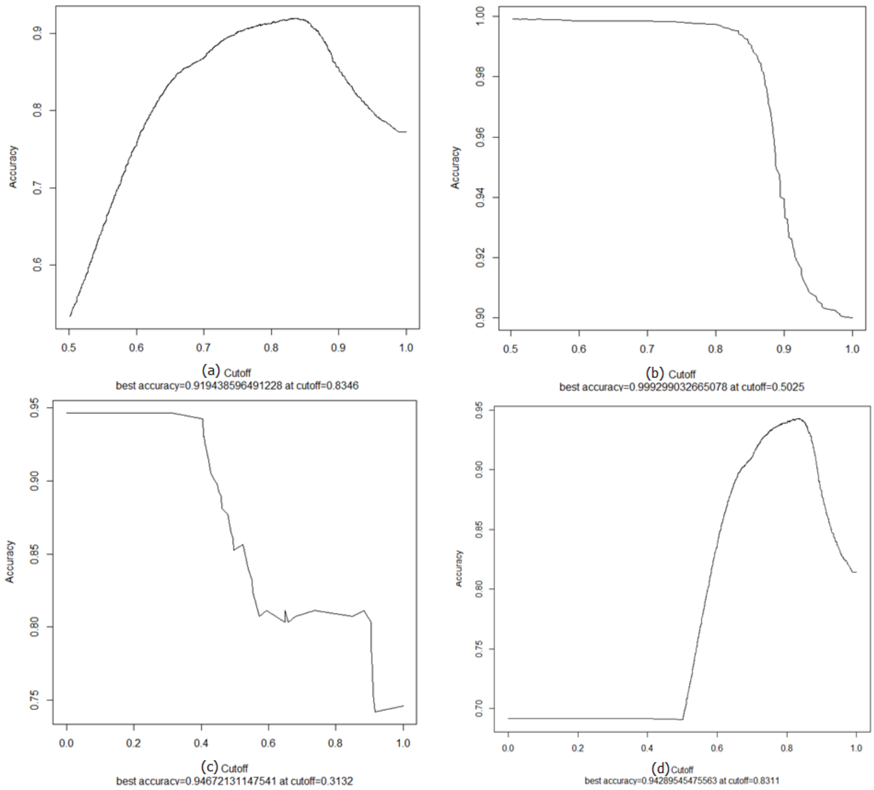


Figure 25: Accuracy and Name Similarity

Therefore, in order to achieve a high accuracy for the entity matching result, one solution is to use different variable values (geographic distance and name similarity) to match the entities based on different datasets. According to the experiment result analysed above, the variables for entity matching is following the matching conditions below:

- Tube station entity matching: geographic distance<=300 meters and name similarity score>=0.3132
- Railway station entity matching: geographic distance<=300 meters and name similarity score>=0.5025
- Restaurant entity matching: geographic distance<=300 meters and name similarity score>=0.8346

The experimental result based on these matching conditions is demonstrated in Table 22. There are 92.85% of train stations in National Railway dataset matched with the train stations in the Wheelmap dataset. Only 21.62% of tube stations are matched with the tube stations in Wheelmap, while 17.27% of the restaurants in Factual are matched with restaurants in Wheelmap. There are 35 of 2415 entities with a conflict of accessibility information in the train station matching. 2 of 48 entities are conflicted in tube station datasets matching and 51 of 1835 entities are conflicted in restaurant datasets mapping. However, there are also a large amount of entities archived with accessibility attributes. For example, there are 2216 train stations (92.76%), 20 tube stations (41.67%) and 1724 restaurant (93.95%) with wheelchair accessibility data matched to the equivalent entities in Wheelmap dataset.

Table 22: Entity Matching Result

	Train wheelmap	Train Station	Tube wheelmap	Tube Station	Food wheelmap	Restaurant Factual
Total	3384	2601	222	362	56970	10629
With Name	3323	2601	119	362	52901	10629
No Name	61	0	103	0	4071	0
Total Matched	2415 (92.85%)		48 (21.62%)		1835 (17.27%)	
Enrichment Entities	2216 (92.76%)		20 (41.67%)		1724 (93.95%)	
No Change Entities	164 (6.79%)		26 (54.17%)		60 (3.27%)	
Conflict Entities	35 (1.45%)		2 (4.16%)		51 (2.78%)	

In additional, as we can see from Figure 26, most of these matched entities are enriched with the accessibility information, which improves the accessibility data quality to address the problem of information uncompleted.

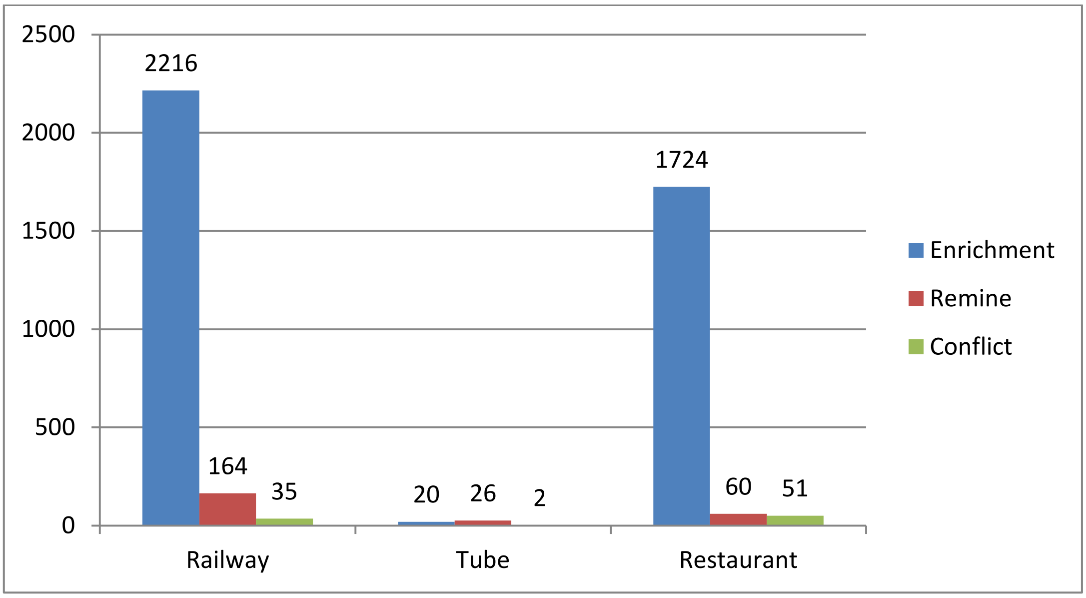


Figure 26: Entity Matching Result

Table 23 also presents the detailed comparison between wheelchair accessibility attributes in matched entities. There are still some entities mismatched, uncompleted accessibility, conflicts or duplicates during the matching process. The data conflict issue not only includes the accessibility information, it also applies to other properties, which are not related to accessibility, such as postcode, telephone or even address.

Table 23: Open Accessibility Data Matching Result

Wheelmap	Railway	No.	Wheelmap	Tube	No.	Wheelmap	Factual	No.
Accessible	Accessible	2415	Accessible	Accessible	48	Accessible	Accessible	1835
Null	No	1063	Null	No	5	Null	Yes	1724
Null	Yes	1151	Null	Yes	6	Yes	Yes	60
Null	Null	26	Null	Null	22	No	Yes	23
Yes	No	22	Yes	No	1	Limited	Yes	28
Yes	Yes	82	Yes	Yes	2			
Yes	Null	2	Yes	Null	0			
No	No	46	No	No	1			
No	Yes	2	No	Yes	1			
No	Null	0	No	Null	9			
Limited	No	10	Limited	No	1			
Limited	Yes	11	Limited	Yes	0			
Limited	Null	0	Limited	Null	0			

5.4 Crowdsourcing the Linked Open Accessibility Data

In the previous section, we demonstrated the approaches to integrate open accessibility data. We also mentioned the approaches to evaluating the matching result by using crowdsourcing. In this section, the Linked Data-driven Web application is proposed to address the problems of incomplete information and data conflicts in the accessibility information. Firstly, the reference architecture of the proposed application is demonstrated, and the prototype application called CrowdAccess is also demonstrated as a proof of the concept in the following sub-sections. The limitations of the approaches are also discussed in the last sub-section.

5.4.1 Reference Architecture

The reference architecture of the proposed Linked Data-driven Web application is presented in Figure 27. This reference architecture could be divided into three main components, namely the remote endpoint component, local server component and republishing component.

1. **Remote Endpoint Component.** Based on the previous research of open accessibility data and crowd-sourced accessibility data in the UK [29], the crowdsourcing approaches demonstrate the power in gathering accessibility information. However, it also proposed the limitations in aspects of the data quality. According to the survey, the open accessibility data published by the government or official organisations is better in data quality than the crowdsourced data. Therefore, the data sources of the remote endpoint component are mainly from other Linked Data platforms, such as other Linked Datasets with more accessibility information or other Linked Datasets with additional non-

accessibility information. Each data source provides the SPARQL endpoint for other servers to process the query.

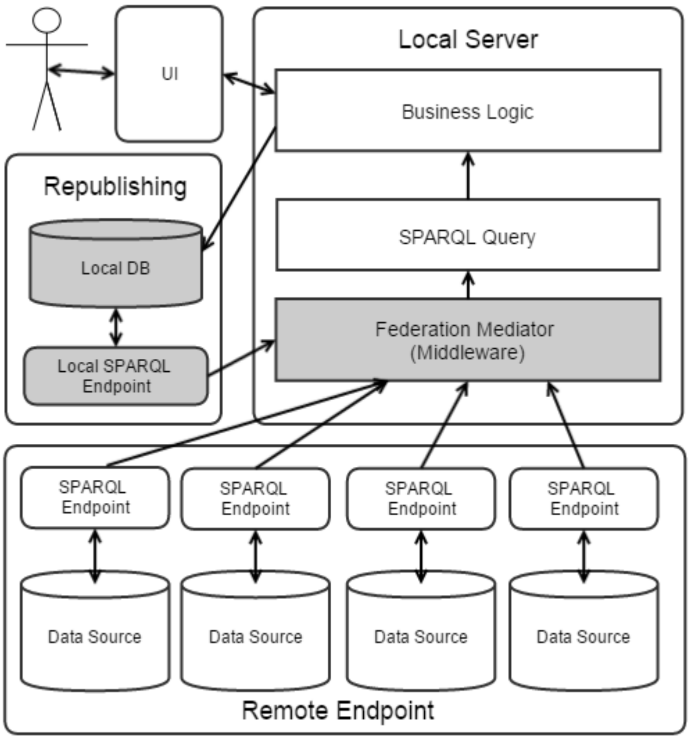


Figure 27: Reference Architecture to crowdsource Linked Open Accessibility Data

2. **Local Server Component**. The local server component includes the federation mediator for federated SPARQL query over the remote endpoints, the SPARQL query model for constructing the query based on the request from the business logic model. The main functionality of the business logic model is handling the request from users. In the current stage of the prototype, there are only two different types of user requests. One is the editing operation for crowdsourcing purposes, which allows users to input the accessibility information. Then the business logical model aggregates the data and caches them in the local DB. Another type of request is the viewing operation, which mainly displays the accessibility information of target objects or places based on the result of federated SPAQRL query over the remote endpoints and the local SPARQL endpoint. Therefore, the business logic model would not only provide the basic functionalities for the users but also provide the federated SPAQRL query over the endpoints of target data sources.

3. **Republishing Component**. The republishing component is the core component for this prototype, which is used to republish the crowdsourced and refined accessibility data as Linked Data. The dataset republishing procedure should follow the Linked Data principles proposed by Tim Berners-Lee [13]:

- Use URIs as names for things
- Use HTTP URIs so that people can look up those names
- When someone looks up a URI, provide useful information, using the standards (RDF, SPARQL)
- Include links to other URIs, so that they can discover more things

The republishing component should provide the aggregated result of the crowd-sourced accessibility data. The aggregation algorithms should be differed from different implementations, but the ontology applied for data publishing should follow the common vocabularies if possible. The UI is loosely coupled with the whole architecture, which means that any device could use the server endpoint to present a different user interface as soon as the application is able to send the request to the server. As a result, the local server component and republishing component could publish a public SPARQL endpoint and the local endpoint could be public open and served as a remote endpoint for other applications or systems to query.

5.4.2 Proof of the Concept

The Web application CrowdAccess is the prototype application based on the reference architecture described in previous section. This prototype application is used to demonstrate the proof of concept of crowdsourcing the Linked Open Accessibility Data. The main purpose of this Linked-driven Web application is to demonstrate how to use the Linked Data principles to improve the data quality of distributed accessibility data sources, thereby to provide the knowledge base for the research of Linked Data-driven accessible travelling decision support systems.

The prototype application is built on the Node JS v0.10.17. There are two different crowdsourcing tasks for this application. One task is to crowdsource the accessibility information while the other is to evaluate entity matching from different data sources and to crowdsource the interlinking of matching entities. The local dataset for the application is generated from the data integration model. However, in order to not confuse users and let them crowdsource clearly, this application currently provides 9 different accessibility related properties for each physical place, namely accessible parking, accessible toilets, baby changing rooms, hearing induction loops, lifts to all floors, and step-free access. All these 9 properties are summarised from the four datasets presented previously. There are five different values for each property, namely Yes, No, Unknown, Limited, Not Applicable. The Points of Interest (POIs) include the basic geographic information, general description and accessibility information. The basic geographic information includes house number, street, city, postcode and general description of the place.

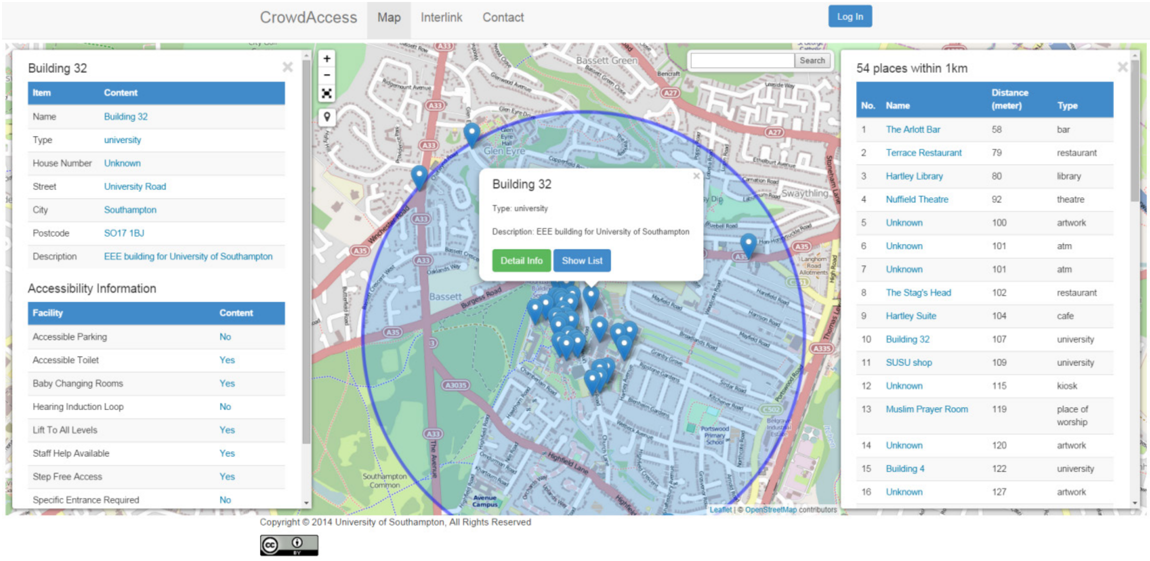


Figure 28: The User Interface of CrowdAccess

As indicated in Figure 28, the CrowdAccess not only allows users to search for places but also allows them to allocate their real-time location and search the surroundings. CrowdAccess provides the functionality to add and update the accessibility information. The application displays the accessibility information based on the aggregation of the federated query over both the local SPARQL endpoint and the remote SPARQL endpoints. All users' contributions are stored in the local database and the aggregation of results calculated by the server is published in the endpoint for other servers to access and query.

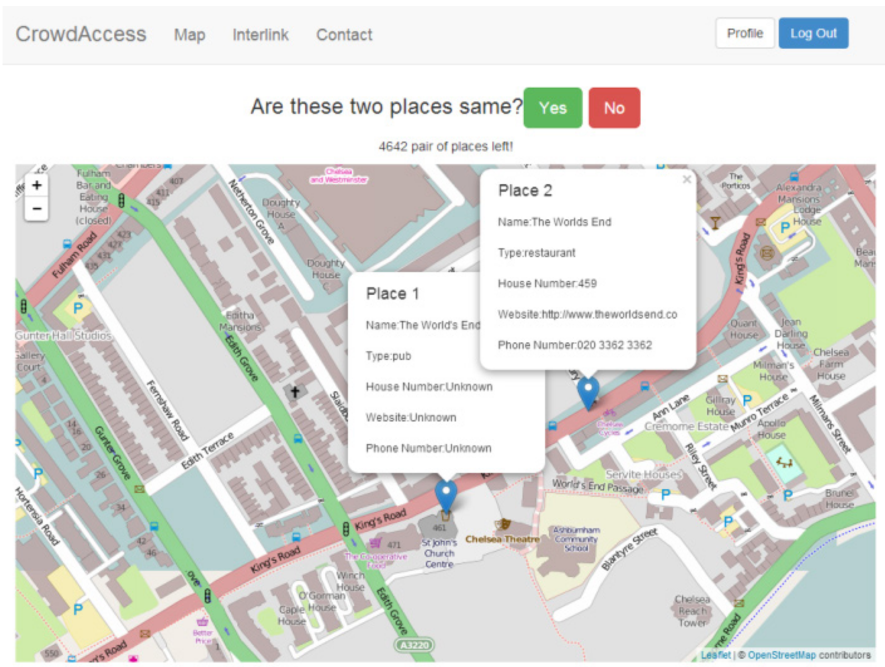


Figure 29: Using Crowdsourcing to evaluate the Open Accessibility Data Integration

Moreover, this application also provides the functionality to use crowdsourcing to test the results of matching rules, which is demonstrated in Figure 29. This voting application allows the user to check whether two places generated by the entity matching algorithms is in fact the same place. This crowdsourcing Linked Open Data approach is inspired by Simperl et al. [90]. The challenge for this voting system is that users need to vote on the places not only based on the information provided but also they need to search for much more information on the Web to make a decision on whether the generated places are the same place.

Based on the result of open accessibility integration and interlinking crowdsourcing described above, the republishing component is republishing the crowdsourced dataset as local Linked Data, and the data model of Linked Data applied in this experiment is JSON-LD, a W3C standard data model for Linked Data. The JSON-LD graph includes the subjects, objects, and relationships between subjects and objects. The RDF store used for data storing and maintenance in the experiment is rdfstore-js[33], which is a pure Javascript based library that supports the W3C standards, such as the full support of SPARQL1.0 and partially support of SPARQL 1.1. This library could parse and store JSON-LD on MongoDB and provides a standalone SPARQL endpoint. There are 13480 places with 236911 triples in current RDF store. The address of this standalone SPARQL endpoint is previously published at:

http://waisvm-cd8e10.ecs.soton.ac.uk/crowdaccess/sparql

The endpoint is now available at:

http://crowdaccess.linkedaccessibility.com/sparql

There is also a transformation between the JSON-LD and the N3 format of the RDF document. Figure 30 is demonstrates the entity of node89137908 in the LinkedGeoData while the example indicated in Figure 31 is the same entity of node 89137908 in CrowdAccess. Both examples are in N3 Format.

[33] https://github.com/antoniogarrote/rdfstore-js

```
@prefix dbpedia: <http://dbpedia.org/resource/> .
@prefix dc: <http://purl.org/dc/elements/1.1/> .
@prefix dcterms: <http://purl.org/dc/terms/> .
@prefix foaf: <http://xmlns.com/foaf/0.1/> .
@prefix gadm-o: <http://linkedgeodata.org/ld/gadm2/ontology/> .
@prefix gadm-r: <http://linkedgeodata.org/ld/gadm2/resource/> .
@prefix geo: <http://www.w3.org/2003/01/geo/wgs84_pos#> .
@prefix j.0: <http://linkedgeodata.org/ontology/ref%3A> .
@prefix j.1: <http://linkedgeodata.org/ontology/naptan%3A> .
@prefix lgd: <http://linkedgeodata.org/triplify/> .
@prefix lgdg: <http://linkedgeodata.org/geometry/> .
@prefix lgdm: <http://linkedgeodata.org/meta/> .
@prefix lgdo: <http://linkedgeodata.org/ontology/> .
@prefix meta: <http://linkedgeodata.org/ld/meta/ontology/> .
@prefix ngeo: <http://geovocab.org/geometry#> .
@prefix ns1: <http://linkedgeodata.org/ontology/naptan%3> .
@prefix ns2: <http://linkedgeodata.org/ontology/ref%3> .
@prefix ogc: <http://www.opengis.net/ont/geosparql#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix spatial: <http://geovocab.org/spatial#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<http://linkedgeodata.org/data/triplify/node89137908> rdfs:label "RDF description of Kenton" ;
    foaf:primaryTopic lgd:node89137908 .

lgd:node89137908 a spatial:Feature,
        lgdm:Node,
        lgdo:RailwayStation,
        lgdo:RailwayThing ;
    rdfs:label "Kenton" ;
    ngeo:geometry lgdg:node89137908 ;
    lgdo:changeset "18643854"^^xsd:int ;
    lgdo:gadmSameAs <http://gadm.geovocab.org/services/withinRegion?lat=51.581532&long=-0.316625#point> ;
    ns1:AAtcoCode "9100KTON" ;
    lgdo:network "London Underground;London Overground" ;
    ns2:Acrs "KTN" ;
    ns2:Astanox "72008" ;
    ns2:Atiploc "KTON" ;
    lgdo:source_ref "http://en.wikipedia.org/wiki/List_of_London_railway_stations;http://en.wikipedia.org/wiki/London_Overground
    lgdo:version "6"^^xsd:int ;
    lgdo:wheelchair false ;
    lgdo:wikipedia "en:Kenton station" ;
    dcterms:contributor lgd:user82783 ;
    dcterms:modified "2013-10-31T23:40:04"^^xsd:dateTime ;
    rdfs:isDefinedBy <http://linkedgeodata.org/triplify/meta/node89137908> ;
    geo:lat 5.158153e+01 ;
    geo:long -3.16625e-01 .
```

Figure 30: Entity Node89137908 of LinkedGeoData in N3 Format

```
@prefix dc: <http://purl.org/dc/elements/1.1/> .
@prefix dcterms: <http://purl.org/dc/terms/> .
@prefix foaf: <http://xmlns.com/foaf/0.1/> .
@prefix geo: <http://www.w3.org/2003/01/geo/wgs84_pos#> .
@prefix geom: <http://geovocab.org/geometry#> .
@prefix lgdo: <http://linkedgeodata.org/ontology/> .
@prefix loado: <http://waisvm-cd8e10.ecs.soton.ac.uk/ontology/> .
@prefix loadod: <http://waisvm-cd8e10.ecs.soton.ac.uk/> .
@prefix ngeo: <http://geovocab.org/geometry#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix schema: <http://schema.org/> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<http://waisvm-cd8e10.ecs.soton.ac.uk/data/node89137908> a "http://geovocab.org/spatial#Feature" ;
    rdfs:label "Kenton" ;
    geom:geometry "POINT(51.5815305 -0.316625)" ;
    dcterms:modified "2014-08-18T09:01:42.621Z" ;
    schema:addressCountry "http://waisvm-cd8e10.ecs.soton.ac.uk/ontology/UnitedKingdom" ;
    schema:addressLocality "http://waisvm-cd8e10.ecs.soton.ac.uk/ontology/LondonBoroughofBrent" ;
    schema:name "Kenton" ;
    schema:streetAddress "Nash Court" ;
    loado:StepFreeAccess "http://waisvm-cd8e10.ecs.soton.ac.uk/ontology/StepFreeAccessno" ;
    loado:version "0" ;
    = "http://linkedgeodata.org/data/triplify/node89137908" ;
    geo:lat "51.5815305" ;
    geo:lng "-0.316625" .
```

Figure 31: Entity Node89137908 of CrowdAccess in N3 Format

5.4.3 Limitations Discussion

As a prototype for the proof of concept, there are a few limitations for the current work in the CrowdAccess application. Firstly, there is no filtering or access control feature to ban malicious voters. This would be a future update to investigate how to build a user filtering mechanism to avoid malicious voting. Another limitation is that there is no personalization information of users in the current application. This could be added to the prototype to provide insight into the relationship between accessible facilities and the abilities of PwDs, and to improve future research of decision support systems for accessible travelling based on this knowledge graph.

Another issue is that, currently, we only provide the function to crowdsource the description of objects in physical places. Based on the research result proposed by Steinfeld et al. [92], they suggest that text with photos should be supported by using citizen sensing approaches to collect related data to improve public transportation, but the use of video may not have additional value to end users. Therefore, we also consider approaches involving photos or pictures combined with text to describe the accessibility information of the target facilities. One of the possible approaches is the interlinking to other Linked Datasets with images, such as the DBpedia. Another technique issue is the choosing of the RDF store. The performance of rdfstore-js used in the current experiment is not as good as the traditional RDF store, which needs to reconsider the alternative RDF stores for the better performance.

5.5 Summary

In summary, in this chapter, we demonstrated the open accessibility data integration model and the experiments designed for this research as well as the result discussion. Firstly, the survey of open accessibility data is presented and analysed. After that, the data schema observation demonstrates the common features and some challenges for integration of open accessibility datasets. We also compared the advantages and disadvantages of ontology-based data integration approaches. Although the hybrid ontology approaches are more advanced compared with the single ontology approaches, in the experiment we applied the most straight forward single ontology approaches to answer RQ1. We also used the results of data integration to demonstrate the how to enrich the open accessibility data.

In order to evaluate the data integration result and entity matching algorithms, the Linked Data-driven Web application applied with the crowdsourcing approach, the prototype CrowdAccess is proposed as the proof of concept. Based on users' voting feedback, the experimental result indicates that there are 92.76% of matched entities of the train station type in both National Railway dataset and Wheelmap dataset with enriched accessibility data. There are 41.67% of matched entities of the tube station type in both TfL dataset and Wheelmap dataset with enriched accessibility data. There are 93.95% of matched entities of the restaurant type in both Factual restaurant dataset and Wheelmap dataset with enriched accessibility information. We also summarised the limitations of current approaches, such as the matching rules that need improved accuracy for the same entity from different datasets, better approaches to address data conflicts for the accessibility information, the performance of the data store, and the challenge for the accessibility attributes mapping between low dimensional data and high dimensional data based on ontology reasoning and inference rules.

In the next chapter, we mainly demonstrate the following subjects: how to classify the limitations for people with mobility difficulties, how to build the ontology to model the limitations and how the domain focused ontology is constructed to model the place accessibility data, and public transport accessibility data.

Chapter 6: Ontologies for Accessible Travelling

In the previous chapter, we demonstrated the methodologies and experiments to conduct research into open accessibility data. All the experimental datasets are collected or extracted from online websites or systems used by users with mobility disabilities or limitations in the real world. As described in the section of data integration and publishing in the previous chapter, the challenges and urgent needs of standard ontologies for the accessible travelling domain are exposed. Therefore, this chapter will demonstrate the research of ontologies for accessible travelling domains as well as the inference rules for ontology reasoning.

In the first section, how to classify the difficulty categories based on the different limitations combination is presented. The classification is based on the research conducted by the researchers or standard organisations in the accessible travelling filed. In order to understand the accessibility requirements based on the limitations, the online questionnaire is designed to conduct the study of accessibility requirements for the people with mobility difficulties in the travelling scenario. All the questions presented in the questionnaire are based on the literature review of accessibility requirements stated in Chapter 2. After that, this chapter mainly introduces the ontologies for accessible travelling domain, which includes the mobility difficulty ontology, place accessibility ontology and transport accessibility ontology. The last section will give a brief summary of this chapter as well as the introduction of next chapter.

6.1 The Classification of Mobility Disabilities

In order to understand the requirements of accessible travelling, this section presents the approaches used to classify the mobility disabilities in this research compared with other classifications, which are conducted by the researchers or standard organisations in accessible travelling domains. Based on the different classifications described in Section 2.1, in order to help identify the activity limitations in the travelling scenarios, the functional difficulties are classified into different functional limitations in this research. As presented in Table 24, the users are classified into the following main categories: (1) lower limb limitations, (2) upper limb limitations, (3) upper body limitations. Each category includes subcategories and the limitation description. The lower limb limitations include light walking limitations, severe walking limitations, manual wheelchair users and powered wheelchair users. The upper limb limitations include light upper and severe upper limb limitations. The upper body limitations include light and severe upper body limitations.

Table 24: Category Classification of Mobility Difficulties and Limitations

Category	Sub-Category	Limitation Description
Lower Limb Limitations	Light Walking Limitations	Can walk ¼ mile but not more distance and can climb 10 steps without rest
	Severe Walking Limitations	Very difficult or cannot walk ¼ mile or very difficult or cannot climb 10 steps without rest
	Wheelchair (Manual)	Use manual wheelchair
	Wheelchair (Power)	Use the powered wheelchair
Upper Limb Limitations	Upper Limb Limitations	Only one upper limb functionalities or both weak upper limbs functionalities, or no upper limb functionalities
Upper Body Limitations	Light Upper Body Limitations	Weak upper body functionalities
	Severe Upper Body Limitations	Very week or no upper body functionalities

In Table 25, it also indicates the short code for 24 categories, which will be used to identify the user categorisation in the following research. Each short code represents the combination of different limitations in different body part.

Table 25: Classification Category of the People with Mobility Difficulties

Category Short Code	Upper Limb Limit.	Upper Body Limit.	Lower Limb Limitation
NNL	No	No	Light Walking Limitation
NNS	No	No	Severe Walking Limitation
NNWM	No	No	Wheelchair (Manual)
NNWP	No	No	Wheelchair (Power)
NLL	No	Light	Light Walking Limitation
NLS	No	Light	Severe Walking Limitation
NLWM	No	Light	Wheelchair (Manual)
NLWP	No	Light	Wheelchair (Power)
NSL	No	Severe	Light Walking Limitation
NSS	No	Severe	Severe Walking Limitation
NSWM	No	Severe	Wheelchair (Manual)
NSWP	No	Severe	Wheelchair (Power)
UNL	Yes	No	Light Walking Limitation
UNS	Yes	No	Severe Walking Limitation
UNWM	Yes	No	Wheelchair (Manual)
UNWP	Yes	No	Wheelchair (Power)
ULL	Yes	Light	Light Walking Limitation
ULS	Yes	Light	Severe Walking Limitation
ULWM	Yes	Light	Wheelchair (Manual)
ULWP	Yes	Light	Wheelchair (Power)
USL	Yes	Severe	Light Walking Limitation
USS	Yes	Severe	Severe Walking Limitation
USWM	Yes	Severe	Wheelchair (Manual)
USWP	Yes	Severe	Wheelchair (Power)

6.2 The Requirements Questionnaire for Accessible Travelling

This section primarily demonstrates the study of the accessibility problems and requirements faced by people with mobility difficulties in accessible travelling scenarios. The online questionnaire is designed to explore the study of the requirements for accessible travelling.

This questionnaire is used as the approach for gathering users' opinions on the criteria and the requirements of accessible travelling for people with mobility disabilities. The user groups include one group aged from 18 to 35 years old and one group aged from 36 to 65 years old, who have mobility limitations or disabilities. There are two main sections in this questionnaire, the first section is the general information of personal limitations, likely the age group, disabilities or limitations and their opinions for planning a trip when they are using public transport or entering unfamiliar buildings. The second section includes the sub-sections, which are the requirements of entering the physical place or built environment and the requirements of using public transport faced by people with mobility difficulties or limitations.

The questionnaire is hosted by the iSurvey website[34], University of Southampton, while open discussion about the survey is hosted on the public repository Github[35] as well as by email. It is mainly introduced to the individual with mobility difficulties via the online website, social networking (Twitter and Facebook etc.), and the mailing list of interested groups as well as personal interviews. The online questionnaire was active from May 2015 to July 2015 and all the participants were anonymous without any personal identified information. There are 9 questions in section one, while there are 24 questions in section two with 15 questions for the requirements of the physical built environment and 9 questions for the requirements of public transport. We are using a 4 points Likert Scale for the candidate answers to the proposed questions (i.e. 4=Strongly Agree, 3= Agree, 2=Disagree, 1=Strongly Disagree). The questionnaire is still online for public access and the response data is attached as the research data with this thesis. The data and result analysis would be demonstrated in the following discussions. There are 48 valid participants in total from May 2015 to July 2015. And 35 of them completed both sections, 13 of them are only completed section one. 23% of the respondents are aged 18 to 35 years old and 77% of the respondents are aged 36 to 64 years old. At the end of the first section, there is one question to ask participants whether they plan their trip before they visit or travel to an unfamiliar place. The option for this question is as follows: I do not plan trips, I plan trips by myself, I plan trips with the assistance of my family members or friends, and I plan trips with the assistance of travel agent.

---

[34] https://www.isurvey.soton.ac.uk/16011
[35]https://github.com/chaohaiding/AccessibleTravellingIssues

The statistics and test results are illustrated in Table 26. A one-sample t-test was run to determine following null hypothesis that the people with mobility disabilities do not plan their trips, plan trips by themselves, plan trips with the help of family or friends, and plan trips by travel agent before travelling was different to the mean score of 2.5.

Table 26: One-Sample Test for the Question of Pre-Trip Planning

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
NoPlan	30	1.6333	.85029	.15524
Myself	30	3.3333	.80230	.14648
FamilyMemberOrFriend	30	2.2333	1.04000	.18988
TravelAgent	30	1.7000	.87691	.16010

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
NoPlan	-5.583	29	.000	-.86667	-1.1842	-.5492
Myself	5.689	29	.000	.83333	.5338	1.1329
FamilyMemberOrFriend	-1.404	29	.171	-.26667	-.6550	.1217
TravelAgent	-4.997	29	.000	-.80000	-1.1274	-.4726

For the null hypothesis of the people with mobility disabilities do not plan their trips, the mean not planning score (M = 1.63, SD = 0.85) was lower than the mean score of 2.5, there was a statistically significant mean difference of 0.83, 95% CI [0.55 to 1.18], t (29) = -5.58, p = .000. There was a statistically significant difference between means (p < .05) and therefore, we can reject the null hypothesis and accept the alternative hypothesis that the people with mobility disabilities plan their trips before they visit or travel to unfamiliar places.

For the null hypothesis of the people with mobility disabilities plan trips by themselves, the mean planning by themselves score (M = 3.33, SD = 0.80) was higher than the mean score of 2.5, a statistically significant mean difference of 0.79, 95% CI [0.53 to 1.13], t(29) = 5.69, p = .000. There was a statistically significant difference between means (p < .05) and, therefore, we can accept the null hypothesis that the people with mobility disabilities plan trips by themselves before they visit or travel to unfamiliar places.

For the null hypothesis of the people with mobility disabilities plan trips with the help of family or friends, the mean with the help of family or friends score (M = 2.23, SD = 1.04) was not statistically significant lower than the mean score of 2.5 with p = .829.

For the null hypothesis of the people with mobility disabilities plan trips by travel agent, the mean not planning score (M = 1.7, SD = 0.88) was lower than the mean score of 2.5, a statistically significant mean difference of 0.76, 95% CI [0.47 to 1.13], $t(29) = -5.00$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and, therefore, we can reject the null hypothesis and accept the alternative hypothesis that the people with mobility disabilities do not plan trips by travel agent before they visit or travel to unfamiliar places.

As a conclusion, this section demonstrates general statistical analysis results of the questionnaire to study the accessibility requirements for the people with mobility difficulties. The following sections discuss the study of requirements for built environments and public transport stated in Section B of the questionnaire.

6.3 Accessibility Requirements for Built Environment

In this section, the study of accessibility requirements in the built environment for the people with mobility difficulties is presented. There are 14 questions using 4 points Likert Scale for the candidate answers, and each question is presented as follows:

1. I consider information about the **level of signs** (height) in and around the buildings or physical places I plan to visit important for me.
2. I consider information about the **entrance** to access to the buildings or physical places I plan to visit important for me.
3. I consider the information about the **door type** (Manual, Pad, or Automatic) of the buildings or physical places I plan to visit important for me
4. I consider the information about the **accessible toilet** in and around the buildings or physical places I plan to visit important for me.
5. I consider the information about the **accessible changing facilities** in and around the buildings or physical places I plan to visit important for me.
6. I consider the information about the **accessible table** (table that could be accessed by wheelchair users) in and around the buildings or physical places I plan to visit important for me.
7. I consider the information about the **handrails** on the wall in and around buildings or physical places I plan to visit important for me.
8. I consider the information about the **road or path surfaces** to the buildings or physical places I plan to visit Important for me.
9. I consider the information about the **road or path slope** to the buildings or physical places I plan to visit Important for me.

10. I consider the information about the **ramp gradient** to the buildings or physical places I plan to visit Important for me.
11. I consider the information about the **space to turn corners** in and around the buildings or physical places I plan to visit important for me.
12. I consider the information about the **lift to all levels** in the buildings or physical places I plan to visit Important for me.
13. I consider the information about the **accessible car parking** around the buildings or physical places I plan to visit important for me.
14. I consider the information about the **personal assistance** in the buildings or physical places I plan to visit important for me.

The statistical result of the participants' answers to these 14 questions is demonstrated in Figure 32. The top six important accessible facilities in physical places for the people with mobility disabilities are as follows: lifts to all floors (90.32%), accessible entrances (87.10%), road slopes to the building (83.87%), the road surface (83.33%) to the place, accessible car parking around the building (83.33%), and accessible toilets (80.65%).

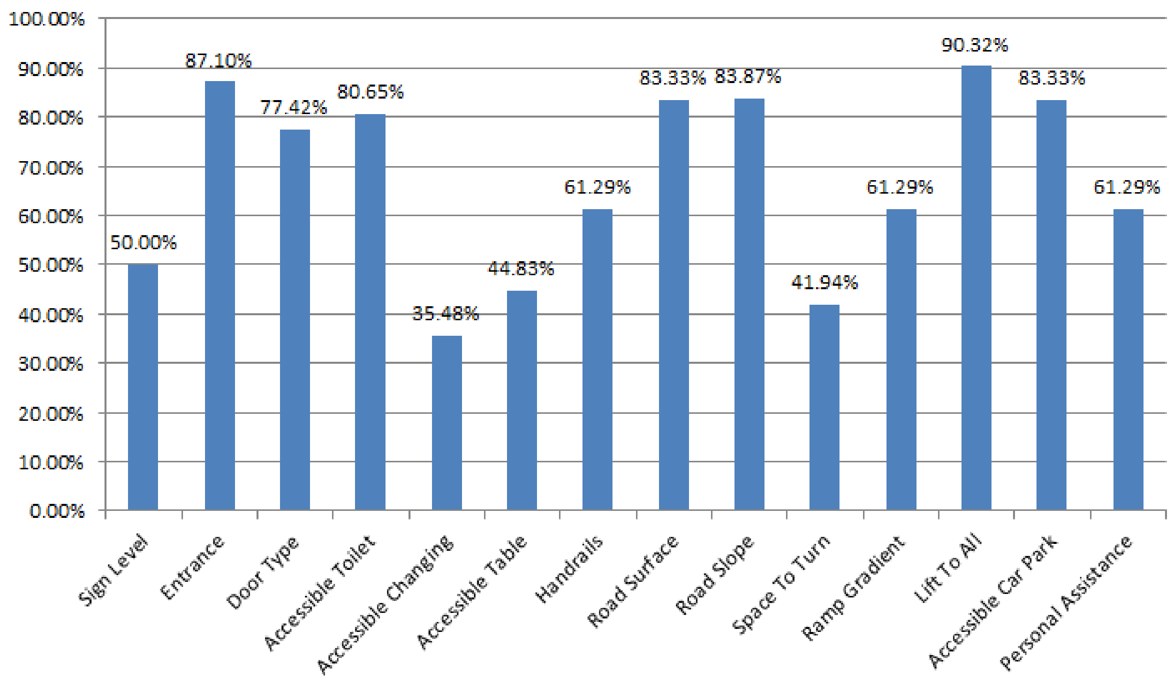


Figure 32: The Importance of Accessible Facilities in Built Environment for the PwMDs

According to the statistical results presented in Table 27, there is a one-sample t-test running on the result to determine the null hypothesis of the people with mobility disabilities consider that the facility is important when they plan to visit the place was different to the comparison value of 2.5.

Table 27: One-Sample Test for the Questions of Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	31	2.6129	2.07649	.37295
Entrance	31	3.3548	.79785	.14330
DoorType	31	3.2258	1.47670	.26522
AccessibleToilet	31	3.0645	.92864	.16679
AccessibleChanging	31	2.4839	1.78645	.32086
AccessibleTable	29	2.4828	.98636	.18316
Handrails	31	2.9032	2.08734	.37490
RoadSurfaces	30	3.2000	.92476	.16884
RoadSlope	31	3.3226	1.27507	.22901
SpacetoTurnCorners	31	2.5161	1.31329	.23587
RampGradients	31	2.9032	1.66042	.29822
LifttoAllLevels	31	3.3548	.87744	.15759
AccessibleCarParking	30	3.0667	1.01483	.18528
PersonalAssistance	31	2.5484	.88840	.15956

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	.303	30	.764	.11290	-.6488	.8746
Entrance	5.965	30	.000	.85484	.5622	1.1475
DoorType	2.737	30	.010	.72581	.1841	1.2675
AccessibleToilet	3.385	30	.002	.56452	.2239	.9051
AccessibleChanging	-.050	30	.960	-.01613	-.6714	.6391
AccessibleTable	-.094	28	.926	-.01724	-.3924	.3579
Handrails	1.076	30	.291	.40323	-.3624	1.1689
RoadSurfaces	4.146	29	.000	.70000	.3547	1.0453
RoadSlope	3.592	30	.001	.82258	.3549	1.2903
SpacetoTurnCorners	.068	30	.946	.01613	-.4656	.4978
RampGradients	1.352	30	.186	.40323	-.2058	1.0123
LifttoAllLevels	5.424	30	.000	.85484	.5330	1.1767
AccessibleCarParking	3.058	29	.005	.56667	.1877	.9456
PersonalAssistance	.303	30	.764	.04839	-.2775	.3743

For the null hypothesis of the people with mobility disabilities considering the information about the following facilities important, **sign level**, **accessible changing room**, **accessible table**, **handrails on the wall**, **space to turn corners**, **ramp gradients to the building**, and **personal assistance**, the mean score of each facility: sign level (*M* = 2.61, *SD* = 2.07), accessible changing room (*M* = 2.48, *SD* = 1.79), accessible table (*M* = 2.48, *SD* = 0.99), handrails on the wall (*M* = 2.9, *SD* = 2.09), space to turn corners (*M* = 2.52, *SD* = 1.32), ramp gradients (*M* = 2.90, *SD* = 1.66), and personal assistance (*M* = 2.55, *SD* = 0.89) were not statistically significant greater than the mean score of 2.5 with *p* = .764 (sign level), *p* = .960 (accessible changing room), *p* = .926 (accessible table), *p* = .291 (handrails on the wall), *p* = .946(space to turn corners), *p* = .186 (ramp gradients), and *p* = .764 (personal assistance). However, there are the following facilities or service with statistically significant result:

- For the null hypothesis of the people with mobility disabilities considering the information about the **entrance** of the building important, the mean score of the entrance (*M* = 3.35, *SD* = 0.80) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.81, 95% CI [0.56 to 1.15], *t*(30) = 5.97, *p* = .000. There was a statistically significant difference between means ($p < .05$) and, therefore, the null hypothesis can be accepted that the people with mobility disabilities considering the information about the entrance of the building important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **door type** of the building important, the mean score of the door type (*M* = 3.23, *SD* = 1.48) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.69, 95% CI [0.18 to 1.27], *t*(30) = 2.74, *p* = .010. There was a statistically significant difference between means ($p < .05$) and, therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the door type of the building important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **accessible toilet** in the building important, the mean score of the accessible toilet (*M* = 3.06, *SD* = 0.93) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.53, 95% CI [0.18 to 1.27], *t*(30) = 3.39, *p* = .002. There was a statistically significant difference between means ($p < .05$) and, therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the accessible toilet in the building important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **road surface** to the building important, the mean score of the road surface (*M* = 3.20, *SD* = 0.92) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.67, 95% CI [0.35 to 1.05], *t*(29) = 4.15, *p* = .000. There was a statistically significant difference between means ($p < .05$) and, therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the road surface to the building important.

- For the null hypothesis of the people with mobility disabilities considering the information about **the road slope** to the building important, the mean score of the road slope (M = 3.23, SD = 1.28) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.78, 95% CI [0.35 to 1.29], $t(30) = 3.59$, $p = .001$. There was a statistically significant difference between means ($p < .05$) and, therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the road slope to the building important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **lift to all levels** in the building important, the mean score of the lift to all levels (M = 3.35, SD = 0.88) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.81, 95% CI [0.53 to 1.18], $t(30) = 5.42$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and, therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the lift to all levels in the building important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **accessible car park** near the building important, the mean score of the accessible car park (M = 3.06, SD = 0.89) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.54, 95% CI [0.19 to 0.95], $t(29) = 3.06$, $p = .005$. There was a statistically significant difference between means ($p < .05$) and, therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the accessible car park near the building important.

Lastly, Question 15 asks for the importance ranking of facilities:

> *Please indicate your preferred importance order of accessibility information using numbers 1-14 where 1 is the most important.*

A Friedman Test was run on the answers to this question and the test results are demonstrated in Table 28. There was a statistically significant difference in the importance of accessible facilities and services that people with mobility difficulties considered important when they plan their trips. $\chi2(2) = 168.589$, $p = 0.000$. The importance ranking is followed by the median ranking score for each facility, and this result is used as the inference rules for ontology reasoning in the next chapter.

Table 28: The Ranking of Accessibility Requirements for the Built Environment

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
SignLevel	25	11.0000	2.76887	3.00	14.00	9.5000	11.0000	14.0000
Entrance	25	3.9600	2.33595	1.00	9.00	2.5000	4.0000	5.5000
DoorType	25	6.4400	2.82961	1.00	12.00	4.5000	6.0000	9.0000
AccessibleToilet	25	5.4000	3.18852	1.00	12.00	2.0000	5.0000	8.0000
AccessibleChanging	25	11.7600	2.16564	7.00	14.00	10.5000	12.0000	13.5000
AccessibleTable	25	11.1200	2.22336	5.00	14.00	10.0000	12.0000	12.5000
Handrails	25	9.2800	3.14272	2.00	13.00	7.0000	10.0000	12.0000
RoadSurfaces	25	5.2400	2.96198	1.00	13.00	3.0000	5.0000	6.5000
RoadSlope	25	5.2800	2.03142	2.00	9.00	4.0000	5.0000	6.5000
SpacetoTurnCorners	25	9.8400	3.68194	2.00	14.00	7.0000	11.0000	13.0000
RampGradients	25	7.2800	2.80654	2.00	14.00	5.5000	7.0000	9.5000
LifttoAllLevels	25	2.4000	1.52753	1.00	8.00	1.5000	2.0000	3.0000
AccessibleCarParking	25	5.5200	3.92768	1.00	13.00	1.0000	6.0000	9.0000
PersonalAssistance	25	10.0000	3.47611	3.00	14.00	7.0000	10.0000	13.5000

Ranks

	Mean Rank
SignLevel	11.06
Entrance	3.96
DoorType	6.54
AccessibleToilet	5.36
AccessibleChanging	11.78
AccessibleTable	11.10
Handrails	9.40
RoadSurfaces	5.28
RoadSlope	5.26
SpacetoTurnCorners	9.90
RampGradients	7.44
LifttoAllLevels	2.40
AccessibleCarParking	5.48
PersonalAssistance	10.04

Test Statistics[a]

N	25
Chi-Square	168.589
df	13
Asymp. Sig.	.000

a. Friedman Test

Furthermore, according to the classification category of the people with mobility difficulties presented in Table 25, accessibility requirements for each category is demonstrated in Table 29 and Table 30, which are statistically significant. The result is based on the statistical analysis results of the online questionnaire. The detail of statistical hypothesis tests is demonstrated in Appendix B.

Table 29: The Accessibility Requirements for the Built Environment (a)

Category	NNL	NNS	NNWM	NNWP	NLL	NLS	NLWM	NLWP	NSL	NSS	NSWM	NSWP
Sign Level												
Entrance		x	x	x		x	x	x	x	x	x	x
Door Type		x		x		x		x	x	x	x	x
Accessible Toilet		x	x	x	x	x	x	x	x	x	x	x
Accessible Changing												
Accessible Table												
Handrails												
Road Surface	x	x	x	x	x	x	x	x	x	x	x	x
Road Slope		x	x	x	x	x	x	x	x	x	x	x
Space To Turn				x				x				x
Ramp Gradient		x		x		x		x		x		x
Lift To All		x	x	x	x	x	x	x	x	x	x	x
Accessible Car Park		x	x	x		x	x	x	x	x	x	x
Personal Assistance				x				x	x	x	x	x

Table 30: The Accessibility Requirements for the Built Environment (b)

Category	UNL	UNS	UNWM	UNWP	ULL	ULS	ULWM	ULWP	USL	USS	USWM	USWP
Sign Level												
Entrance	x	x	x	x	x	x	x	x	x	x	x	x
Door Type	x	x	x	x	x	x	x	x	x	x	x	x
Accessible Toilet	x	x	x	x	x	x	x	x	x	x	x	x
Accessible Changing	x	x	x	x	x	x	x	x	x	x	x	x
Accessible Table												
Handrails												
Road Surface	x	x	x	x	x	x	x	x	x	x	x	x
Road Slope	x	x	x	x	x	x	x	x	x	x	x	x
Space To Turn				x				x				x
Ramp Gradient		x		x		x		x				x
Lift To All	x	x	x	x	x	x	x	x	x	x	x	x
Accessible Car Park	x	x	x	x	x	x	x	x	x	x	x	x
Personal Assistance				x				x	x	x	x	x

6.4 Accessibility Requirements for Public Transport

In this section, the study of accessibility requirements in public transport for the people with mobility difficulties is presented. There are 9 questions in total using 4 points Likert Scale for the candidate answers. Each question is presented as follows:

1. I consider information about the **level of signs** (height) important when I use public transport.
2. I consider information about the **ramps that allow to access** important when I use public transport.
3. I consider information about the **accessible toilet** important when I use public transport.
4. I consider information about the **accessible table** important when I use public transport.
5. I consider information about the **personal assistance** (provided by staff) important when I use public transport.
6. I consider information about the **personal assistance** (provided by staff) important when I use public transport.
7. I consider information about the **accessible interchange** important when I use public transport.
8. I consider information about the **accessible ticket machine** important when I use public transport.
9. I consider information about the **accessible ticket hall** important when I use public transport.

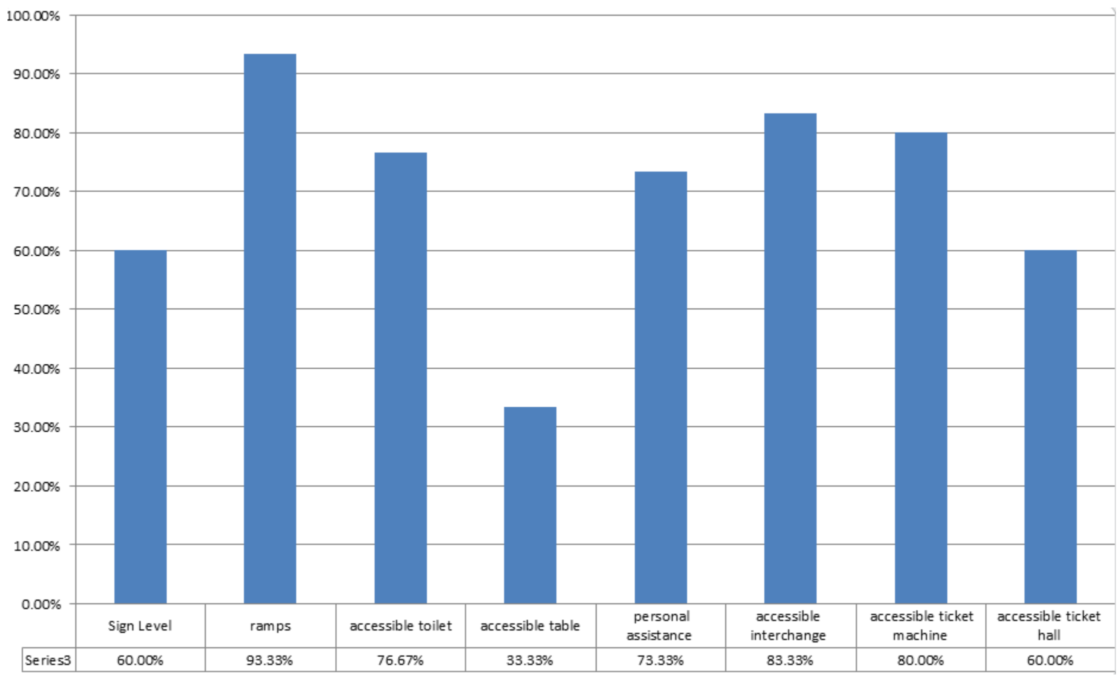


Figure 33: The Importance of Transport Facilities for the PwMDs

The statistical results of the participants' answers to these 9 questions are demonstrated in Figure 33. The top five important accessible facilities in the physical places for people with mobility disabilities are as follows: ramps access (93.33%), accessible interchanges (83.33%), accessible ticket machines (80.00%), accessible toilets (76.67%), and personal assistance (73.33%).

Table 31: The Accessibility Requirements for the Public Transportation

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	29	2.6207	.90292	.16767
Ramp	29	3.4138	.62776	.11657
AccessibleToilet	29	3.1379	.87522	.16252
AccessibleTable	29	2.4483	.86957	.16148
PersonalAssistance	29	2.8621	1.05979	.19680
AccessibleInterchange	29	3.2414	.91242	.16943
AccessibleTicketMachine	29	3.1379	.83342	.15476
AccessibleTicketHall	29	3.3103	.84951	.15775

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	.71981	28.00000	.47761	.12069	-.22276	.46414
Ramp	7.83881	28.00000	.00000	.91379	.67500	1.15258
AccessibleToilet	3.92514	28.00000	.00051	.63793	.30502	.97085
AccessibleTable	-.32032	28.00000	.75110	-.05172	-.38249	.27904
PersonalAssistance	1.83980	28.00000	.07642	.36207	-.04105	.76519
AccessibleInterchange	4.37567	28.00000	.00015	.74138	.39431	1.08845
AccessibleTicketMachine	4.12203	28.00000	.00030	.63793	.32092	.95495
AccessibleTicketHall	5.13686	28.00000	.00002	.81034	.48721	1.13348

According to the statistical results presented in Table 31, for the null hypothesis of the people with mobility disabilities considering the information about the following services important, **sign level**, **accessible table**, and **personal assistance**, the mean score of each service: sign level (M = 2.62, SD = 0.90), accessible table (M = 2.45, SD = 0.87), and personal assistance(M = 2.9, SD = 1.06) were not statistically significantly greater than the mean score of 2.5 with p = .478 (sign level), p = .751 (accessible table), and p = .008 (personal assistance). However, there are the following facilities or services with statistically significant results:

- For the null hypothesis of the people with mobility disabilities considering the information about the **ramp access to the public transport** important, the mean score of the ramp access to the public transport (M = 3.41, SD = 0.63) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.86, 95% CI [0.68 to 1.15], $t(28) = 7.84$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the ramp access to the public transport important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **accessible toilet** of the public transport important, the mean score of the accessible toilet ($M = 3.41$, $SD = 0.63$) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.86, 95% CI [0.68 to 1.15], $t(28) = 7.84$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and therefore, we can accept the null hypothesis that the people with mobility disabilities considering the information about the accessible toilet in the public transport important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **accessible interchange** of the public transport important, the mean score of the accessible interchange of the public transport ($M = 3.24$, $SD = 0.91$) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.70, 95% CI [0.39 to 1.09], $t(28) = 4.38$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and therefore, the null hypothesis can be accepted that the people with mobility disabilities considering the information about the accessible interchange of the public transport important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **accessible ticket machine** of the public transport important, the mean score of the accessible ticket machine ($M = 3.14$, $SD = 0.83$) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.65, 95% CI [0.32 to 0.95], $t(28) = 4.12$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and therefore, the null hypothesis can be accepted that the people with mobility disabilities considering the information about the accessible ticket machine in the public transport important.

- For the null hypothesis of the people with mobility disabilities considering the information about the **accessible ticket hall** of the public transport important, the mean score of the accessible ticket hall ($M = 3.31$, $SD = 0.85$) was greater than the comparison value of 2.5, a statistically significant mean difference of 0.77, 95% CI [0.49 to 1.13], $t(28) = 5.14$, $p = .000$. There was a statistically significant difference between means ($p < .05$) and therefore, the null hypothesis can be accepted that the people with mobility disabilities considering the information about the accessible ticket hall of the public transport important.

As last, Question 29 asks for the importance ranking of facilities or services in public transport:

Please indicate your preferred importance order of accessibility information using numbers 1-14 where 1 is the most important.

Table 32: The Accessibility Requirements Ranking for the Public Transportation

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	Percentiles 50th (Median)	Percentiles 75th
Ramp	23	2.5217	2.35236	1.00	7.00	1.0000	1.0000	5.0000
AccessibleToilet	23	4.0435	1.63702	1.00	7.00	3.0000	4.0000	5.0000
AccessibleTable	23	6.7391	1.60163	3.00	8.00	7.0000	7.0000	8.0000
PersonalAssistance	23	4.4348	2.10683	1.00	8.00	2.0000	4.0000	6.0000
AccessibleInterchange	23	3.3043	1.49042	1.00	6.00	2.0000	3.0000	5.0000
AccessibleTicketMachine	23	4.1304	2.05170	1.00	8.00	3.0000	4.0000	5.0000
AccessibleTicketHall	23	4.1304	1.86607	1.00	7.00	2.0000	4.0000	6.0000
SignLevel	23	6.6957	1.55021	3.00	8.00	6.0000	7.0000	8.0000

Ranks

	Mean Rank
Ramp	2.52
AccessibleToilet	4.04
AccessibleTable	6.74
PersonalAssistance	4.43
AccessibleInterchange	3.30
AccessibleTicketMachine	4.13
AccessibleTicketHall	4.13
SignLevel	6.70

Test Statistics[a]

N	23.0000
Chi-Square	60.0435
df	7.0000
Asymp. Sig.	.0000

a. Friedman Test

A Friedman Test was run on the answers to this question and the test results are demonstrated in Table 32, there was a statistically significant difference in the importance of accessible facilities that people with mobility difficulties considered when they plan their trip. $\chi2(2) = 60.044$, $p = 0.000$. The importance ranking is followed by the median of ranking scores for each facility, and this result will be used for the inference rule of ontology reasoning in the next chapter. Based on the classification of the people with mobility difficulties presented in Table 25, the accessibility requirements for each category for the public transport are demonstrated in Table 33. The result is based on the analysis results of the online questionnaire. The detail of the statistical hypothesis tests are demonstrated in Appendix B.

Table 33: The Accessibility Requirements for the Public Transportation

Category	**NNL**	**NNS**	**NNWM**	**NNWP**	**NLL**	**NLS**	**NLWM**	**NLWP**	**NSL**	**NSS**	**NSWM**	**NSWP**
Sign Level												
Ramp to Transportation		x	x	x		x	x	x	x	x	x	x
Accessible Toilet												
Accessible Table												
Personal Assistance												
Accessible Interchange				x				x	x	x	x	x
Accessible Ticket Machine												
Accessible Ticket Hall				x				x	x	x	x	x
Category	**UNL**	**UNS**	**UNWM**	**UNWP**	**ULL**	**ULS**	**ULWM**	**ULWP**	**NSL**	**NSS**	**NSWM**	**NSWP**
Sign Level												
Ramp to Transportation	x	x	x	x	x	x	x	x	x	x	x	x
Accessible Toilet												
Accessible Table												
Personal Assistance												
Accessible Interchange				x				x	x	x	x	x
Accessible Ticket Machine												
Accessible Ticket Hall				x				x	x	x	x	x

6.5 Ontologies for Accessible Travelling

In the Semantic Web, the ontology is the formal, explicit specification of a shared conceptualization [45]. With the existence of a shared conceptualization, the ontology should be widely reused. In this research, it is difficult to find a one-size-fits-all ontology to model the knowledge of accessible travelling domains for people with mobility difficulties.

Table 34: Ontologies for Accessible Travelling Domain

Core Ontologies	
Ontology	Namespace
FOAF	http://xmlns.com/foaf/0.1/
geo	http://www.w3.org/2003/01/geo/wgs84_pos#
SKOS	http://www.w3.org/2004/02/skos/core#
Schema	http://schema.org/
Places Ontology	http://purl.org/ontology/places#
Spatial Relations Ontology	https://www.ordnancesurvey.co.uk/docs/ontologies/spatialrelations.owl
Constructed Ontologies	
Ontology	Namespace
MODO (Mobility Difficulty Ontology)	http://purl.org/net/ontology/modo#
PACO (Place Accessibility Ontology)	http://purl.org/net/ontology/paco#
TACO (Transport Accessibility Ontology)	http://purl.org/net/ontology/taco#

Therefore, as demonstrated in Table 34, there is a list of core shared vocabularies and ontologies involved in the ontologies for accessible travelling domains. FOAF ontology vocabulary is the core vocabulary to linking people and information using the Web. The Geo Ontology is a basic RDF vocabulary that provides the WGS84 reference datum to represent the latitude and longitude of the spatially-located things. And SKOS provides a common data model for sharing the linking of basic structure and content of concept schemes on the Semantic Web. The Schema.org is an initiative launched by search engine companies to create and share a common set of structured metadata on the Web. Places Ontology is a lightweight ontology for describing the places of geographic interest. Spatial Relations Ontology is an ontology describing basic spatial relations proposed by Ordnance Survey.

There some contracted ontologies introduced in order to represent the knowledge of accessible travel domain. The MODO (Mobility Difficulty Ontology) is an ontology designed to model the category of people with mobility limitations in the accessible travel domain. PACO (Place Accessibility Ontology) is the ontology designed to model the accessibility facilities and services of the built environment in physical places. TACO (Transport Accessibility Ontology) is the ontology designed to model the accessibility facilities and services of public transport in the accessible travel domain. The following subsections will demonstrate detailed information on these ontologies.

6.5.1 Mobility Difficulty Ontology (MODO)

As mentioned in Section 6.1, there is a discussion about the reasons to create a new categorization of limitations and difficulties, combined with the ICF limitation framework and ASK-IT classification. The mobility difficulty ontology is a lightweight ontology that models the categorization of people with mobility limitations and difficulties in accessible travelling domains.

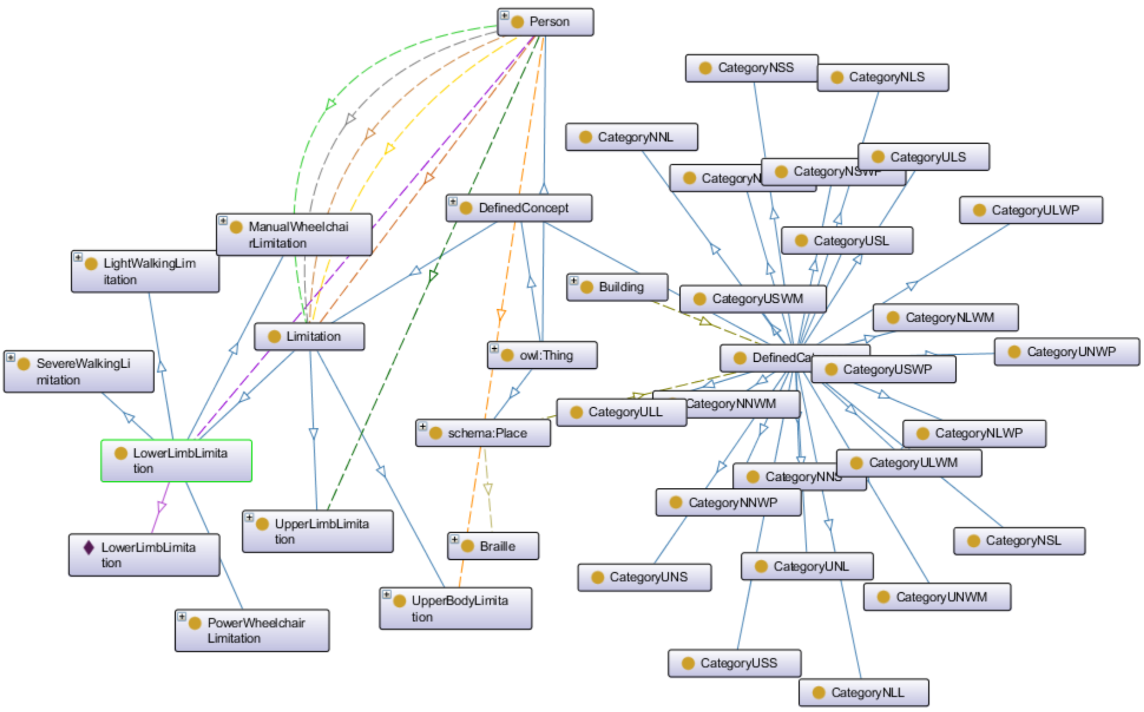


Figure 34: Overview of Ontology Hierarchy for the Categories of Mobility Difficulties

The overview of the ontology hierarchy for the categories of mobility difficulties is demonstrated in Figure 34, which includes the two main classes, namely the class DefinedCategory and the class Limitation. In order to classify the different requirements of the user groups and to generate more accurate decision support results, the ontology of mobility difficulties initially involves the Negative Property Assertion Pattern (NPAs) in the processing of the ontology engineering due to the new features of OWL2. For example, Figure 35 demonstrates the instance named Person_1 in the Person Class, with following annotation comment: Category NNL (No-Upper-Limb-Limitation, No-Upper-Body-Limitation, and Light-Walking-Limitation). There are two negative object property assertions applied in this entity to validate the ontology consistency. However, the built-in OWL2 negative object property assertions are not reasoning based on the Semantic Web Rule Language (SWRL). Another proposed solution is to apply the reasoning rule in the data querying phase, where the SPARQL1.1 supports the negation feature. However, the SAPRQL query plugin in the latest version of the protégé only supports SPARQL1.0.

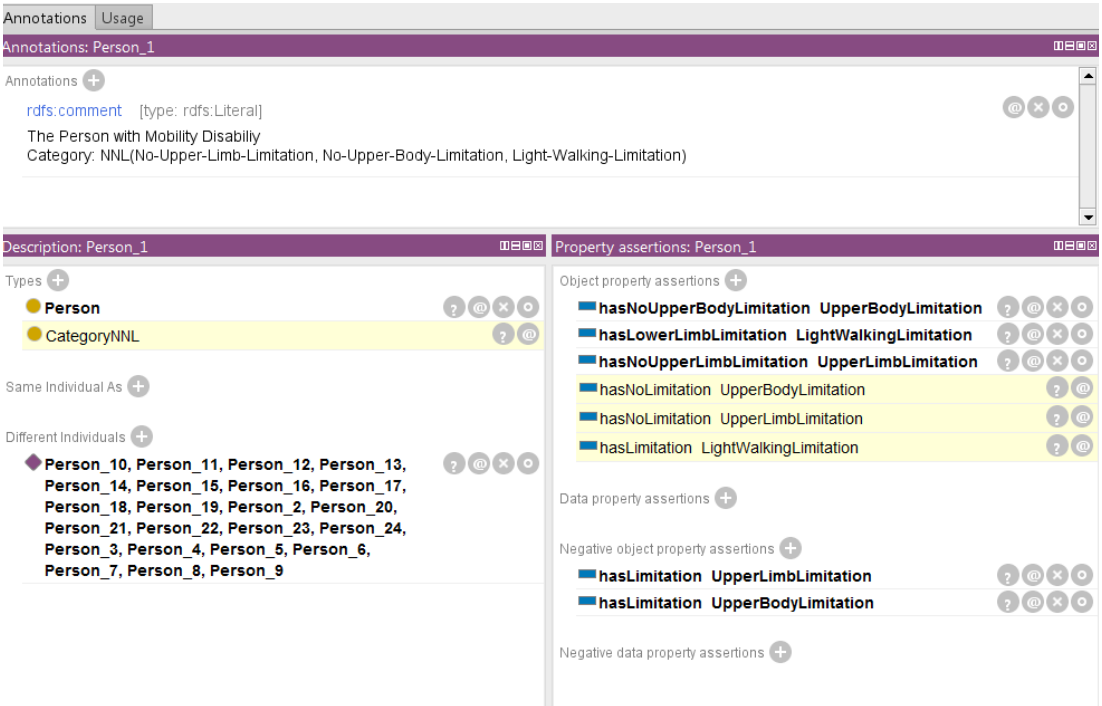


Figure 35: The Example Instance with Negative Property Assertions

Therefore, in order to model the categorization of people with mobility difficulties in the ontology level, the object property assertion with negative meaning is applied to support ontology reasoning. For example, the hasNoUpperBodyLimitation is the object property assertion with negative meaning, which is separate from the property hasUpperBodyLimitation. This example is only to present the reasoning result. The recommended approach to representing the negation in the querying phase will be discussed in the following chapter. Figure 36 above also presents the reasoning result of the instance Person_1, who is defined as the type of CategoryNNL. The reasoning result is generated by HermiT 1.3.8 and Pellet reasoner by applying the SWRL rule language in in Protégé 5.0. However, the SWRL rules are not working with the reasoner FaCT++ 1.65 in Protégé 5.0. The following code is the example SWRL rule syntax to infer the CategoryNNL:

```
Person(?p),hasNoUpperLimbLimitation(?p,?ull),
UpperLimbLimitation(?ull), hasNoUpperBodyLimitation(?p,?ubl),
UpperBodyLimitation(?ubl),
hasLowerLimbLimitation(?p,?lowerLimbLimitation),
LightWalkingLimitation(?lowerLimbLimitation) → CategoryNNL(?p)
```

However, due to the open world assumption, another approach is proposed in the SWRL document to represent the negative property without the support of Negative as Failure (NSF)[36]. The recommended approach is to use the following syntax:

```
Person(?p) ^ (hasCar = 0)(?p) -> CarlessPerson(?p)
```

Therefore, this approach is applied in the ontology to represent the reasoning rule of mobility categorisation with the following rule syntax. However, this approach is not working in the reasoner HermiT 1.3.8 and Pellet in Protégé 5.0. The full description of reasoning rules for mobility categorisation in MODO is presented in Appendix C.

```
Person(?p) ^ (hasUpperLimbLimitation = 0)(?p) ^
(hasUpperBodyLimitation = 0)(?p)^ hasLowerLimbLimitation(?p, ?lll),
LightWalkingLimitation(?lll)  -> CategoryNNL(?p)
```

6.5.2 Place Accessibility Ontology (PACO)

This section presents the Place Accessibility Ontology (PACO) for describing the accessible facility and service of physical places and the built environment. There is a list of existing ontologies for describing the places, buildings and spatial things.

- The Places Ontology[37] is a simple lightweight ontology for describing places of geographic interest.
    i. Namespace: http://purl.org/ontology/places#
    ii. DL expressivity: AL (D)
    iii. A simple lightweight ontology for describing places of geographic interest
    iv. Currently 404 Not Found

[36] https://github.com/protegeproject/swrlapi/wiki/SWRLLanguageFAQ#Does_SWRL_support_Negation_as_Failure

[37] http://vocab.org/places/schema.html

- ifcOwl Ontology is proposed by W3C Community Group on Linked Building Data[38]
  i. namespace: http://linkedbuildingdata.net/resources/IFC4_ADD1.owl
  ii. DL expressivity: ALUHOIQ(D)
  iii. Standardized Building Information Modelling (BIM) Ontology
- LinkedGeoData[39] ontology has been derived from concepts defined by Open Street Map
  i. Namespace: http://linkedgeodata.org/ontology
  ii. DL expressivity: unknown
  iii. Publish the Open Street Map data as the Linked Data

The Places Ontology is a lightweight ontology for describing the geographic places. In this research, the main purpose of using the ontology is to formally describe the accessible facilities and services of a physical place. Therefore, the Places Ontology is only reusable for describing the places of geographic interest.

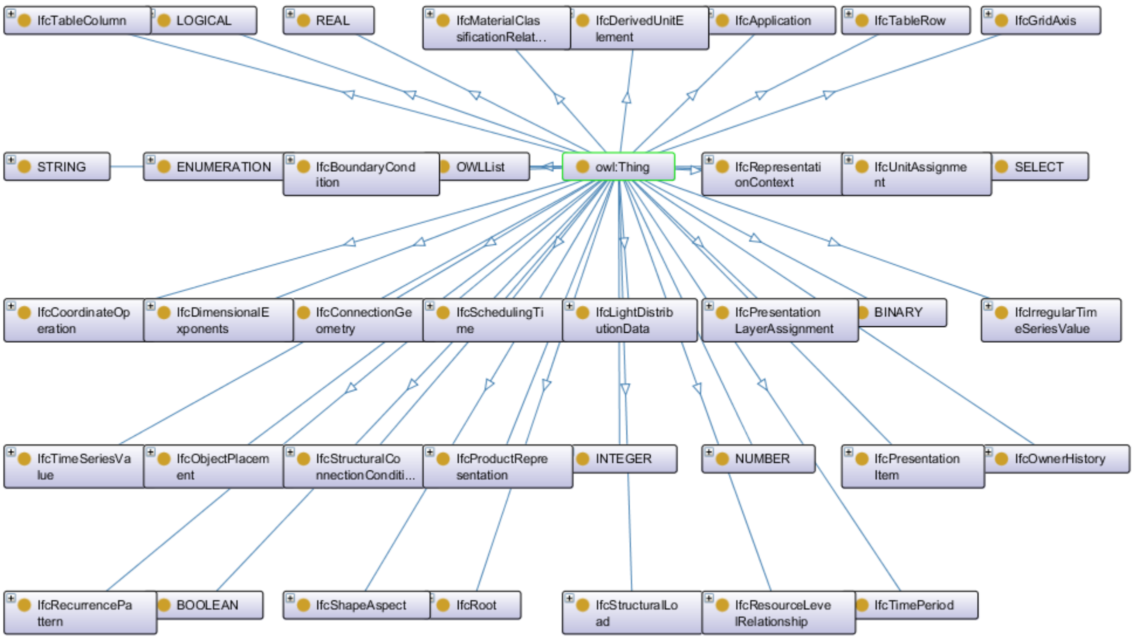


Figure 36: The ifcOWL Ontology Overview

As demonstrated in Figure 36, the ifcOWL is a formal description of the BIM (Building Information Management) information, which is extremely complex for the usage of accessible travelling domains. However, the PACO ontology would extend the linking to the ifcOWL ontology in future work. The LinkedGeoData is the Linked Data version of Open Street Map. In the experiments

[38] https://www.w3.org/community/lbd/
[39] http://linkedgeodata.org/ontology

demonstrated in the previous chapter, most of the open accessibility data is captured from Wheelmap, which is based on Open Street Map. Therefore, the PACO ontology extended the LinkedGeoData ontology to add more vocabularies to describe the accessibility information of facilities and services in the built environment. In the PACO ontology, the place class is the major class, which is equivalent to schema:Place using the object property owl:sameAs. The building class is the subclass of the Class geo:SpatialThing. The example syntax of the ontology could be described as follows:

```
spatialrelations:contains(Place, Building)
spatialrelations:within(Building, Place)
```

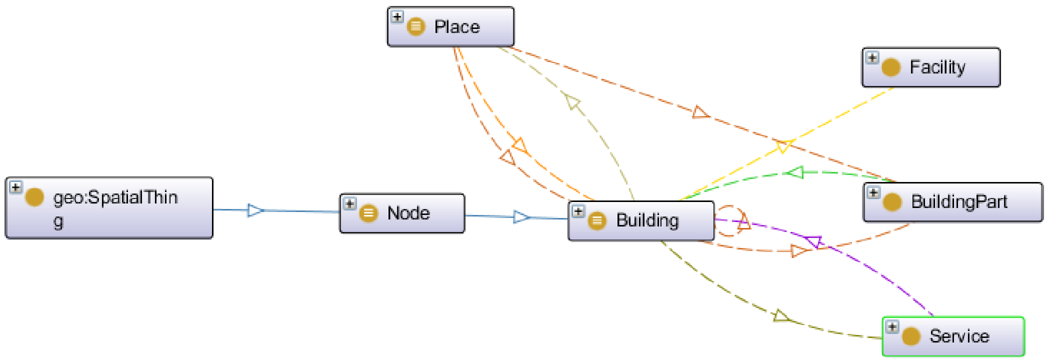


Figure 37: The Top Classes in Place Accessibility Ontology

There are two primary classes to describe the accessibility facilities and service, the facility class and the service class, which are presented in Figure 37 with the following syntax:

```
spatialrelations:contains (Building, BuildingPart)
rdfs:subClassOf (Entrance, BuildingPart)
rdfs:subClassOf(Floor, BuildingPart)
rdfs:subClassOf(Room, BuildingPart)
spatialrelations:contains (Building, BuildingPart) ^ rdfs:subClassOf
(Entrance, BuildingPart)
-> spatialrelations:contains (Building, Entrance)
spatialrelations:contains (Building, BuildingPart) ^ rdfs:subClassOf(Floor,
BuildingPart)
-> spatialrelations:contains (Building, Floor)
spatialrelations:contains (Building, BuildingPart) ^ rdfs:subClassOf(Room,
BuildingPart)
-> spatialrelations:contains (Building, Room)
```

As described in Figure 38, the Building Part class includes the basic classes of buildings, namely the Floor, Room, and Entrance. The Room class includes Reception, Changing Room, Waiting

Room, Meeting Point and Toilet. And the Entrance class includes Accessible Entrance, Inaccessible Entrance, MainEntrance, and OtherEntrance.

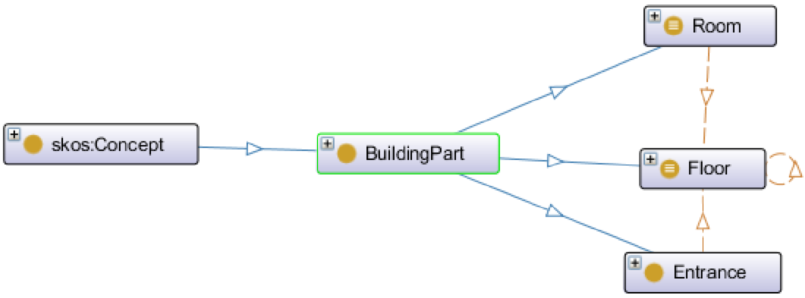


Figure 38: The Subclasses of Building Part Class in PACO Ontology

Moreover, Figure 39 also demonstrates the subclasses of the facility class and service class. The facility class includes some main facility classes mentioned in the requirements analysis section, such as Accessible Table, Lift, Parking, Door, Ramp(to the Building), Signage, Ticket Gate, Ticket Hall, Ticket Machine and some additional classes mentioned in other datasets, such as Vending Machine, Escalator, Pay Phone, and Seats. The subclass of the service class includes Personal Assistance (owl:sameAs Staff Help) and other additional classes including Braille, Staff with Disability Awareness, Hearing Enhancement System, Help Point, Helpline, Large Print, and Sign Language. The Transport Accessibility Ontology described in the following section also uses the Place Accessibility Ontology to describe the vocabularies of accessibility facilities and services in bus stops, tube stations, train stations and other terminals.

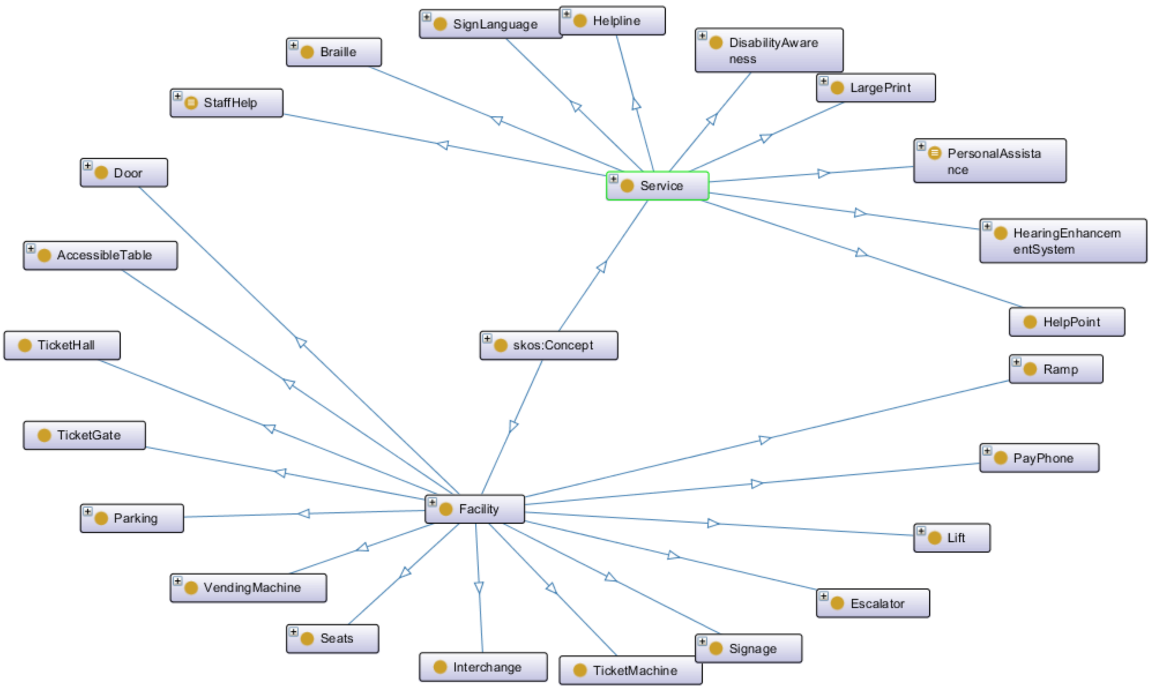


Figure 39: The Subclasses of Facility and Service Class

6.5.3 Transport Accessibility Ontology (TACO)

This section demonstrates the Transport Accessibility Ontology (TACO), which is built on top of LinkedGTFS[40] vocabularies and extends the ontology to enrich the vocabularies of accessibility facilities and services in public transport domains. LinkedGTFS (The Linked General Transit Feed Specification) is the mapping of the GTFS (General Transit Feed Specification) towards RDF. GTFS is an open standard for publishing the transport data proposed by Google, and the LinkedGTFS is developed by the open transport working group, one of the featured working groups under the Open Knowledge Foundation. The overview of the LinkedGTFS vocabularies is presented in Figure 40. The vocabularies of LinkedGTFS are mainly following the standard terminology and relationship of each terminology in GTFS.

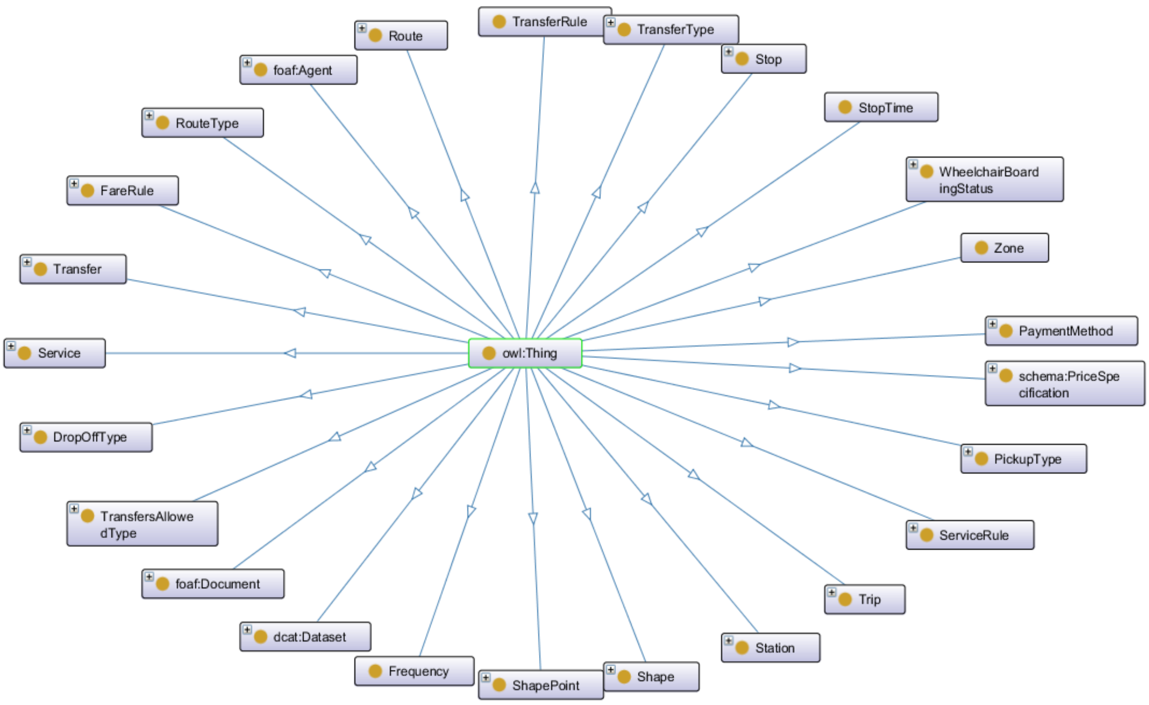


Figure 40: Vocabularies of the LinkedGTFS

As the class hierarchy illustrated in Figure 41, LinkedGTFS uses the only WheelchairBoardingStatus class to describe the wheelchair boarding information. There are three different instances within this class, namely CheckParentStation, NoWheelchairAccessible, WheelchairAcceibsle. Therefore, the TACO ontology will provide the vocabularies of accessible facilities and service in public transport domains by reusing and extending the LinkedGTFS ontology. The TACO ontology would also directly import the PACO ontology to describe the physical place accessibility information in transport scenarios, such as the stations, stops, and terminals.

[40] http://vocab.gtfs.org/terms#

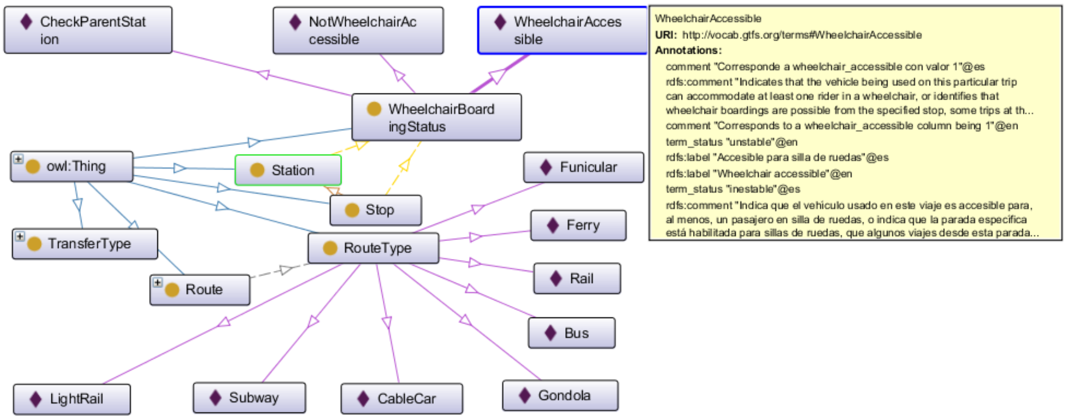


Figure 41: Class Wheelchair Boarding in the LinkedGTFS

The overview class hierarchy of the TACO ontology is demonstrated in Figure 42. The service class is the service related to the public transport when the passenger is on board as well as the facility class. This ontology is reusing the PACO ontology to describe the accessibility facilities and service in stations, stops and terminals. The Facility class is designed to describe the accessibility facilities on board, which includes several sub-classes, namely AccessibleSeat, AccessibleTable and AccessibleToilet. And the Service class includes the PersonalAssistance class to describe the personal assistance on board. In LinkedGTFS ontology, the vocabulary to describe the accessibility information of the public transport is the WheelchairBoardingStatus class. This class includes three individual instances to represent the different status of wheelchair boarding.

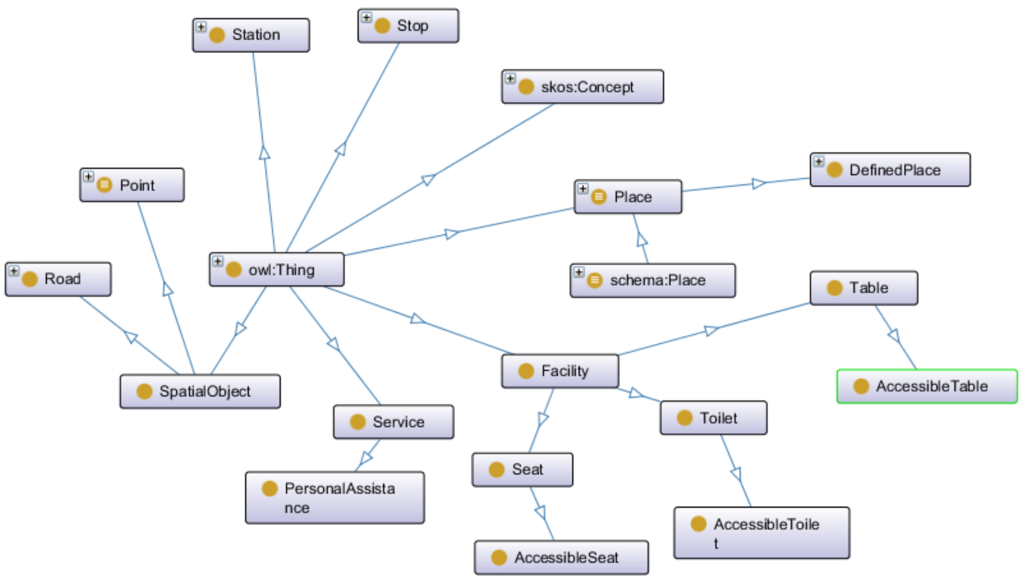


Figure 42: Facility and Service Class in the Transport Accessibility Ontology

The Transport Accessibility Ontology defines the accessibility facilities and services as the class, where the particular facilities could be inserted as the individual instance with object properties and data properties. As a result, it will provide more information about particular facilities or services when users are querying.

6.6 Summary

As a consequence, this chapter primarily demonstrates the study of the accessibility requirements for people with different mobility limitations in the accessible travelling domain. The study of the accessibility requirements is conducted using the online questionnaire. The result of the study is statistically analysed and some of the results will be used as the inference rules in Chapter 8 to conduct the ontology reasoning in the decision support system for accessible travelling. The ontologies for accessible travelling are introduced in this chapter. The ontologies are proposed to address the challenges of urgent needs of standard ontologies in this domain. All these three ontologies are lightweight ontologies to provide the formal vocabularies to model the limitation categorization, and accessibility information of accessible travelling domain. The mobility difficulty ontology (MODO) provides the classification of people with mobility difficulties based on their limitations. The place accessibility ontology (PACO) focuses on the vocabularies to describe the accessibility facilities and services in the built environment. The transport accessibility ontology (TACO) extends both place accessibility ontology and LinkedGTFS vocabularies to provide the domain knowledge of the accessibility facilities and services in public transport. The next chapter will give an introduction of publishing the Linked Open Accessibility Data by using the proposed ontologies.

Chapter 7: Linked Open Accessibility Data

In the previous chapter, three lightweight ontologies are proposed to address the challenges of urgent needs of standard ontologies in this domain. All these three ontologies provide the formal vocabularies to modelling the limitation categorisation and accessibility information of accessible travelling domain. Therefore, this chapter would mainly demonstrate the research of publishing the Open Accessibility Data as Linked Data, and it will also answer the following question:

- RQ1.2: How to use URI naming and referencing to publish the accessibility data in accessible travelling domain?

The main approach to publishing the accessibility data is basically following the Best Practice for Publishing Linked Data[41]. Chapter 5 highlights the issues with the technique used when choosing the rdfstore-js as the triple store in the experiment, such as the performance of data querying, triple indexing and rule-based inference.

Therefore, the experiments of data publishing and maintenance demonstrated in this section are based on the GraphDB powered by the Ontotext[42]. The GraphDB is a semantic graph database that serves organisations to store and manage the semantically enriched data. The GraphDB server[43] in the experiment is running on the virtual server base on the Linux 3.2.0 OS with 2048MB memory. Moreover, the GraphDB performs the reasoning based on forward-chaining. This is done applying the total materialisation strategy, which is the only strategy to provide the scalable reasoning. For the ontology reasoning, there are two principle strategies for rule-based inference, namely forward-chaining and backward-chaining. The forward-chaining method is mainly applying the inference rules to the known facts to generate new facts. The advantage of this method is that it finds the answer for the query quickly because of all the facts that are inferred during the data setup. However, it would also increase the time for data loading as well as space and memory usage. Compared with forward-chaining, there is no inferencing cost at the start-up of the project in the backward-chaining method. It is also less cost in terms of space and memory usage. However, the backward-chaining method is applying the inference rules to the facts during the real-time querying, which is extremely time-consuming for the complex query. The following sections will demonstrate the approaches to publishing the user's preference data, place accessibility data, transport accessibility data as the Linked Data.

---

[41] https://www.w3.org/TR/ld-bp/
[42] http://ontotext.com/
[43] http://www.linkedaccessibility.com

7.1 User Preference as the Linked Data

As demonstrated in the previous chapter of ontologies for accessible travelling, the Mobility Difficulty Ontology (MODO) is mainly modelling and describing the categorisation of users based on the mobility limitations, which enables the user querying with pre-defined features. And the recommended usage of MODO ontology is for internal usage within the decision support system or in a closed system environment. In order to publish the user's preference as the Linked Data, the syntax below is to publish the user instance (modo:Person_1) with following limitations: no upper limb limitation, no upper body limitation and has light walking limitation. Base URI is the URIs chosen for publishing the dataset. Person_1 could be the unique identifier for the entity.

$$PREFIX\ rdf:\ < http://www.w3.org/1999/02/22-rdf-syntax-ns\# >$$
$$PREFIX\ modo:\ < http://purl.org/net/ontology/modo\# >$$
$$PREFIX\ owl:\ < http://www.w3.org/2002/07/owl\# >$$

$$\begin{array}{lll} < modo{:}Person\_1 > & rdf{:}type & modo{:}Person; \\ & rdf{:}type & owl{:}NamedIndividual; \\ modo{:}hasNoUpperLimbLimitation & & modo{:}UpperLimbLimitation; \\ modo{:}hasNoUpperBodyLimitation & & modo{:}UpperBodyLimitation; \\ modo{:}hasLowerLimbLimitation & & modo{:}LightWalkingLimitation. \end{array}$$

Moreover, in order to infer the category of limitations automatically, there are some pre-defined inference rules for category class reasoning. According to the limitations of the person defined in the syntax above, there are a set of inference rules defined to infer the person instance into the corresponding category automatically. The following statement is the customised OW2L-RL ruleset in the GraphDB, which represents the inference rule of the CategoryNNL (No Upper Limb Limitation, No Upper Body Limitation, and Light Walking Limitation).

```
Prefices
{
        rdf   : http://www.w3.org/1999/02/22-rdf-syntax-ns#
        modo  : http://purl.org/net/ontology/modo#
}
Rules
{
      Id:category_nnl
        x <rdf:type> <modo:Person>
        x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
        x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
        x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
        -------------------------------
        x <rdf:type> <modo:CategoryNNL>                                   }
```

As a result, the reasoner engine embed in the GraphDB could apply the forwarding chaining strategy to infer the entity (modo:Person_1) that has the class of CategoryNNL. Figure 43 demonstrates the result after applying the ruleset into the dataset. The triple[44] with the object (modo:CategoryNNL) is the implicit context inferred by the rule engine reasoner. The explicit context is the asserted statement and the implicit context is the inferred statement.

Person_1

Source: http://purl.org/net/ontology/modo#Person_1

subject | predicate | object | context | all

	subject	predicate	object	
1	modo:Person_1	modo:hasLowerLimbLimitation	modo:LightWalkingLimitation	http://www.ontotext.com/explicit
2	modo:Person_1	modo:hasNoUpperBodyLimitation	modo:UpperBodyLimitation	http://www.ontotext.com/explicit
3	modo:Person_1	modo:hasNoUpperLimbLimitation	modo:UpperLimbLimitation	http://www.ontotext.com/explicit
4	modo:Person_1	rdf:type	modo:CategoryNNL	http://www.ontotext.com/implicit
5	modo:Person_1	rdf:type	modo:Person	http://www.ontotext.com/explicit
6	modo:Person_1	rdf:type	owl:NamedIndividual	http://www.ontotext.com/explicit
7	modo:Person_1	rdfs:comment	The Person with Mobility Disabiliy Category: NNL(No-Upper-Limb-Limitation, No-Upper-Body-Limitation, Light-Walking-Limitation)	http://www.ontotext.com/explicit

Figure 43: Person Instance Inferred with OWL2-RL Ruleset

Compared with the approach by applying the rule-based inference when publishing the dataset, the approach using SPARQL querying to insert the ruleset into the triple store is present as follows to provide the update to date rules to infer the answers for the question querying.

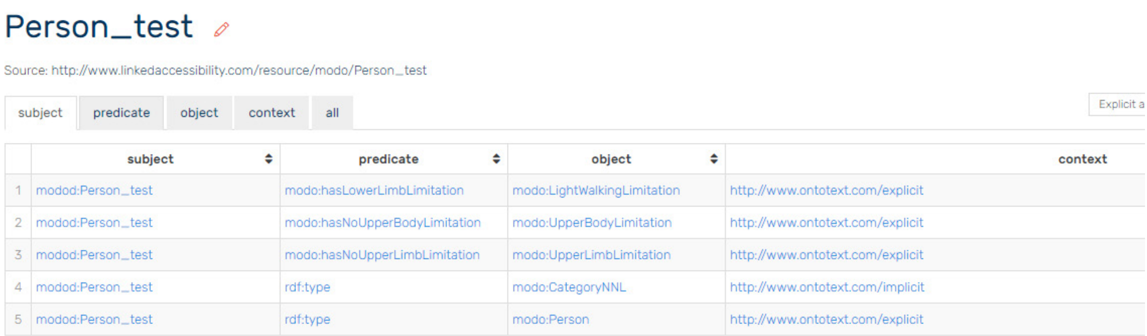
```
PREFIX sys: <http://www.ontotext.com/owlim/system#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX modo: <http://purl.org/net/ontology/modo#>
INSERT DATA {  <:custom>  sys:addRuleset   '''
                    Prefices {
                            rdf:  http://www.w3.org/1999/02/22-rdf-syntax-ns#
                            modo:  http://purl.org/net/ontology/modo#}
                     Axioms {}
                     Rules{
                        Id:category_nnl
                            x <rdf:type> <modo:Person>
                            x  <modo:hasNoUpperLimbLimitation>  <modo:UpperLimbLimitation>
                            x  <modo:hasNoUpperBodyLimitation>  <modo:UpperBodyLimitation>
                            x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
                              -------------------------------
                            x <rdf:type> <modo:CategoryNNL>         }'''
}
```

[44] http://www.linkedaccessibility.com/resource/modo/Person_1

In the scenario of decision support system, the user preference model allows the user to input their personal preference. The user preference could be published as the Linked Data for the usage of system internal, and category of accessibility requirement could be inferred atomically based on the inference rules. The following example is the SPARQL update query used to insert a test user instance with preference into the dataset:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX modo: <http://purl.org/net/ontology/modo#>
PREFIX modod: <http://www.linkedaccessibility.com/resource/modo/>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
INSERT DATA
{
        <modod:Person_test>  rdf:type modo:Person;
                        rdf:type owl:NamedIndividual;
                        modo:hasNoUpperLimbLimitation modo:UpperLimbLimitation;
                        modo:hasNoUpperBodyLimitation modo:UpperBodyLimitation;
                        modo:hasLowerLimbLimitation modo:LightWalkingLimitation.
}
```

This example instance[45] is automatically inferred by the reasoner engine. As presented in Figure 44, the inferred statement modo:CategoryNNL is the implicit context generated by the inference rule.



	subject	predicate	object	context
1	modod:Person_test	modo:hasLowerLimbLimitation	modo:LightWalkingLimitation	http://www.ontotext.com/explicit
2	modod:Person_test	modo:hasNoUpperBodyLimitation	modo:UpperBodyLimitation	http://www.ontotext.com/explicit
3	modod:Person_test	modo:hasNoUpperLimbLimitation	modo:UpperLimbLimitation	http://www.ontotext.com/explicit
4	modod:Person_test	rdf:type	modo:CategoryNNL	http://www.ontotext.com/implicit
5	modod:Person_test	rdf:type	modo:Person	http://www.ontotext.com/explicit

Figure 44: Test User Instance Inference based on OWL2-RL Ruleset

Moreover, the MODO ontology currently is only providing the lightweight vocabularies to describe the mobility difficulty categories based on the social model of disabilities. However, this ontology also provides the opportunities to extend the vocabularies and link to other ontologies

[45] http://www.linkedaccessibility.com/resource/modod/Person_test

based on the medical model of disabilities. For example, the ontology could infer the user with the light walking limitations based on the several medical conditions.

7.2 Accessibility Data of Built Environment as the Linked Data

The Place Accessibility Ontology (PACO) provides the vocabularies to the accessibility information of the built environment. In this section, it would mainly demonstrate how to use the PACO ontology to publish the accessibility data of built environment as the Linked Data. This experiment is running on the GraphDB server, and the repository address is as follows:

http://www.linkedaccessibility.com/repositories/paco

There are some guidelines to publishing the data as the Linked Data followed by the best practice for publishing the Linked Data, such as the stakeholder preparation, dataset selection, data modelling license choose, and URIs for naming. This section would only discuss how to use standard vocabularies to publish the accessibility of the built environment. And these are following proposed steps:

The first step is to publish the data of the place area that building is within. In general, there are multiple buildings within one place area. And the place instance could include the name, geographic information, category and contact, etc. The properties of the place instance could follow the place class in the standard vocabularies such as the schema.org.

The second step is to publish the building data, which includes the name, geographic information, category, organisation and contact, etc. The PACO ontology provides these vocabularies by reusing the other ontologies like the GeoNames ontology, SKOS, Schema.org, and GeoSPARQL. As presented in Figure 45, the place entity (UniversityOfSouthampton) contains the building entity (Building32_University_of_Southampton). And the building entity contains several floor entities.

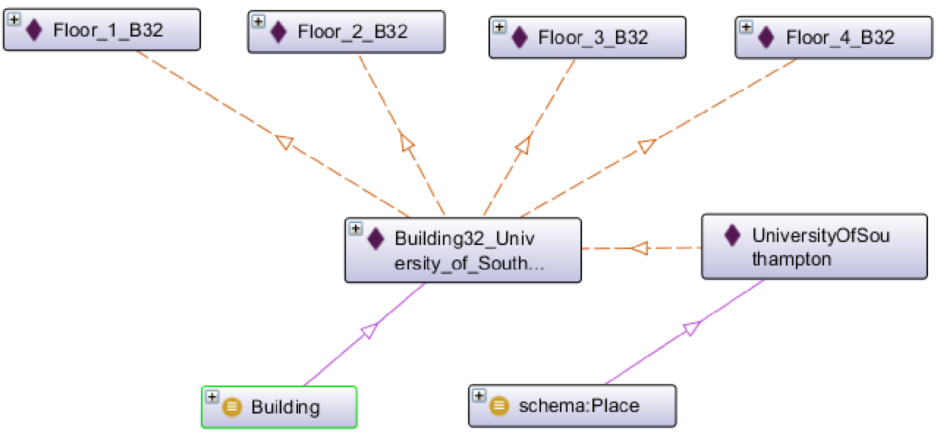


Figure 45: The Example of Floor Instances within the Building Instance

The third step is to publish the accessible facilities and services connecting all floors, such as the lifts and stairs. For example, as stated in Figure 46, the lift entities (NorthLift_B32 and SouthLift_B32) are the lifts within the building entity (Building32_Univeristy_of_Southampton). And all the yellow lines in this figure are the object property:

$$spatialrelations: within$$

Therefore, the lift entity (NorthLift_B32) is within the following entities: floor entity (Floor_2_B32, Floor_1_B32, and Floor_3_B32), while the entity (SouthLift_B32) is within all four floors. Moreover, the lift entity (NorthLift_B32) is indicated as the accessible lift by using the data property with the following statement:

$$<: NorthLift\_B32 > \;\; paco: isAccessible \;\; true\char`^\char`^xsd: Boolean;$$

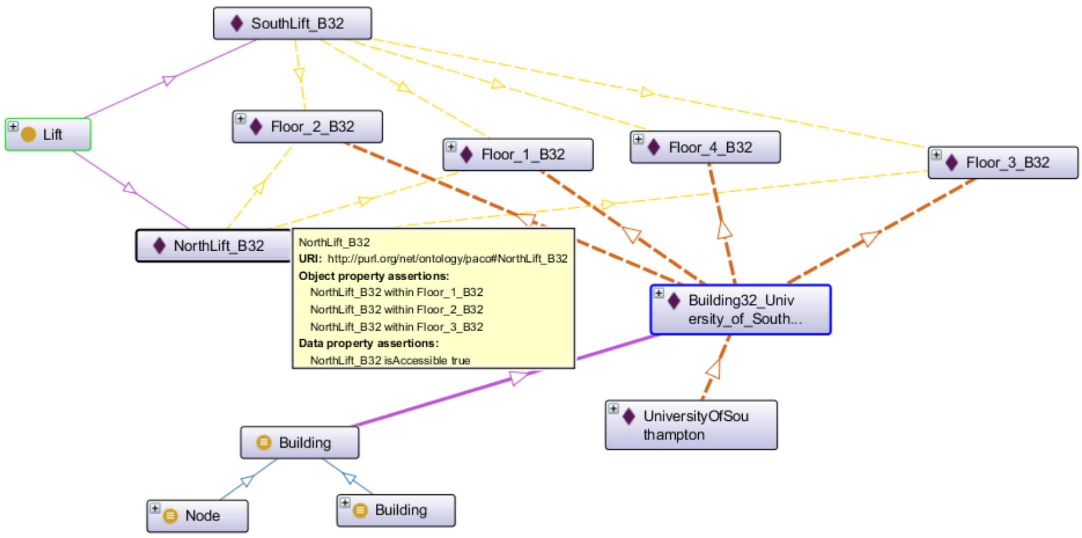


Figure 46: The Lift Instances within the Building Instance

The last step is to publish the rooms, accessible facilities and services within each floor. For example, Figure 47 demonstrates the relationship between the entities, namely rooms, facilities, services and the floors. The statement for the room entity (Room1_Floor1_B32) within the entity (Floor_1_B32) could be represented in the following syntax:

$$<: Room1\_Floor1\_B32 > \;\; rdf: type \;\; < paco: Room >;$$
$$<: Room1\_Floor1\_B32 > \;\; spatialrelations: within \;\; <: Floor1\_B32 >;$$

The statement for the entrance entity (CentralEntrance_B32) within the floor entity (Floor_1_B32) could be represented in the following syntax:

$$<: CentralEntrance\_B32 > \;\; rdf: type \;\; < paco: Entrance >;$$
$$<: CentralEntrance\_B32 > \;\; spatialrelations: within \;\; <: Floor1\_B32 >;$$

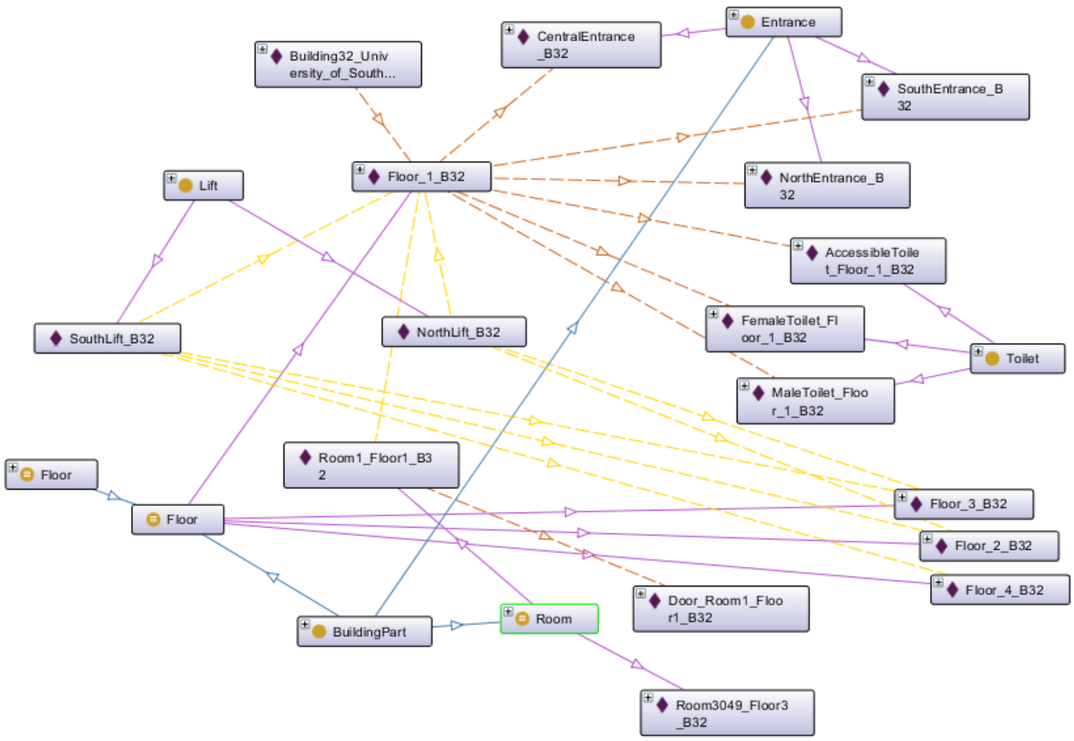
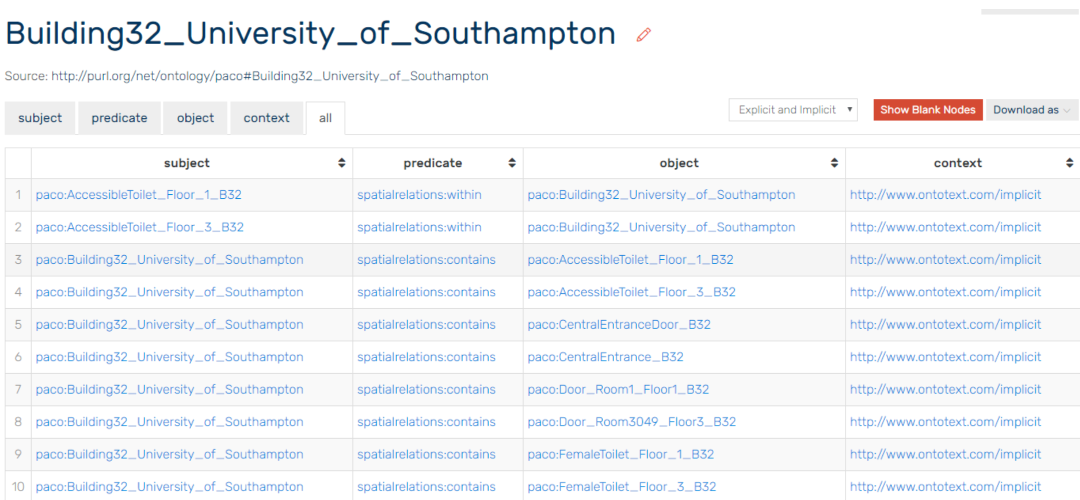


Figure 47: The Relationship of the Rooms, Facilities and Services within the Floor Instance

The door type of the entrance is very important for the people with mobility difficulties. Therefore, there is a statement of the entrance door type represented in the following syntax. It indicates the door type of central entrance in the entity (Building32_Univeristy_of_Southampton) is manual, which might not be accessible for some people with both lower limb and upper limb limitations. And Figure 48 demonstrates the entity (Building32_Univeristy_of_Southampton) in the GraphDB.

$$<:CentralEntrance\_B32>\ paco:contains\ <:CenralEntranceDoor\_B32>$$
$$<:CenralEntranceDoor\_B32>paco:hasDoorType\ <paco:ManualDoorType>$$



Building32_University_of_Southampton

Source: http://purl.org/net/ontology/paco#Building32_University_of_Southampton

subject | predicate | object | context | all

Explicit and Implicit | Show Blank Nodes | Download as

	subject	predicate	object	context
1	paco:AccessibleToilet_Floor_1_B32	spatialrelations:within	paco:Building32_University_of_Southampton	http://www.ontotext.com/implicit
2	paco:AccessibleToilet_Floor_3_B32	spatialrelations:within	paco:Building32_University_of_Southampton	http://www.ontotext.com/implicit
3	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:AccessibleToilet_Floor_1_B32	http://www.ontotext.com/implicit
4	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:AccessibleToilet_Floor_3_B32	http://www.ontotext.com/implicit
5	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:CentralEntranceDoor_B32	http://www.ontotext.com/implicit
6	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:CentralEntrance_B32	http://www.ontotext.com/implicit
7	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:Door_Room1_Floor1_B32	http://www.ontotext.com/implicit
8	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:Door_Room3049_Floor3_B32	http://www.ontotext.com/implicit
9	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:FemaleToilet_Floor_1_B32	http://www.ontotext.com/implicit
10	paco:Building32_University_of_Southampton	spatialrelations:contains	paco:FemaleToilet_Floor_3_B32	http://www.ontotext.com/implicit

Figure 48: The Example Triples of the Building in GraphDB

As a consequence, the PACO ontology provides the vocabularies to describe the basic information of built environment. It primarily provides the vocabularies to represent the accessibility facilities and services within the built environment. This section demonstrates the guidelines and methods to publish the building data as the Linked Data.

7.3 Accessibility Data of Public Transport as the Linked Data

In the previous section, it demonstrated the methods to use the Place Accessibility Ontology (PACO) to publish accessibility information of the built environment as the Linked Data. In this section, the methods to publish the accessibility information of public transport using the PACO and Transport Accessibility Ontology (TACO) are presented. This experiment is also running on the GraphDB server, and the repository address is as follows:

http://www.linkedaccessibility.com/repositories/taco

As described previously, the best practice for publishing the Linked Data is the standard guideline to publish the data as the Linked Data. This section demonstrated how to use standard vocabularies to publish the accessibility information of the public transport. The TACO ontology is reused the Linked GTFS, which provides the standard vocabularies from Google's GTFS schema. The way to publish the transport data and route data is introduced in the Linked Connections[46]. The class (Trip) is representing the journey taken by a vehicle through stops. The class (WheelcahirBoardingStatus) is used to describe the information of wheelchair accessible in both Class Trip and Class Stop in Linked GTFS. In the TACO, it provides additional vocabularies to describe the accessibility information of these two classes (Trip and Stop). Firstly, publishing the accessibility data of the class (Stop) is similar to the steps to publish the built environment data stated in the previous section. The proposed steps are as follows:

The first step to publishing the entity of built environment in the public transport (i.e. stations, terminals or stops). In this experiment, the data of railway station from National Rail Open Data is published as the instance. All the source data is stored in the experiment server [47] in JSON format. The example instance in this section is mapping the data scheme to ontology manually. However, there are some approaches to publish the dataset with a large amount of entities automatically, such as using the schema mapping in D2Rserver, using the OntoRefine in GraphDB or other programmatically approaches. The example train station entity is the Southampton Airport Parkway Station. As indicated in Figure 49, the station entity includes a few data properties, such

[46] http://linkedconnections.org/
[47] http://waisvm-cd8e10.ecs.soton.ac.uk/data/railways.json

as name, description, data identifiers (ID, AtcoCode, and CrsCode, etc.) or geographic information (latitude, longitude, easting, and northing), and data provider. In this phase, there are some core ontologies that provide such vocabularies to describe these metadata. The station entity also contains the other building entities, such as the floors, platforms, and car parks. In this figure, the station entity (SouthamptonAirportParkway) includes the floor entity (Floor_1_SOA), the platform entity (Platform_1_SOA), the platform entity (Platform_2_SOA), and two accessible car parks, namely the entity (AccessibleCarPakr_1_SOA) and the entity (AccessibleCarPakr_2_SOA), separately.

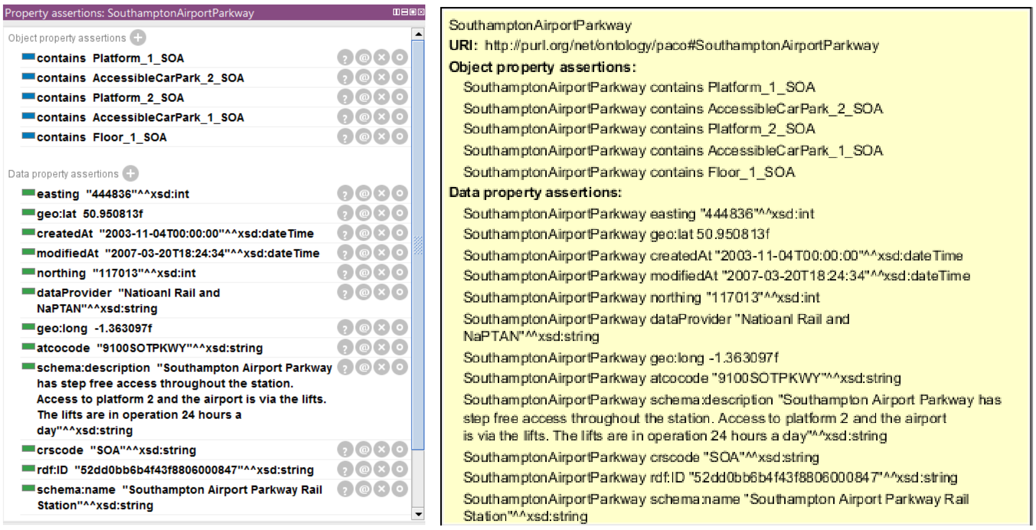


Figure 49: The Example Train Station Instance in Public Transport

The second step is to publish the entities of accessible facilities and services connecting all floors, and platforms, such as the lifts and stairs. In this example, there is only one floor within the station. However, there is a lift on each platform. The syntax could be represented as follows.

$$<: Platform\_1\_SOA > \quad spatialrelations: contains \quad < paco: Lift\_Platform\_1\_SOA >.$$

$$< paco: Lift\_Platform\_1\_SOA > \quad rdf: type \quad < paco: Lift >.$$

$$< paco: Lift\_Platform\_1\_SOA > \quad taco: isAccessible \quad true\hat{}\hat{}xsd: boolean.$$

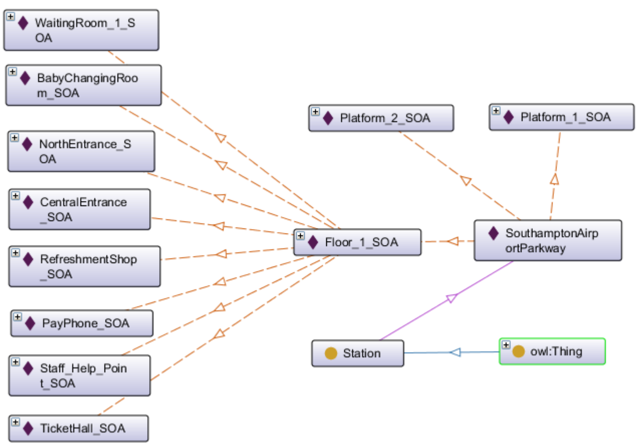
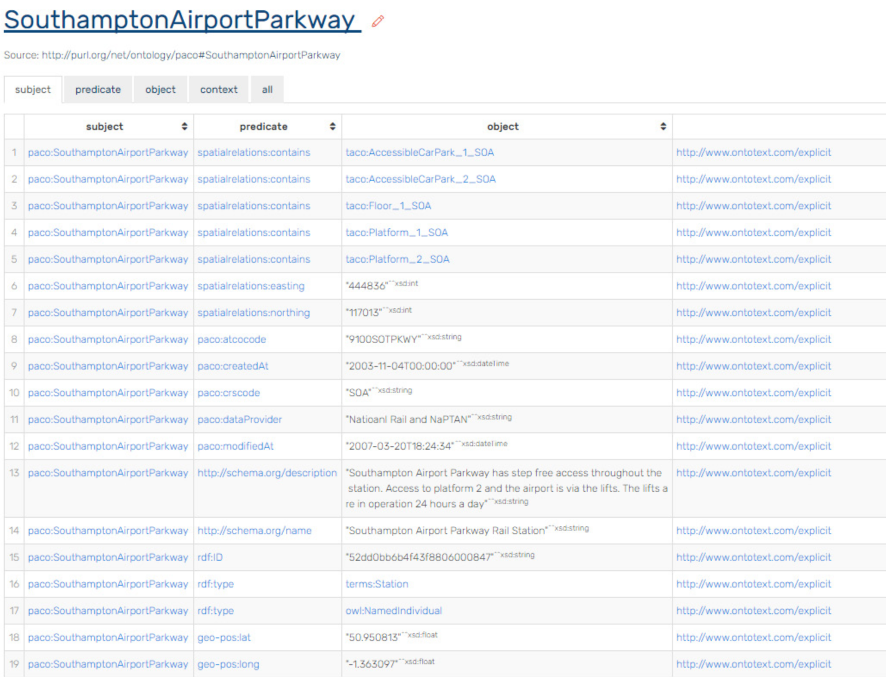


Figure 50: The Example Triples of the Building in GraphDB

The last step is to publish the entities of rooms, accessible facilities and services within each floor and platform. Figure 50 demonstrates the relationships between the room entities (waiting rooms, baby changing rooms), facility entities (accessible toilets, female toilets, and male toilets etc.), service entities (induction loop, staff help etc.) and the entrance entities (main entrance, and other entrances) within the floor instance. The transitive object property could be inferred by the reasoner in the triple store, which could generate new facts of this station. Figure 51 demonstrates the triples of the train station entity (:SouthamptonAirportParkway) published in the GraphDB[48].


SouthamptonAirportParkway

Source: http://purl.org/net/ontology/paco#SouthamptonAirportParkway

subject | predicate | object | context | all

	subject	predicate	object	
1	paco:SouthamptonAirportParkway	spatialrelations:contains	taco:AccessibleCarPark_1_SOA	http://www.ontotext.com/explicit
2	paco:SouthamptonAirportParkway	spatialrelations:contains	taco:AccessibleCarPark_2_SOA	http://www.ontotext.com/explicit
3	paco:SouthamptonAirportParkway	spatialrelations:contains	taco:Floor_1_SOA	http://www.ontotext.com/explicit
4	paco:SouthamptonAirportParkway	spatialrelations:contains	taco:Platform_1_SOA	http://www.ontotext.com/explicit
5	paco:SouthamptonAirportParkway	spatialrelations:contains	taco:Platform_2_SOA	http://www.ontotext.com/explicit
6	paco:SouthamptonAirportParkway	spatialrelations:easting	"444836"^^xsd:int	http://www.ontotext.com/explicit
7	paco:SouthamptonAirportParkway	spatialrelations:northing	"117013"^^xsd:int	http://www.ontotext.com/explicit
8	paco:SouthamptonAirportParkway	paco:atcocode	"9100SOTPKWY"^^xsd:string	http://www.ontotext.com/explicit
9	paco:SouthamptonAirportParkway	paco:createdAt	"2003-11-04T00:00:00"^^xsd:dateTime	http://www.ontotext.com/explicit
10	paco:SouthamptonAirportParkway	paco:crscode	"SOA"^^xsd:string	http://www.ontotext.com/explicit
11	paco:SouthamptonAirportParkway	paco:dataProvider	"Natioanl Rail and NaPTAN"^^xsd:string	http://www.ontotext.com/explicit
12	paco:SouthamptonAirportParkway	paco:modifiedAt	"2007-03-20T18:24:34"^^xsd:dateTime	http://www.ontotext.com/explicit
13	paco:SouthamptonAirportParkway	http://schema.org/description	"Southampton Airport Parkway has step free access throughout the station. Access to platform 2 and the airport is via the lifts. The lifts a re in operation 24 hours a day"^^xsd:string	http://www.ontotext.com/explicit
14	paco:SouthamptonAirportParkway	http://schema.org/name	"Southampton Airport Parkway Rail Station"^^xsd:string	http://www.ontotext.com/explicit
15	paco:SouthamptonAirportParkway	rdf:ID	"52dd0bb6b4f43f8806000847"^^xsd:string	http://www.ontotext.com/explicit
16	paco:SouthamptonAirportParkway	rdf:type	terms:Station	http://www.ontotext.com/explicit
17	paco:SouthamptonAirportParkway	rdf:type	owl:NamedIndividual	http://www.ontotext.com/explicit
18	paco:SouthamptonAirportParkway	geo-pos:lat	"50.950813"^^xsd:float	http://www.ontotext.com/explicit
19	paco:SouthamptonAirportParkway	geo-pos:long	"-1.363097"^^xsd:float	http://www.ontotext.com/explicit

Figure 51: Triples of the Train Station Entity in GraphDB

For publishing the accessibility data of public transport route as the Linked Data, in the Linked GTFS, the class (WheelchairBoardingStatus) is used to describe terminology of the wheelchair accessibility in both Class Trip and Class Stop. The TACO ontology provides additional vocabularies to describe the accessibility information of the class (Route and Station). The relationship between trip entities, route entities, stop entities and station entities is described in the following syntax:

$$<terms:Trip\_example> \quad terms:trip \quad <terms:Trip\_1>.$$

$$<terms:Trip\_example> \quad terms:trip \quad <terms:Trip\_2>.$$

$$<terms:Trip\_1> \quad terms:route \quad <terms:Route\_1>.$$

$$<terms:Route\_1> \quad terms:stop \quad <terms:Stop\_1>.$$

$$<terms:Stop\_1> \quad terms:stop \quad <terms:Station\_1>.$$

[48] http://www.linkedaccessibility.com/resource/paco/SouthamptonAirportParkway

The representation of the accessibility data in stations was already introduced previously. To publish the accessible facilities and services of the public transport route, it could be divided into two different ways, namely adding accessibility data to the route directly or adding accessibility data to the entity of transport means. The method to add accessibility data (services and facilities) to the route directly can be described as follows:

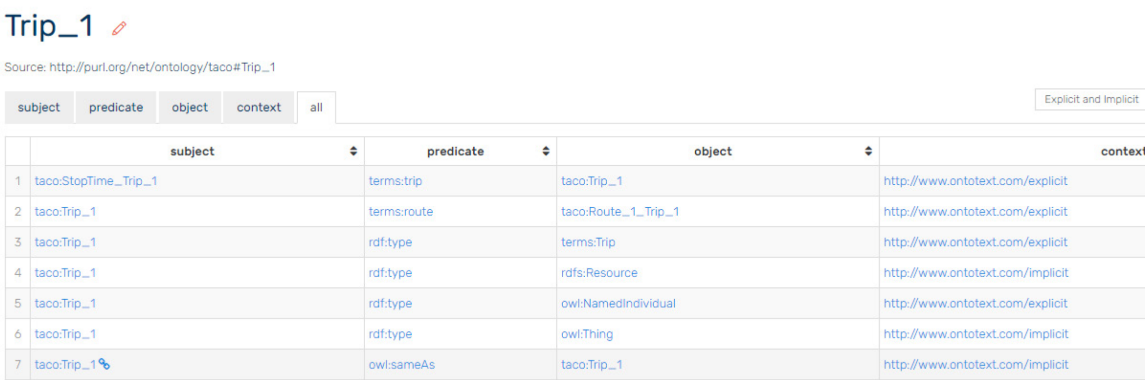
$$< terms{:}Route_1 > \quad spatialrelations{:}contains \quad < taco{:}PersonalAssistacne\_1 >.$$
$$< taco{:}PersonalAssistacne\_1 > \quad rdf{:}type \quad < taco{:}Service > .$$
$$< terms{:}Route_1 > \quad spatialrelations{:}contains \quad < taco{:}AccessibleToilet\_1 >.$$
$$< taco{:}AccessibleToilet\_1 > \quad rdf{:}type \quad < taco{:}AccessibleToilet > .$$
$$< terms{:}Route_1 > \quad spatialrelations{:}contains \quad < taco{:}AccessibleTable\_1 >.$$
$$< taco{:}AccessibleTable\_1 > \quad rdf{:}type \quad < taco{:}AccessibleTable > .$$

And the method to add accessibility data to entity of transport means can be described with the following syntax code:

$$< terms{:}Route_1 > \quad spatialrelations{:}contains \quad < paco{:}Train\_1 >.$$
$$< terms{:}Train\_1 > \quad spatialrelations{:}contains \quad < taco{:}PersonalAssistacne\_1 >.$$
$$< taco{:}PersonalAssistacne\_1 > \quad rdf{:}type \quad < taco{:}Service > .$$
$$< terms{:}Route_1 > \quad spatialrelations{:}contains \quad < taco{:}AccessibleToilet\_1 >.$$
$$< taco{:}AccessibleToilet\_1 > \quad rdf{:}type \quad < taco{:}AccessibleToilet > .$$
$$< terms{:}Route_1 > \quad spatialrelations{:}contains \quad < taco{:}AccessibleTable\_1 >.$$
$$< taco{:}AccessibleTable\_1 > \quad rdf{:}type \quad < taco{:}AccessibleTable > .$$

This experiment is using the method of adding the accessibility data (services and facilities) to the route directly. The example trip entity (terms:Trip_1) is published in the GraphDB. Figure 52 shows the both explicit and implicit statements, which could be accessed on the following address:

$$http://www.linkedaccessibility.com/resource/taco/Trip\_1$$



	subject	predicate	object	context
1	taco:StopTime_Trip_1	terms:trip	taco:Trip_1	http://www.ontotext.com/explicit
2	taco:Trip_1	terms:route	taco:Route_1_Trip_1	http://www.ontotext.com/explicit
3	taco:Trip_1	rdf:type	terms:Trip	http://www.ontotext.com/explicit
4	taco:Trip_1	rdf:type	rdfs:Resource	http://www.ontotext.com/implicit
5	taco:Trip_1	rdf:type	owl:NamedIndividual	http://www.ontotext.com/explicit
6	taco:Trip_1	rdf:type	owl:Thing	http://www.ontotext.com/implicit
7	taco:Trip_1	owl:sameAs	taco:Trip_1	http://www.ontotext.com/implicit

Figure 52: Triples of the Public Transport Trip Entity in GraphDB

7.4 Summary

To summary, this chapter demonstrates the experiments by applying three lightweight ontologies and other core ontologies to publish the open accessibility data as the Linked Data. This chapter introduced the methods to address the URI naming and referencing by following the standard practice guidelines for publishing the Linked Data. In order to generate the Linked Data knowledge base for decision support, there are three different types of datasets introduced in this chapter, namely publishing the user preference data as the Linked Data, built environment data as the Linked Data, and public transport data as the Linked Data.

In the first section of user preference data publishing, it demonstrates the methods using the reasoning rules to infer the category of user difficulties automatically. There is also a discussion around the future works of applying the medical model based ontologies to link to the MODO ontology. The second section describes how to publish the accessibility data of the built environment as the Linked Data. It mainly demonstrates using PACO ontology to publish the accessibility facilities and services within the physical place. The third section introduces the method using PCAO and TACO ontologies to publish the train station entity as the Linked Data. There is a discussion on the approaches for publishing the route accessibility data of public transport.

To conclude, this chapter describes the methods and process to publish the open accessibility data as the Linked Data. In the published Linked Data, there are 2577 railway station entities, 362 tube station entities, 10629 restaurant entities and 6586 place entities with accessibility information within 421666 entities. The next chapter would primarily discuss the accessible travelling decision support based this Linked Open Accessibility Data.

Chapter 8: Linked Data Driven Decision Support

In previous chapters, there are some discussions about the open accessibility data, the ontologies for accessible travelling domain and the data publishing of the Linked Open Accessibility Data. This chapter mainly explores the research of decision support model of the Linked Data Driven Decision support system for accessible travelling. Based on the Linked Open Accessibility Data for accessible travelling, this chapter will answer the following research question:

- RQ2.1: How to apply the decision support algorithms in the Linked Data knowledge base to provide decision support for accessible travelling?

In order to explore this research question, the first section would introduce the scenarios for accessible travelling decision support involved in this research. This section will discuss how to provide the accessible travelling decision support based on the Linked Open Accessibility Data. And the next section mainly explored the question answering over the Linked Data to provide the simple decision support for accessible travelling with personalised categorised of difficulties.

The third section primarily discusses how to apply the decision support algorithms to this decision support model based on the Linked Open Accessibility Data. There were some preliminary discussions stated in Chapter 2 to explore some commonly used methods for the Multi-Criteria Decision Making (MCDM) methods, such as the Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR method, and Analytic Network Process (ANP). This section would demonstrate the strategy to apply the MCDM methods to the Linked Data to provide decision support for accessible travelling. The last section gives a brief summary of this chapter.

8.1 Accessible Travelling Decision Support Scenarios

The accessible trip planning could be modelled as the graph presented in Figure 53. In the graph of route networks for accessible trip planning, the circles are representing the points of place, and both the solid and dotted lines with the arrow between circles are representing the routes with the direction between places. The solid lines present the route of public transport and the dotted lines are representing the non-public transport, such as driving, taxi and walking.

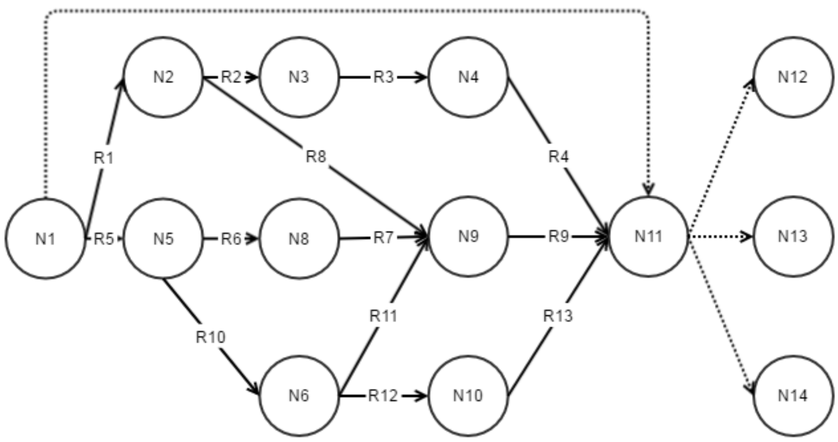


Figure 53: The Graph of Route Network for Route Planning

In this research, there are two primary scenarios explored to support users to make decisions for accessible trip planning. One of decision support scenarios for accessible trip planning is to provide users with the decision support to determine whether the place is accessible and how accessible based on their personal disabilities preference. For example, this scenario could be described as follows:

> *The user with mobility difficulties wants to plan a trip to visit the place (N11). The user could go directly from N1 to N11 regardless the route accessibility (i.e. by taxi). What the user wants to know is that whether the Point of Place (N11) is accessible for the user as well as the surround places (N12, N13 and N14). Then the user could make decisions based on the information provided by the decision support model.*

Another decision support scenario of accessible trip planning is to provide users with the decision support to determine whether routes are accessible for the users and how accessible based on their personal disabilities preference, which could be described as follows:

> *The user with mobility difficulties wants to plan a trip to visit the place (N11) from Place (N1). There are some routes generated by the route planning services regardless the accessibility requirements (i.e. shortest path, quickest path). What the user wants to know*

whether the route is the accessible route based on the user preference. Then the user could make decisions based on the route accessibility information provided decision support model.

Therefore, the following sections in this chapter would mainly demonstrate how the decision support model in the proposed model of Linked Data driven DDS could provide the decision support for accessible trip planning. There are several approaches applying the Linked Open Accessibility Data to the decision support model, namely using the query and inference engine without decision support algorithms; applying the algorithms to the inference rules; applying algorithms to the querying and applying algorithms to the query result. The next section will demonstrate the straightforward approach to using the query and inference engine as a question answering system to provide decision support for accessible travelling.

8.2 Decision Support with Question Answering

As described in Chapter 2, there are some advantages to using the Linked Data as the knowledge base for decision support system, namely the real-time reasoning, automatic inference, and interlinking to other resources. These advantages could empower the approach to apply the question answering (QA) as the decision support model to provide the decision support for accessible trip planning. The major task of the QA system is to represent the user's information need expressed in natural language in relation to the data that is required [98]. However, this section will only demonstrate how to use the query and inference engine to gather the accessibility information based on the users' preference to provide decision support. There are a few questions illustrated in the following examples to demonstrate how the question answering over the Linked Data to provide decision support for accessible trip planning. The example questions and answers are based on the example data for validation purpose, which is not reflecting the real accessibility data. These questions are mainly designed to examine the dataset in four aspects, namely aggregating function, comparison, superlative and temporal reasoning [98], which are presenting as follows:

1. Ask whether the particular accessible facilities or services exist?
2. Count the number of the accessible facilities or services asked by the user.
3. Ask the particular facilities or service that user could not access.
4. Ask whether the particular facilities or services are accessible based on user's preference?
5. Ask whether the place is accessible based on user's mobility limitations?
6. Automatic inferring the limitation category based on user's limitation.
7. Ask whether the place is accessible based on pre-defined mobility category?

Question 1: Is there any accessible entrance in the Building 32, University of Southampton?

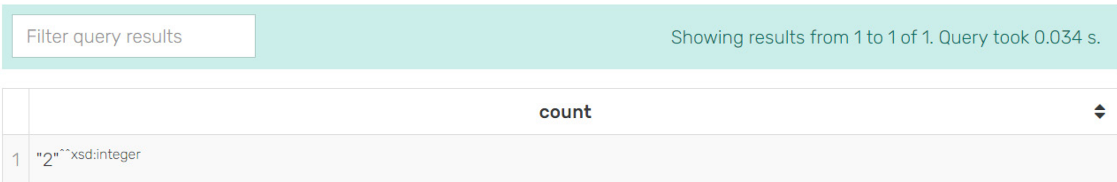
```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
ASK WHERE {
        paco:Building32_University_of_Southampton spatialrelations:contains ?o.
        ?o rdf:type paco:AccessibleEntrance.
        ?s rdf:type paco:Building.
}
```

Yes, there is an accessible entrance in the Building 32.

Question 2: Count the number of accessible toilets in the Building 32.

```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT (COUNT(*) AS ?count) WHERE {
        paco:Building32_University_of_Southampton spatialrelations:contains ?floor.
        ?toilet rdf:type paco:AccessibleToilet.
        ?toilet spatialrelations:within ?floor.
        ?floor rdf:type paco:Floor.
}
```

There are 2 accessible toilets in the Building 32.



Question 3: In Building 32, Can I access to all the floors with the accessible lift?

```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT  ?s  ?o  ?f   WHERE {
                ?s spatialrelations:contains ?o.
                ?s spatialrelations:contains ?f.
                ?o rdf:type paco:AccessibleLift.
                ?s rdf:type paco:Building.
                ?f rdf:type paco:Floor.
                FILTER NOT EXISTS { ?o spatialrelations:within ?f.}
}
```

There is no access for the accessible lift to the floor 4 in Building 32.

Filter query results

Showing results from 1 to 1 of 1. Query took 0.07 s.

	s	o	f
1	paco:Building32_University_of_Southampton	paco:NorthLift_B32	paco:Floor_4_B32

Question 4: I need a wider door (wider than 1300 mm) to access the entrance with a Sensor Door, which entrances I could access in Building 32.

```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT * WHERE {
        paco:Building32_University_of_Southampton spatialrelations:contains ?entrance.
        ?entrance rdf:type paco:Entrance.
        ?entrance spatialrelations:contains ?door.
        ?door  paco:hasDoorType paco:SensorDoorType.
        ?door paco:hasDoorWide ?doorwide.
        Filter (?doorwide > "1300"^^xsd:integer).
}
```

The result indicated that the user could access the entrance NorthEntrance and SouthEntrance, each of them has 2100 mm wide.

Filter query results

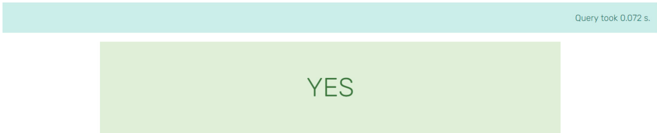
Showing results from 1 to 2 of 2. Query took 0.089 s.

	entrance	door	doorwide
1	paco:NorthEntrance_B32	paco:NorthEntranceDoor_B32	"2100"^^xsd:integer
2	paco:SouthEntrance_B32	paco:SouthEntranceDoor_B32	"2100"^^xsd:integer

Question 5: I must need the accessible entrance, accessible toilet, and accessible lift when I am accessing to the Building 32.

```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
ASK WHERE {
paco:Building32_University_of_Southampton    spatialrelations:contains    ?entrance;
                                              spatialrelations:contains ?lift;
                                              spatialrelations:contains ?accessibletoliet;
                                              spatialrelations:contains ?floor.
                    ?entrance rdf:type paco:AccessibleEntrance.
                    ?accessibletoliet rdf:type paco:AccessibleToilet.
                    ?lift rdf:type paco:AccessibleLift.
                    ?floor spatialrelations:contains ?lift.
}
```

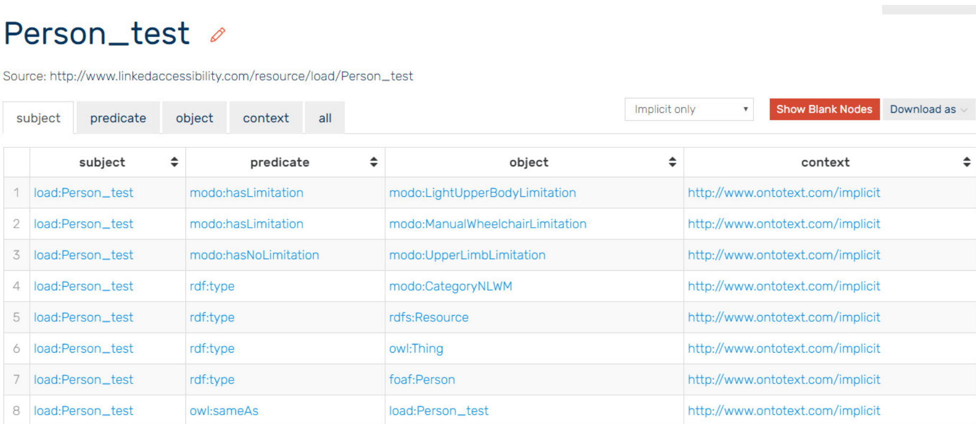
Yes, the Building 32 is accessible for the user who needs the accessible entrance, accessible toilet, and accessible lift



Question 6: What the category the user belongs to with no upper limb limitation, light upper body limitation, and using the manual wheelchair (Category NLWM)?

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX modo: <http://purl.org/net/ontology/modo#>
INSERT DATA
{ <http://www.linkedaccessibility.com/resource/load/Person_test> rdf:type modo:Person;
        modo:hasNoUpperLimbLimitation modo:UpperLimbLimitation;
        modo:hasUpperBodyLimitation modo:LightUpperBodyLimitation;
        modo:hasLowerLimbLimitation modo:ManualWheelchairLimitation.
}
```

The person entity is inferred as the entity has the type of CategoryNLWM automatically.



	subject	predicate	object	context
1	load:Person_test	modo:hasLimitation	modo:LightUpperBodyLimitation	http://www.ontotext.com/implicit
2	load:Person_test	modo:hasLimitation	modo:ManualWheelchairLimitation	http://www.ontotext.com/implicit
3	load:Person_test	modo:hasNoLimitation	modo:UpperLimbLimitation	http://www.ontotext.com/implicit
4	load:Person_test	rdf:type	modo:CategoryNLWM	http://www.ontotext.com/implicit
5	load:Person_test	rdf:type	rdfs:Resource	http://www.ontotext.com/implicit
6	load:Person_test	rdf:type	owl:Thing	http://www.ontotext.com/implicit
7	load:Person_test	rdf:type	foaf:Person	http://www.ontotext.com/implicit
8	load:Person_test	owl:sameAs	load:Person_test	http://www.ontotext.com/implicit

Question 7: Is the Building 32 accessible for the user with no upper limb limitation, light upper body limitation, and using manual wheelchair (Category NLWM)?

```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX modo: <http://purl.org/net/ontology/modo#>
SELECT * WHERE {
        paco:Building32_University_of_Southampton paco:isPlaceAccessible ?category.
         ?p rdf:type modo:Person;
         modo:hasNoUpperLimbLimitation modo:UpperLimbLimitation;
        modo:hasUpperBodyLimitation modo:LightUpperBodyLimitation;
        modo:hasLowerLimbLimitation modo:ManualWheelchairLimitation.
         ?p rdf:type ?category.
}
```

As demonstrated from the result that the entity (load:Person_test) is the user with categoryNLWM and the entity (Building 32) is accessible for the user with categoryNLWM based on the accessibility requirements stated in Table 29.

Filter query results — Showing results from 1 to 2 of 2. Query took 0.068 s.

	category	p
1	modo:CategoryNLWM	modo:Person_7
2	modo:CategoryNLWM	load:Person_test

In summary, this section demonstrates the approach to use the SPARQL query and inference engine as a simple question answering system to provide decision support for accessible trip planning. The results of example questions above demonstrate that this approach would provide the inference result to support users to make decision for the accessible trip planning. The next section will discuss the research of applying algorithms to the decision support model based on the Linked Open Accessibility Data.

8.3 Decision Support Algorithms with the Linked Data

Compared with the approach described above, there are other three approaches to combine the decision support algorithms to the Linked Data, namely the applying the decision support algorithms to the inference rules (forward-chaining), applying algorithms to the querying (backward-chaining) and applying algorithms to the query result. The advantage of the forward-chaining method is that it finds the answer for the query quickly, but it would also increase the time for data loading and additional usage of space and memory. The backward-chaining method is applied the inference rules to the facts during the real-time querying, which is less cost for space and memory usage as well as no inference cost for the data loading. But it is extremely time consuming for the complex query. However, there is no difference in applying algorithms to the query result in the Linked Data Driven DDSs than using the algorithms in traditional DDSs.

The problem of Linked Data-driven decision support for accessible travelling would be divided into the problem to rank the candidate trips to help users to decide which trip to choose based on the accessible facilities and services and user preference. Figure 54 illustrates the example of trip planning from Place x to Place y. There are three candidate routes generated by the standard route planning service without any accessibility constraints, namely Trip A, Trip B and Trip C. Each trip is represented as the group of triples in the Linked Data. For example, the following syntax represents the triple pattern of the trip entity Trip A, which includes the place entity (Place A and Place B) and the route entity (Route A). Each entity also includes the entities of accessible facilities and services.

PREFIX rdf: < http://www.w3.org/1999/02/22 − rdf − syntax − ns# >
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX taco: <http://purl.org/net/ontology/taco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX load: < http://www.linkedaccessibility.com/resource/load/>

load: RouteA rdf: type taoc: Route;
spatialrelations: contains load: ToiletBuildingB;
spatialrelations: contains load: InterchangeRouteA;
spatialrelations: contains load: RampAccessRouteA.
load: PlaceA rdf: type paco: Place;
spatialrelations: contains load: BuildingA.
load: PlaceB rdf: type paco: Place;
spatialrelations: contains load: BuildingB.
load: BuildingA rdf: type paco: Building;
spatialrelations: contains load: ToiletBuildingA;
spatialrelations: contains load: LiftBuildingA;
spatialrelations: contains load: EntranceBuildingA;
load: BuildingB rdf: type paco: Building;
spatialrelations: contains load: ToiletBuildingB;
spatialrelations: contains load: EntranceBuildingB;
spatialrelations: contains load: CarParkBuildingB;
load: TripA rdf: type taco: Trip;
spatialrelations: contains load: RouteA;
patialrelations: contains load: PlaceA;
patialrelations: contains load: PlaceB;

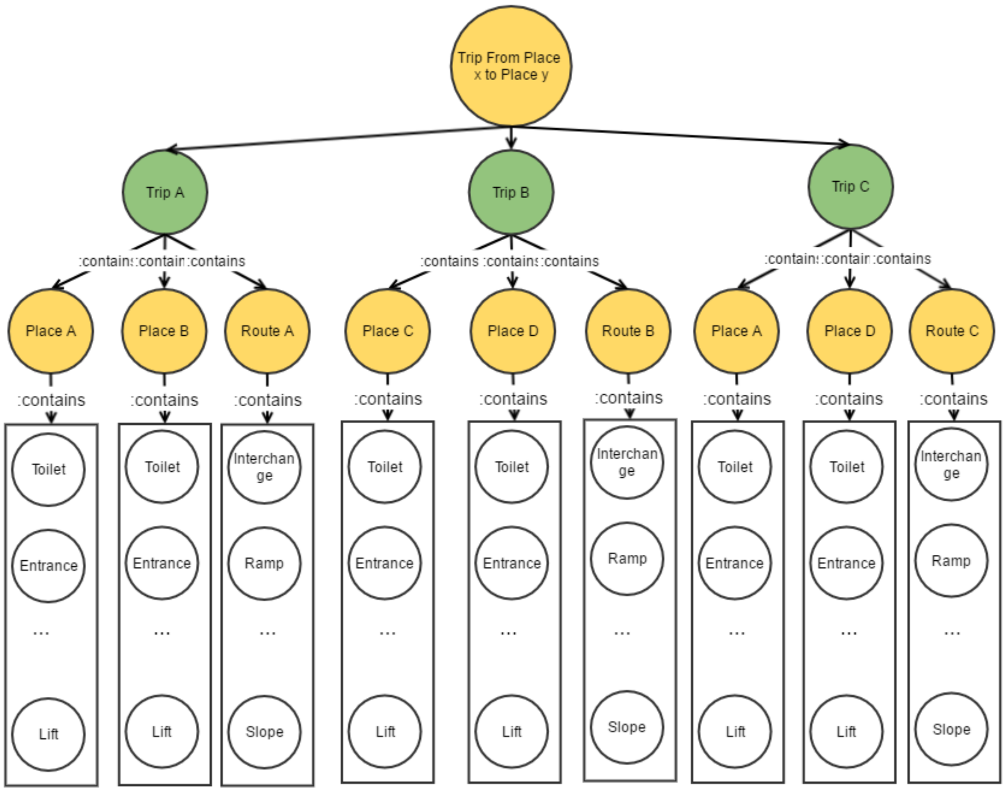


Figure 54: Decision Support for Trip Planning in the Linked Data

In summary, the problem of decision support for accessible travelling in the Linked Data could be transformed to the ranking problem of the trip accessibility, and this ranking problem could be divided into several sub-problems, namely, the ranking of place accessibility and the ranking of route accessibility. In the chapter of literature review, there are some multiple criteria decision-making (MCDM) methods discussed, such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR method, and Analytic Network Process (ANP). For the categories of MCDM methods, M.Ayhan [5] summarised that the AHP is one of the best-known method for the value measurement models. And the TOPSIS is one of the most important methods for the goal, aspiration, and reference models. The TOPSIS method is based on the concept that the chosen alternatives should have the shortest geometric distance from the positive ideal solution (PIS) and the longest geometric distance from the negative ideal solution (NIS). The VIKOR method was developed for multi-criteria optimisation in the complex situation, which is focussed on ranking and selecting alternatives, and determining optimised solutions for a problem with conflicting criteria. The Analytic Network Process (ANP) is a more general form of the analytic hierarchy process (AHP) used in scenarios that alternatives have the influence on the criteria. Compared with these MCDM methods, the AHP method converts the decision problem into a hierarchy of sub-problems and establishes priorities among its elements by evaluating their importance, which could be used to address the ranking problem of the trip accessibility in the Linked Data. Moreover, there are some recent works applying the AHP method to the Linked Data to solve the ranking problems [35], [57].

Therefore, the following part of this section would mainly demonstrate how to apply the AHP method to the decision support model based on the Linked Open Accessibility Data. In general, the AHP algorithm includes two steps:

1. Determine the relative weights of the decision criteria: computing the vector of the criteria weights with the pairwise comparison
2. Determine the relative rankings (priorities) of alternatives

Table 35: The Fundamental Scale for Pairwise Comparison [82]

Intensity of importance on an absolute scale	Definition
1	Equal Importance
3	Moderate Importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme Importance
2,4,6,8	Intermediate values

Pairwise comparisons are the fundamental in the use of AHP and Table 35 demonstrate the fundamental scale for pairwise comparisons proposed by R.W. Saaty [82]. Figure 55 demonstrates the AHP hierarchy in the decision support for accessible travelling. The objective is to choose an accessible trip for the user from alternatives by ranking the accessibility of each alternative. The criteria include the place accessible and route accessibility.

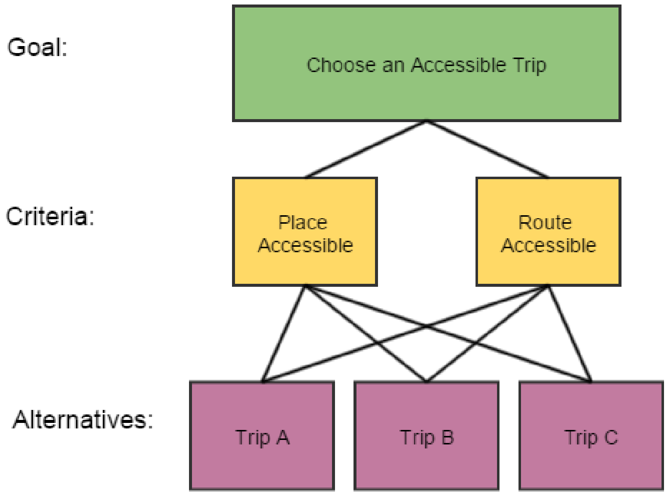


Figure 55: AHP Hierarchy for choosing an Accessible Trip

The weight of criteria for determining the place accessibility is based on the result of the Wilcoxon Signed-Rank Test, which is running on the question of place accessibility ranking in the questionnaire presented in Section 6.3. Combined with the test result and the fundamental scale, the weight of criteria is illustrated in Table 36, and the computed the priority vector is presented in Table 37.

Table 36: Determine the Weight of Criteria for Place Accessibility

	EN	DT	AT	Lift	ACP	AC	STT	RG	PA
Entrance	**1**	4	1	1/4	1	8	8	5	7
Door Type	1/4	**1**	1/2	1/6	1	7	4	1	6
Accessible Toilet	1	2	**1**	1/4	1	7	7	5	7
Lift	4	6	4	**1**	2	9	8	8	9
Accessible Car Park	1	1	1	1/2	**1**	7	4	2	6
Accessible Changing	1/8	1/7	1/7	1/9	1/7	**1**	1/2	1/6	1
Space To Turn	1/8	1/4	1/7	1/7	1/4	2	**1**	1/3	1
Ramp Gradient	1/5	1	1/5	1/8	1/2	6	3	**1**	3
Personal Assistance	1/7	1/6	1/7	1/9	1/6	1	1	1/3	**1**
sum	7 59/70	15 47/84	8 9/70	2 331/504	7 5/84	48	36 1/2	22 5/6	41

Consistency Index (CI) and Consistency Ratio (CR) to measure the consistency of subjective judgment are calculated as follows:

$$\lambda_{max} = 9.9459, \text{n=9}, CI = \frac{\lambda_{max}-n}{n-1} = \frac{9.9459-9}{9-1} = 0.1182, RI = 1.45$$

$$CR = \frac{CI}{RI} = \frac{0.1182}{1.45} = 8.15\% < 10\% \text{ (Consistent)}$$

Table 37: The Priority Vector for Place Accessibility

	EN	DT	AT	Lift	ACP	AC	STT	RG	PA	Wt
Entrance	70/549	227/883	70/569	67/712	84/593	1/6	16/73	30/137	7/41	16.88%
Door Type	8/251	59/918	35/569	17/271	84/593	7/48	8/73	6/137	6/41	8.97%
Accessible Toilet	70/549	59/459	70/569	67/712	84/593	7/48	14/73	30/137	7/41	14.91%
Lift	280/549	59/153	280/569	67/178	168/593	3/16	16/73	48/137	9/41	33.60%
Accessible Car Park	70/549	59/918	70/569	67/356	84/593	7/48	8/73	12/137	6/41	12.60%
Accessible Changing	4/251	1/109	10/569	11/263	12/593	1/48	1/73	1/137	1/41	1.90%
Space To Turn	4/251	4/249	10/569	5/93	21/593	1/24	2/73	2/137	1/41	2.74%
Ramp Gradient	14/549	59/918	14/569	4/85	42/593	1/8	6/73	6/137	3/41	6.18%
Personal Assistance	10/549	3/280	10/569	11/263	14/593	1/48	2/73	2/137	1/41	2.21%
sum	1	1	1	1	1	1	1	1	1	1
Adjusted Wt	18.12%	9.63%	16.01%	36.07%	13.53%	0	0	6.64%	0	

The weight of criteria for determining the transport route accessibility is also based on the result of the Wilcoxon Signed-Rank Test, which is running on the question of public transport accessibility importance in the questionnaire presented in Section 6.4. As a result, the weight of criteria demonstrated in Table 38 is based on the test result, where the weight annotation is 1 if there is no significant different in the statistics test. The priority vector is presented in Table 39. The examination of Consistency Index (CI) and Consistency Ratio (CR) is calculated as follows:

$$\lambda_{max} = 8.0115, n = 8, CI = \frac{\lambda_{max}-n}{n-1} = \frac{8.0115-8}{8-1} = 0.00164, RI = 1.41$$

$$CR = \frac{CI}{RI} = \frac{0.00164}{1.41} = 0.1164\% < 10\%\text{(Consistent)}$$

Table 38: Determine the Weight of Criteria for Transport Route Accessibility

	SL	Ramp	ATLT	ATBL	PA	ATC	ATKTM	ATKTH
Sign Level	**1**	1/6	1/3	1	1/3	1/5	1/5	1/5
Ramp	6	**1**	3	7	4	2	3	1
Accessible Toilet	3	1/3	**1**	5	2	1	1	1/2
Accessible Table	1	1/7	1/5	**1**	1/4	1/5	1/5	1/6
Personal Assistance	3	1/4	1/2	4	**1**	1/3	1/2	1/3
Accessible Interchange	5	1/2	1	1/9	3	**1**	1	1
Accessible Ticket Machine	5	1/3	1	1/7	2	1	**1**	1/3
Accessible Ticket Hall	5	1	2	1/8	3	1	3	**1**
Sum	29	3 61/84	9 1/30	18 191/504	15 7/12	6 11/15	9 9/10	4 8/15

Table 39: The Priority Vector for Transport Route Accessibility

	SL	**Ramp**	**ATLT**	**ATBL**	**PA**	**ATC**	**ATKTM**	**ATKTH**	**Wt**
Sign Level	1/29	14/313	10/271	29/533	4/187	3/101	2/99	3/68	3.57%
Ramp	6/29	84/313	90/271	219/575	48/187	30/101	10/33	15/68	28.32%
Accessible Toilet	3/29	28/313	30/271	219/805	24/187	15/101	10/99	15/136	13.30%
Accessible Table	1/29	12/313	6/271	29/533	3/187	3/101	2/99	5/136	3.15%
Personal Assistance	3/29	21/313	15/271	190/873	12/187	5/101	5/99	5/68	8.52%
Accessible Interchange	5/29	42/313	30/271	5/827	36/187	15/101	10/99	15/68	13.57%
Accessible Ticket Machine	5/29	28/313	30/271	3/386	24/187	15/101	10/99	5/68	10.40%
Accessible Ticket Hall	5/29	84/313	60/271	1/147	36/187	15/101	10/33	15/68	19.17%
Sum	1	1	1	1	1	1	1	1	1
Adjusted Wt	0	33.41%	15.69%	0	0	16.02%	12.27%	22.62%	

With applying the adjusted weight for each factor to determine the accessibility of the places or route, the next step is how to apply the AHP to the Linked Data-driven decision support model. Applying the forward-chaining method means to apply the AHP method in the inference rules to infer the ranking of the alternatives. The following syntax is the example of using inference rules to infer the AHP weight based on the availability of the accessible facilities or services.

```
Prefices{
          rdf    :  http://www.w3.org/1999/02/22-rdf-syntax-ns#
          paco: http://purl.org/net/ontology/paco#
          spatialrelations: http://data.ordnancesurvey.co.uk/ontology/spatialrelations/
}
Rules{
        Id:place_lift_ahp_weight
                                  x <rdf:type> <paco:Building>
                                   x <spatialrelations:contains> y
                                   y <rdf:type> <paco:Lift>
               ------------------------------ ------------------------------
                                   x <paco:weight_lift_AHP> "0.3607"^^xsd:float

        Id:place_toilet_ahp_weight
                                  x <rdf:type> <paco:Building>
                                   x <spatialrelations:contains> y
                                   y <rdf:type> <paco:AccessibleToilet>
               ------------------------------ ------------------------------
                                   x <paco:weight_toilet_AHP> "0.1601"^^xsd:float
        Id:place_carpark_ahp_weight
                                   x <rdf:type> <paco:Building>
                                   x <spatialrelations:contains> y
                                   y <rdf:type> <paco:AccessibleCarPark>
               ------------------------------------------------------------
                x <paco:weight_carpark_AHP> "0.0963"^^xsd:float
}
```

Filter query results | Showing results from 1 to 75 of 75. Query took 0.033 s

	p	o
1	paco:weight_AHP	"0.0963"^^xsd:float
2	paco:weight_carpark_AHP	"0.0963"^^xsd:float
3	paco:weight_AHP	"0.1601"^^xsd:float
4	paco:weight_toilet_AHP	"0.1601"^^xsd:float
5	paco:weight_AHP	"0.1812"^^xsd:float
6	paco:weight_entrance_AHP	"0.1812"^^xsd:float
7	paco:weight_AHP	"0.3607"^^xsd:float
8	paco:weight_lift_AHP	"0.3607"^^xsd:float

As a result of the example ruleset demonstrated above, the inference rule could generate the weight for each factor. The sum of the weight of place accessibility could be aggregated by using the SAPRQL query language as well as the aggregation functions to order the ranking of alternatives. However, this approach does not work when applying it to the scenarios as follows:

- The accessibility data of facilities or services needs to be changed and re-inferred due to the temporary issues.
- The dataset needs to be changed and re-inferred regularly.
- Apply the adjusted weight of criteria for different limitation preference, which is stated in Table 40.

Table 40: The Adjusted Weight of Place Accessibility for Categories of Limitations

	EN	DT	AT	AC	STT	RG	Lift	ACP	PA
NNL									
NNS/NLS	18.12%	9.63%	16.01%			6.64%	36.07%	13.53%	
NNWM NLWM	21.64%		19.12%				43.08%	16.16%	
NNWP NLWP NSWP	17.21%	9.14%	15.20%		2.79%	6.30%	34.25%	12.85%	2.25%
NLL			30.74%				69.26%		
NSL	18.93%	10.06%	16.72%				37.68%	14.13%	2.48%
NSS	17.70%	9.41%	15.64%			6.48%	35.24%	13.21%	2.32%
NSWM	18.93%	10.06%	16.72%				37.68%	14.13%	2.48%
UNL/ULL ULWM UNWM	19.00%	10.09%	16.78%	2.14%			37.81%	14.18%	
UNS/ULS	17.76%	9.44%	15.69%	2.00%		6.50%	35.35%	13.26%	
UNWP ULWP USWP	16.88%	8.97%	14.91%	1.90%	2.74%	6.18%	33.60%	12.60%	2.21%
USL/USS USWM	18.08%	9.61%	15.97%	2.04%			35.99%	13.50%	2.37%
Wt	16.88%	8.97%	14.91%	1.90%	2.74%	6.18%	33.60%	12.60%	2.21%
Adjusted Wt	18.12%	9.63%	16.01%	0.00%	0.00%	6.64%	36.07%	13.53%	0.00%

Therefore, the forward-chaining approach by applying the AHP method to accessible travelling decision support based on the Linked Data is more suitable for the small scale of datasets with personal decision support. On the other hand, the strategy of Backward-chaining method is to apply the AHP algorithm in the query language, and the weight of criteria is signed and aggregated during the process of querying dynamically. As a result, this approach could provide real-time answers without the extra cost of space and memory, but it would lead to the extremely time cost when the query is complex.

When combining the advantages of the forward-chaining and backward-chaining approaches, the hybrid strategy is proposed to apply the AHP to the Linked Open Accessibility Data which provides decision support for accessible trip planning. This can be described in the following steps:

1. Use the forward-chaining approach to apply the inference rules to the facts of accessible facilities and service to infer whether the facility or service is accessible against the standards. For example, with the British Standards of the maximum gradient (1:12), the rules for the slope of the road could be expressed as follows:

$$Road(?r), float[\leq 0.083](?slope), hasRoadSlope(?r, ?slope) \rightarrow isAccessible(?r, true)$$
$$Road(?r), float[> 0.083](?slope), hasRoadSlope(?r, ?slope) \rightarrow isAccessible(?r, false)$$

2. Each entity of place, route and road in the candidate alternatives could be inferred with the help of the built-in ruleset.
3. Apply the AHP method in the query language (SPARQL) to sign the weight of criteria to each entity in the candidate alternative based on the user difficulties categories.
4. Use the aggregation function in query language to generate the ranking of the alternatives in the real-time.

The hybrid strategy combined the forward-chaining and backword-chaining could not only reduce the inferencing cost at the start-up of the dataset but also reduce the query complexity. This strategy also provides the real-time answers with preferred user difficulties categories. For example, the code demonstrated below is the general SPARQL query to apply the AHP algorithm in the real-time querying. There are already some inferred facts in the place entity based on the built-in inference rules. The example code is using the SPARQL to sign the weight of criteria to the place entity based on the user difficulty category and accessibility of facilities and services. The difficulty category in the example is the NLWP (No-Upper-Limb-Limitation, Light Upper-Body Limitation, and Powered Wheelchair). The query is using the pre-defined adjusted weight stated in Table 40 to evaluate the accessibility importance score of the target place entity. The aggregation result is the same as the result by applying forward-chaining approach.

```
PREFIX paco: <http://purl.org/net/ontology/paco#>
PREFIX spatialrelations: <http://data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX spif: <http://spinrdf.org/spif#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

INSERT {
        paco:Building32_University_of_Southampton paco:weight_AHP ?weightvalue.
}
WHERE{

  BIND(EXISTS{
        paco:Building32_University_of_Southampton spatialrelations:contains ?entrance.
        ?entrance rdf:type paco:AccessibleEntrance.} AS ?ent)
  BIND(EXISTS{
        paco:Building32_University_of_Southampton spatialrelations:contains
?accessibletoilet.
        ?accessibletoilet rdf:type paco:AccessibleToilet. } AS ?at)
  BIND(EXISTS{
        paco:Building32_University_of_Southampton spatialrelations:contains ?lift.
        ?lift rdf:type paco:Lift. } AS ?liftvalue)
  BIND(EXISTS{
        paco:Building32_University_of_Southampton spatialrelations:contains
?accessiblecarpark.
        ?accessiblecarpark rdf:type paco:AccessibleCarPark.} AS ?acp)
  BIND(EXISTS{
        paco:Building32_University_of_Southampton spatialrelations:contains
?personalassistance.
        ?personalassistance rdf:type paco:PersonalAssistance.} AS ?pa)
  BIND(EXISTS{
        paco:Building32_University_of_Southampton spatialrelations:contains ?ramp.
        ?ramp rdf:type paco:AccessibleRamp. } AS ?rampvalue)
  BIND(EXISTS{
        paco:Building32_University_of_Southampton paco:hasSpaceToTurn ?stt.} AS
?sttvalue)

  BIND(IF(?ent,0.1721, 0) AS ?weight_1).
  BIND(IF(?at,?weight_1+0.152, ?weight_1) AS ?weight_2).
  BIND(IF(?liftvalue,?weight_2+0.3425, ?weight_2) AS ?weight_3).
  BIND(IF(?acp,?weight_3+0.1285, ?weight_3) AS ?weight_4).
  BIND(IF(?pa,?weight_4+0.0225, ?weight_4) AS ?weight_5).
  BIND(IF(?rampvalue,?weight_5+0.1520, ?weight_5) AS ?weight_6).
  BIND(IF(?sttvalue,IF(?stt, ?weight_6+0.1520, ?weight_6 ),?weight_6) AS ?weightvalue).
 }
```

Filter query results — Showing results from 1 to 1 of 1. Query took 0.054 s.

	subject	predicate	object
1	paco:Building32_University_of_Southampton	paco:weight_AHP	"0.7951"^^xsd:decimal

8.4 Summary

This chapter mainly discussed how to apply the decision support algorithms to the decision support model to provide decision support for accessible travelling based on the Linked Open Accessibility Data. As introduced in the first section, there are two main scenarios of accessible travelling decision support. According to these two scenarios, the decision support problem could be divided into two sub-problems: One is to provide the decision support to determine the places accessibility, such as whether accessible and how accessible. Another one is to provide the decision support to determine route accessibility, including the walking path and transport route.

Based on these two sub-problems, the second section demonstrated the approach to involve the question answering (QA) system as the decision support model to provide the natural way for accessible travelling decision support. However, this section only demonstrated how to use the query language and inference engine to gather the accessibility data based on the users' questions and preference without any decision support algorithms applied. After discussing the limitations of different decision support algorithms for the Linked Data-driven decision support, the third section mainly demonstrated the hybrid strategy to apply the AHP method to the Linked Open Accessibility Data to provide decision support for accessible trip planning. Combined with the advantages of the forward-chaining and backward-chaining approaches, the proposed strategy could not only reduce the inference cost at the start-up of the dataset and usage of space and memory but also reduce the time complexity of real-time querying.

As a consequence, there are two approaches proposed to apply to the decision support model in this chapter, namely the simple question answering system and the hybrid strategy. These two approaches could be used to support decision making for accessible travelling based on different scenarios and personalised preference. The next chapter is the last chapter of this thesis, which will conclude this research and expose some future works.

Chapter 9: Conclusion and Future Work

This chapter provides an overview of the previous chapters and will also summarise the contribution of this research. Finally, this chapter discusses future work related to this research.

9.1 Conclusions

With the aim of addressing the gap between users' needs and complex environmental barriers in the real world in the scenarios of accessible travelling, this thesis initially explains the motivation to investigate the research of a Linked Data-driven decision support system to provide accessible travelling decision support for people with mobility difficulties. After reviewing related projects that aimed to address the travelling problems faced by the people with disabilities relating to accessibility, limitations and challenges were exposed by these projects, namely the lack of accessibility metadata, accessibility data isolation, urgent needs to find methods for data integration, and better algorithms for decision making. It was found that by applying the advantages of Linked Data principles and the Semantic Web to publish, interlink and consume the accessibility data could be the solution to address the problems stated above. Therefore, this research has proposed the conceptual model of Linked Data-driven DSS for accessible travelling. Proposed research questions (RQs) were as follows:

RQ1: What is an appropriate method for publishing and integrating heterogeneous accessibility related datasets with incomplete information?

- RQ1.1: How to integrate and enrich heterogeneous open accessibility data?
- RQ1.2: How to use URI naming and referencing to publish the open accessibility data as the Linked Data in accessible travelling domain?

RQ2: What decision support algorithms work appropriately with the linked open accessibility data for accessible travelling?

- RQ2.1: What kinds of accessibility data does a user need for accessible travelling?
- RQ2.2: How to apply the decision support algorithms in the Linked Data knowledge base to provide decision support for accessible travelling?

In this thesis, the experiments to explore the answers to the RQ1 were mainly demonstrated in Chapter 5, Chapter 6, and Chapter 7. The RQ1.1 was answered in Section 5.4 and 5.5. The RQ1.2 was answered in Chapter 6 and Chapter 7. The RQ2.1 was explored in Section 5.2, 5.3 and Chapter 6. The research of RQ2.2 was demonstrated in Chapter 8. The main contributions of this research were as follows:

1. **The Empirical Study of the Open Accessibility Data** (Chapter 5): the study was based on the survey of the open accessibility data collected from the real world, such as crowdsourcing applications and data publishers. This study presented the challenges and limitations of open accessibility data in current situation in Section 5.2.6.

2. **The Entity Matching Algorithm for the Open Accessibility Data** (Chapter 5): a proposed entity matching algorithm was used to match and interlink the entities with accessibility metadata from different sources.

3. **The Model of the Open Accessibility Data Integration** (Chapter 5): the model of the open accessibility data integration was the fundamental model of the Linked Data-driven decisions support system for accessible travelling, which now includes the integration of the various accessibility datasets, and interlinking the same entities across the datasets

4. **The CrowdAccess Crowdsourcing Platform** (Chapter 5): this platform is part of the components in the data integration model. It is a proof of concept to demonstrate the use of the crowdsourcing method to address the issues of accessibility data conflict and evaluation.

5. **The Ontologies for the Accessible Travelling Domain** (Chapter 6): these have been based on the empirical study of the categorisation of limitations and accessibility requirements for people with mobility difficulties in accessible travelling. By reusing some core ontologies, these ontologies provide the standard vocabularies to describe accessibility data of the built environment, public transport and limitations of mobility difficulties.

6. **Linked Open Accessibility Data Publishing** (Chapter 7): this introduced the approaches to publishing the accessibility data of the built environment, public transport and personal limitations as the core knowledge base for the decision support model.

7. **Applying the decision support method to the Linked Open Accessibility Data** (Chapter 8): this introduced the strategies to apply the decision support method (AHP) to the Linked Open Accessibility Data and demonstrated the examples of decision support based on the Linked Data for accessible travelling.

The literature review in Chapter 2 mainly explained the background information related to the disabilities, accessible tourism, principles of Linked Data and decision support systems. It demonstrated the classification of disability, the models of tourism and disabilities, and the process sequence of accessible tourism as well as the concept of Linked Data-driven web applications. The related vocabularies and ontologies for disabilities and accessibility and the brief introduction of DSSs were also introduced in this chapter.

Chapter 3 mainly discussed the research questions. It summarised the problems and challenges of current research to support accessible travelling for people with disabilities. Based on the literature review in the previous chapter, this chapter introduced the research motivation and proposed the conceptual model of the Linked Data-driven DSS for accessible travelling to answer the research questions. The core of this conceptual model included three sub-models, namely the data integration model, the decision support model, and the evaluation model.

In Chapter 4, some software metrics were defined to evaluate the linked open accessibility data generated from the data integration model, the data integration approaches, and the algorithms. Based on the literature review of some standard accessibility measurements, the measurement metric for open accessibility data was based on the guidelines of metrics for web accessibility. The evaluation metrics of data integration was based on the Goal Question Metrics approach (GQM) approach. The proposed measurement for linked open accessibility data followed some criteria in the assessment of data quality for linked datasets.

Chapter 5 demonstrated the research undertaken for the open accessibility data integration model to answer research question RQ1. The survey of the open accessibility data collected from multiple heterogeneous sources was presented. The data schema observation demonstrated the common features of the open accessibility data, which exposed the challenges for open accessibility data integration. The single ontology approach was also applied in the experiment to perform the data integration. Combined the Linked Data-driven Web application and crowdsourcing, the CrowdAccess is the proof of the concept application proposed to evaluate the result of data integration and entity matching algorithms. Based on the evaluation result, this chapter also summarised the limitations of current approaches.

In Chapter 6, the accessibility requirements for people with different mobility limitations in the accessible travelling domain were discussed. A study of the accessibility requirements was conducted by an online questionnaire. The result of the study was statistically analysed and results were used as the inference rules and the criteria were weighted in Chapter 8. The ontologies for accessible travelling were proposed to address the challenges of urgent needs of standard ontologies in this domain. Three ontologies are the lightweight ontologies that provided the formal vocabularies to describe the limitation categorisation, and accessibility information of the accessible travelling domain, namely the Mobility Difficulty Ontology (MODO), the Place Accessibility Ontology (PACO) and the Transport Accessibility Ontology (TACO).

In Chapter 7, demonstrated the way in which the three lightweight ontologies were applied along with other core ontologies to publish the open accessibility data as the Linked Data. This chapter introduced the methods used to address the URI naming and referencing by following the standard practice guidelines for publishing the Linked Data. In order to generate the Linked Data knowledge base for decision support, there are three different types of datasets introduced in this chapter, namely using the MODO ontology to publish the user preference data as the Linked Data, using the PACO ontology to publish the built environment data as the Linked Data, and using the PACO ontology and TACO ontology to publish public transport data as the Linked Data.

In Chapter 8, this chapter mainly discussed the research to answer the research question RQ2. Two main scenarios of accessible travelling decision support have been discussed in the first section. Based on these two scenarios, the decision support problem have been divided into two sub-problems. The approach applied the SPARQL query and inference engine as the simple question answering (QA) system over the Linked Data because the decision support model provided a natural way to address the first scenario of accessible travelling decision support. The third section demonstrated the hybrid strategy to apply the AHP method to the Linked Open Accessibility Data having compared the limitations of different decision support algorithms. Combined with the advantages of the forward-chaining and backward-chaining approaches, the proposed strategy could not only address the problem of the extra inference cost at the start-up of the dataset but also reduce the time complexity of real-time querying. As a result, the proposed strategy to apply the AHP method to the Linked Open Accessibility Data could for the Linked Data-driven decision support, provide decision support for accessible trip planning.

As a consequence, this research presented the research of the conceptual model of Linked Data-driven decision support system for accessible travelling. As a data-driven approach, this research explored the area of open accessibility data, accessibility data integration and interlinking. Based on the elevation result, the proposed model could address the problems of the lack of accessibility data and data isolation. However, the result also exposed the limitations of proposed approach, such as the needs of standard vocabularies to publish the accessibility data. Therefore, there are the three proposed ontologies that have been used to publish the accessibility data in the accessible travelling domain. Finally, this research also discussed and demonstrated the approach to applying the decision support methods for the proposed model for accessible travelling decision support.

9.2 Future Work

As the conclusion of the thesis has presented in the previous section, there are some challenges and limitations that have been exposed in this research of the conceptual model of Linked Data-driven decision support system for accessible travelling. Therefore, this section illustrates future work related to these challenges and limitations, namely the challenges for data integration and crowdsourcing, revision, maintenance and improvement of proposed ontologies, and the need for a user interface model for the proposed conceptual model of Linked Data-driven decision support system.

9.2.1 Challenges for Data Integration and Crowdsourcing

The data integration model highlighted certain limitations to the current approaches. The need for general matching rules to improve the accuracy for the same entity from different datasets. As demonstrated in Section 5.4, the proposed matching rule demonstrated a relatively successful result for entity matching in the experiment datasets. However, in order to improve the matching accuracy, the matching rule will need to be modified and improved when applying it to other datasets. There is also need for better approaches to address the data conflict issues in the accessibility metadata mapping and data crowdsourcing in the future works. One of the possible approaches could be signing the priority weight to the dataset based on the reputation of data publisher.

9.2.2 Ontology Maintenance, Revision and Improvement

In the Semantic Web, ontology is the formal, explicit specification of a shared conceptualization. The ontology should be widely reused and maintained. The proposed three ontologies provide the formal vocabularies to describe the limitation categorisation, and accessibility information of accessible travelling domain. However, the vocabularies for accessible facilities and services are limited to the current research scope and other core ontologies. Therefore, these ontologies would need to be revised and extended regularly to meet the requirements of the accessible requirements, especially for the Place Accessibility Ontology (PACO) and the Transport Accessibility Ontology (TACO). The improvement of the Mobility Difficulty Ontology (MODO) will also be explored in future work to link to the other ontologies that provide the vocabularies based on the medical model of disabilities.

9.2.3 User Interface Model

The user interface model is the presentation component in the concept model of Linked Data-driven DSS for accessible travelling. Although the research of the user interface model is out of the scope of this research, it is one of the core components in the DSSs. The research around the user interface model, as future work, would be divided into two parts: the accessible user input interface and accessible user presentation interface. The accessible user input interface would involve the area of human-computer interaction. One aspect of the accessible user input interface would be the research into using the natural language input for a question answering system to provide accessible travelling decision support. The accessible user presentation interface would mainly explore the research of simplified or symbolised user interface to provide accessible travelling decision support for the people with cognitive disabilities.

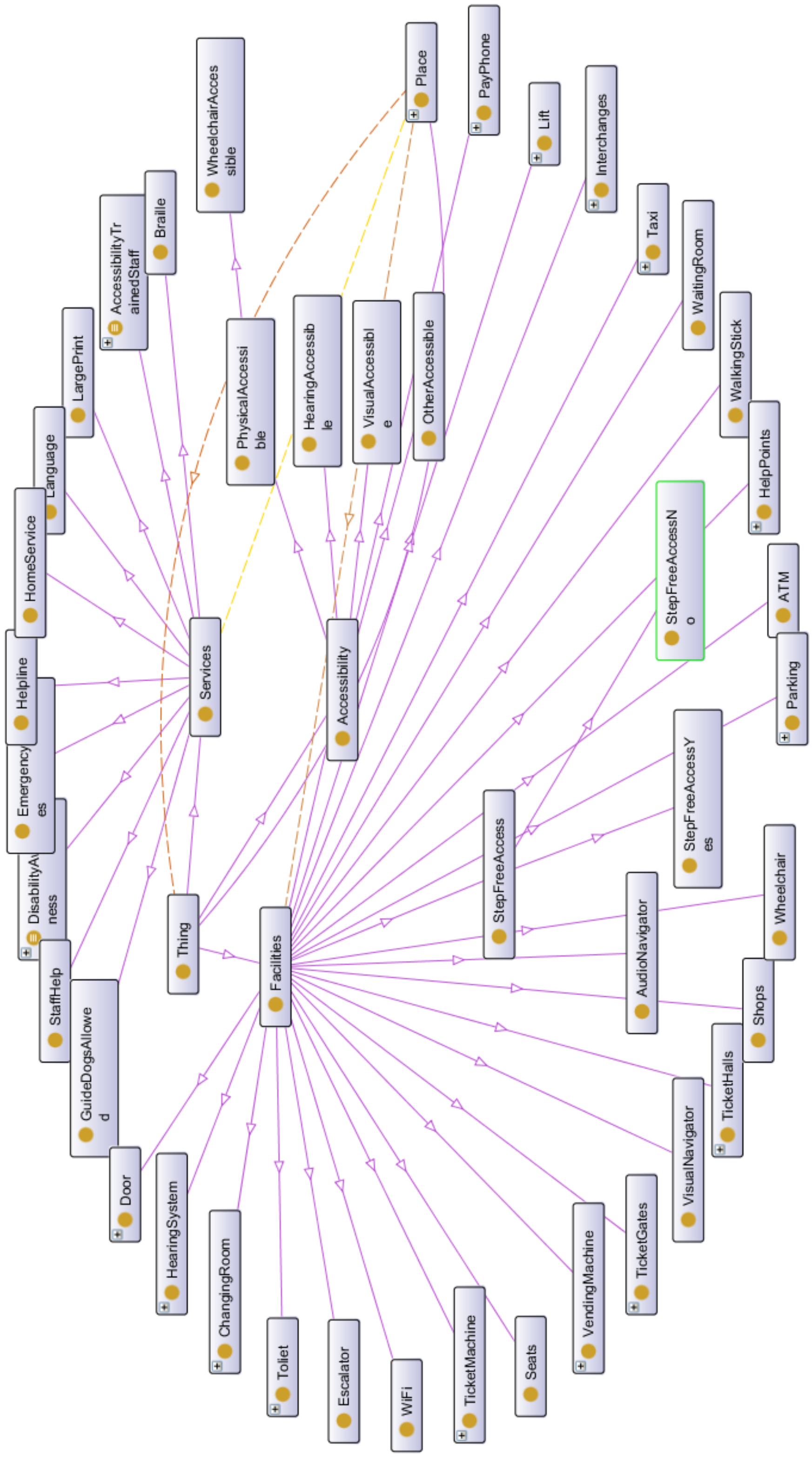
Appendices

The Chapter of the Appendices mainly demonstrate a few materials mentioned in this thesis, which includes:

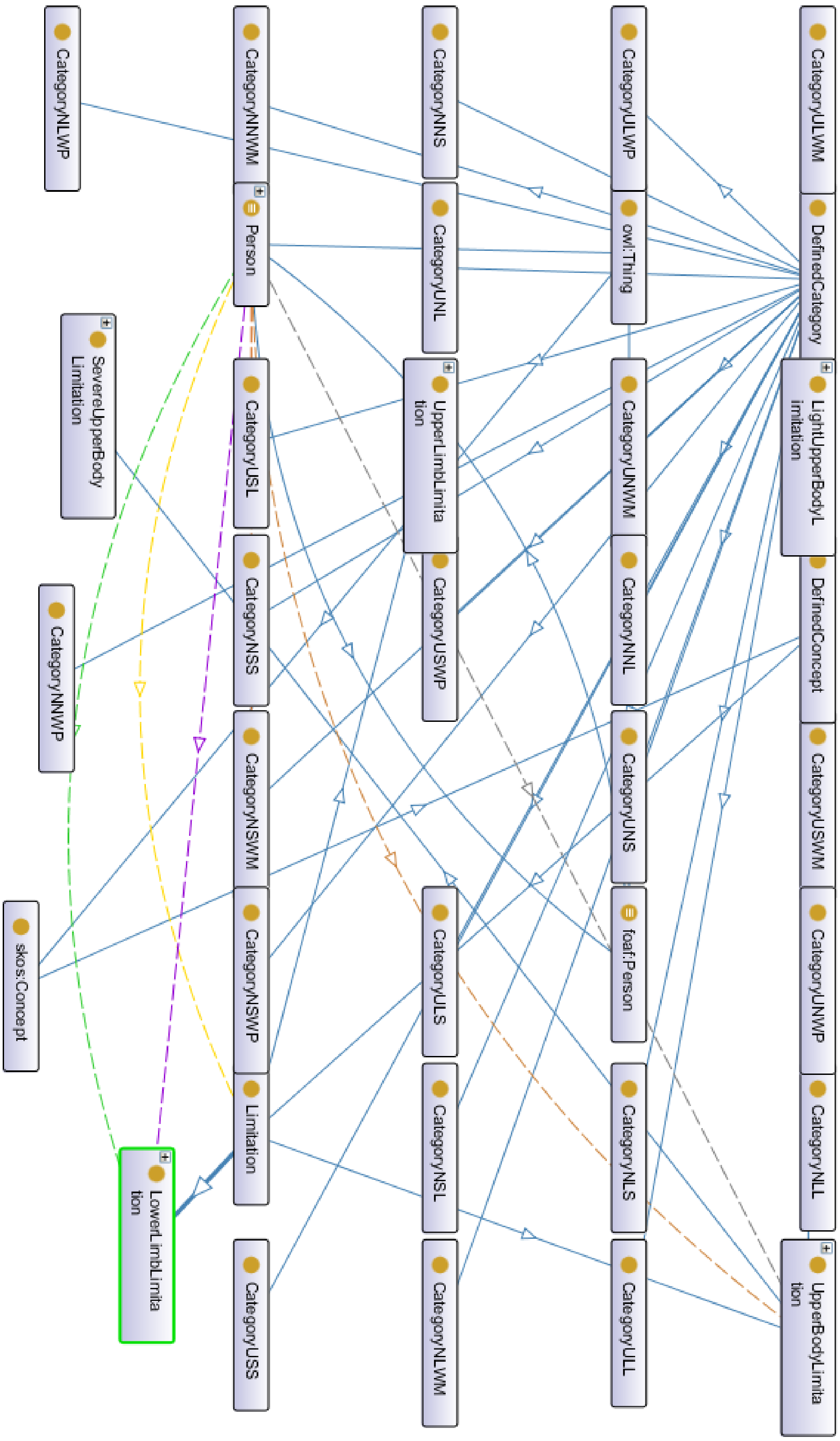
- The hierarchy overview of the ontologies for accessible travelling domain
- The statistical analysis result of the question for studying the requirement of accessible travelling
- Example Code of SWRL ruleset for inference in the Mobility Difficulties Ontology
- Example OWL2-RL ruleset for inference in the Mobility Difficulties Ontology
- Example SPARQL query to insert the accessibility data of built environment

Appendix A The Ontologies for Accessible Travelling

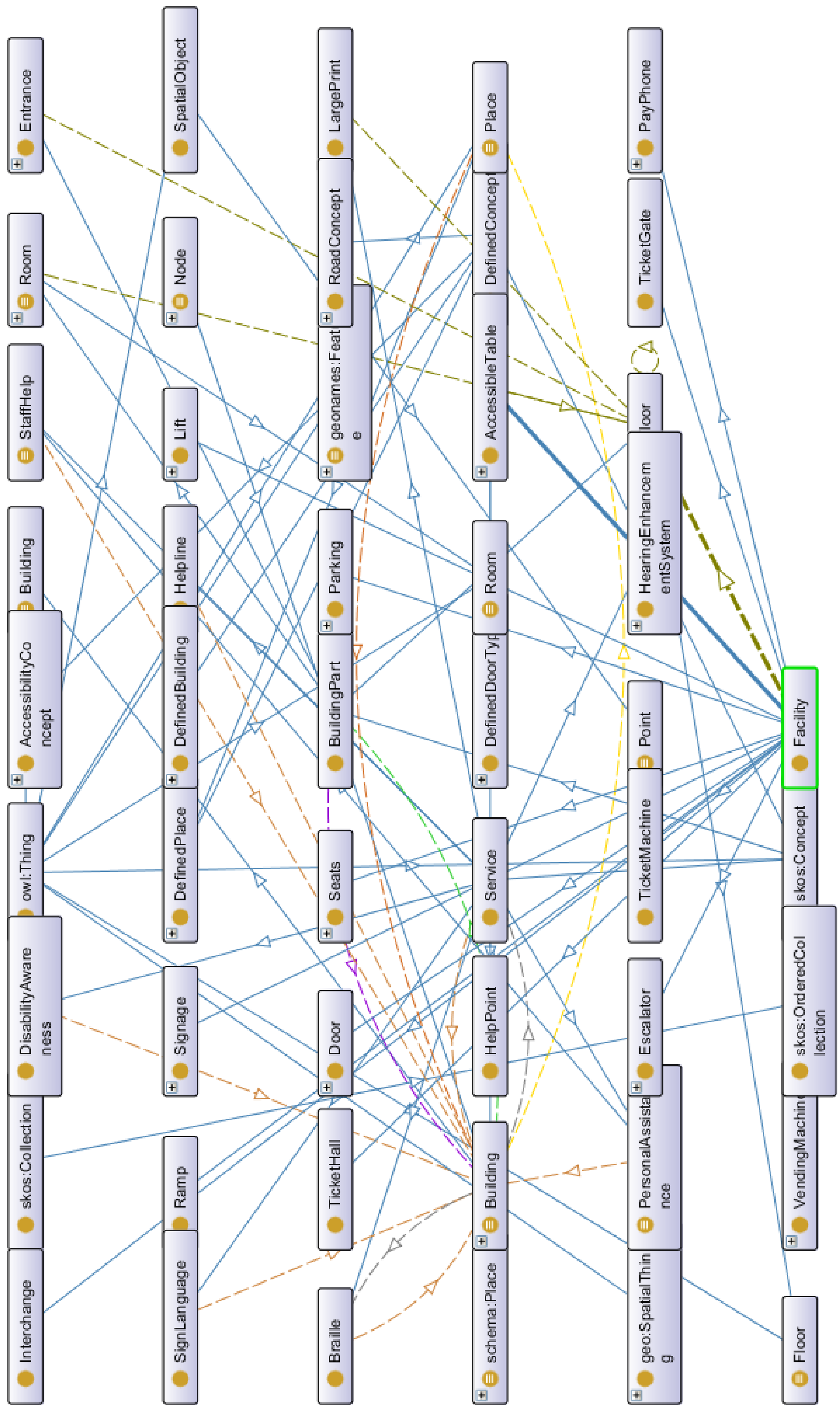
A.1 The PlaceAccess Ontology (PAO)



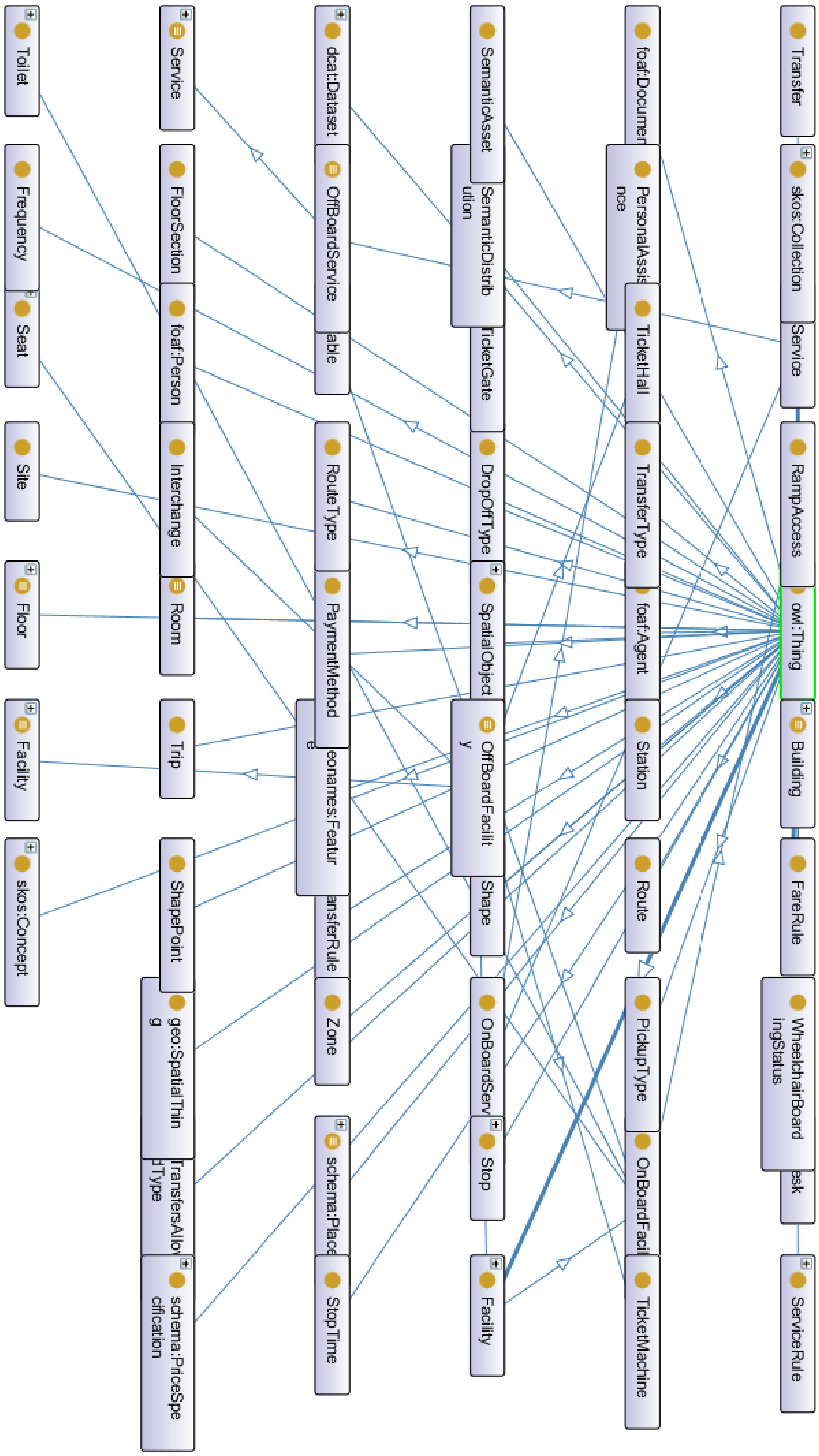
A.2 The Mobility Difficulty Ontology (MODO)



A.3 The Place Accessibility Ontology (PACO)



A.4 The Transport Accessibility Ontology (TACO)



Appendix B Statistics Analysis of the Questionnaire

B.1 The People with Mobility Difficulties in Built Environment

Requirements for the People with Upper Limb Limitations

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	19	2.2632	1.09758	.25180
Entrance	20	3.4000	.88258	.19735
DoorType	20	3.1500	.93330	.20869
AccessibleToilet	20	3.1500	.81273	.18173
AccessibleChanging	20	2.1000	.85224	.19057
AccessibleTable	19	2.3684	.76089	.17456
Handrails	20	2.6000	.88258	.19735
RoadSurface	20	3.3000	.86450	.19331
RoadSlope	20	3.3500	.87509	.19568
SpaceToTurn	20	2.3500	1.03999	.23255
RampGradient	20	2.7500	1.01955	.22798
LiftToAll	20	3.5000	.82717	.18496
AccessibleCarPark	20	3.2500	.96655	.21613
PersonalAssistance	20	2.6000	.88258	.19735

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.941	18	.359	-.23684	-.7659	.2922
Entrance	4.560	19	.000	.90000	.4869	1.3131
DoorType	3.115	19	.006	.65000	.2132	1.0868
AccessibleToilet	3.577	19	.002	.65000	.2696	1.0304
AccessibleChanging	-2.099	19	.049	-.40000	-.7989	-.0011
AccessibleTable	-.754	18	.461	-.13158	-.4983	.2352
Handrails	.507	19	.618	.10000	-.3131	.5131
RoadSurface	4.138	19	.001	.80000	.3954	1.2046
RoadSlope	4.344	19	.000	.85000	.4404	1.2596
SpaceToTurn	-.645	19	.527	-.15000	-.6367	.3367
RampGradient	1.097	19	.287	.25000	-.2272	.7272
LiftToAll	5.407	19	.000	1.00000	.6129	1.3871
AccessibleCarPark	3.470	19	.003	.75000	.2976	1.2024
PersonalAssistance	.507	19	.618	.10000	-.3131	.5131

Appendix B

Requirements for the People with Upper Body Limitations

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	19	2.2632	1.09758	.25180
Entrance	20	3.3500	.87509	.19568
DoorType	20	3.1500	.93330	.20869
AccessibleToilet	20	3.1000	.78807	.17622
AccessibleChanging	20	2.1000	.85224	.19057
AccessibleTable	20	2.3500	.74516	.16662
Handrails	20	2.6500	.93330	.20869
RoadSurface	20	3.2500	.85070	.19022
RoadSlope	20	3.3500	.87509	.19568
SpaceToTurn	20	2.3500	1.03999	.23255
RampGradient	20	2.7000	1.03110	.23056
LiftToAll	20	3.5000	.82717	.18496
AccessibleCarPark	20	3.2000	.95145	.21275
PersonalAssistance	20	2.7000	.92338	.20647

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.941	18	.359	-.23684	-.7659	.2922
Entrance	4.344	19	.000	.85000	.4404	1.2596
DoorType	3.115	19	.006	.65000	.2132	1.0868
AccessibleToilet	3.405	19	.003	.60000	.2312	.9688
AccessibleChanging	-2.099	19	.049	-.40000	-.7989	-.0011
AccessibleTable	-.900	19	.379	-.15000	-.4987	.1987
Handrails	.719	19	.481	.15000	-.2868	.5868
RoadSurface	3.943	19	.001	.75000	.3519	1.1481
RoadSlope	4.344	19	.000	.85000	.4404	1.2596
SpaceToTurn	-.645	19	.527	-.15000	-.6367	.3367
RampGradient	.867	19	.397	.20000	-.2826	.6826
LiftToAll	5.407	19	.000	1.00000	.6129	1.3871
AccessibleCarPark	3.290	19	.004	.70000	.2547	1.1453
PersonalAssistance	.969	19	.345	.20000	-.2322	.6322

Requirements for the People with Light Upper Body Limitations in Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	10	2.4000	1.07497	.33993
Entrance	11	3.1818	1.07872	.32525
DoorType	11	2.9091	1.04447	.31492
AccessibleToilet	11	3.0909	.83121	.25062
AccessibleChanging	11	2.0909	1.04447	.31492
AccessibleTable	11	2.2727	.90453	.27273
Handrails	11	2.7273	1.00905	.30424
RoadSurface	11	3.3636	1.02691	.30963
RoadSlope	11	3.3636	1.02691	.30963
SpaceToTurn	11	2.1818	1.07872	.32525
RampGradient	11	2.7273	1.19087	.35906
LiftToAll	11	3.2727	1.00905	.30424
AccessibleCarPark	11	3.2727	1.19087	.35906
PersonalAssistance	11	2.4545	1.03573	.31228

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.294	9	.775	-.10000	-.8690	.6690
Entrance	2.096	10	.062	.68182	-.0429	1.4065
DoorType	1.299	10	.223	.40909	-.2926	1.1108
AccessibleToilet	2.358	10	.040	.59091	.0325	1.1493
AccessibleChanging	-1.299	10	.223	-.40909	-1.1108	.2926
AccessibleTable	-.833	10	.424	-.22727	-.8349	.3804
Handrails	.747	10	.472	.22727	-.4506	.9052
RoadSurface	2.789	10	.019	.86364	.1737	1.5535
RoadSlope	2.789	10	.019	.86364	.1737	1.5535
SpaceToTurn	-.978	10	.351	-.31818	-1.0429	.4065
RampGradient	.633	10	.541	.22727	-.5728	1.0273
LiftToAll	2.540	10	.029	.77273	.0948	1.4506
AccessibleCarPark	2.152	10	.057	.77273	-.0273	1.5728
PersonalAssistance	-.146	10	.887	-.04545	-.7413	.6504

Appendix B

Requirements for the People with Severe Upper Body Limitations in Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	11	2.2727	1.19087	.35906
Entrance	11	3.7273	.46710	.14084
DoorType	11	3.3636	.67420	.20328
AccessibleToilet	11	3.1818	.75076	.22636
AccessibleChanging	11	2.2727	.64667	.19498
AccessibleTable	11	2.4545	.52223	.15746
Handrails	11	2.5455	.82020	.24730
RoadSurface	11	3.2727	.64667	.19498
RoadSlope	11	3.4545	.68755	.20730
SpaceToTurn	11	2.5455	.82020	.24730
RampGradient	11	2.9091	.83121	.25062
LiftToAll	11	3.7273	.46710	.14084
AccessibleCarPark	11	3.3636	.67420	.20328
PersonalAssistance	11	2.9091	.53936	.16262

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.633	10	.541	-.22727	-1.0273	.5728
Entrance	8.714	10	.000	1.22727	.9135	1.5411
DoorType	4.249	10	.002	.86364	.4107	1.3166
AccessibleToilet	3.012	10	.013	.68182	.1775	1.1862
AccessibleChanging	-1.166	10	.271	-.22727	-.6617	.2072
AccessibleTable	-.289	10	.779	-.04545	-.3963	.3054
Handrails	.184	10	.858	.04545	-.5056	.5965
RoadSurface	3.963	10	.003	.77273	.3383	1.2072
RoadSlope	4.605	10	.001	.95455	.4926	1.4164
SpaceToTurn	.184	10	.858	.04545	-.5056	.5965
RampGradient	1.632	10	.134	.40909	-.1493	.9675
LiftToAll	8.714	10	.000	1.22727	.9135	1.5411
AccessibleCarPark	4.249	10	.002	.86364	.4107	1.3166
PersonalAssistance	2.516	10	.031	.40909	.0467	.7714

Requirements for the People with Light Walking Limitations in Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	11	2.4545	.93420	.28167
Entrance	12	2.9167	.99620	.28758
DoorType	12	2.8333	1.02986	.29729
AccessibleToilet	12	2.8333	.93744	.27061
AccessibleChanging	12	2.0000	.95346	.27524
AccessibleTable	12	2.2500	.96531	.27866
Handrails	12	2.6667	1.07309	.30977
RoadSurface	12	3.1667	.93744	.27061
RoadSlope	12	3.1667	1.11464	.32177
SpaceToTurn	12	2.0833	.99620	.28758
RampGradient	12	2.4167	1.08362	.31282
LiftToAll	10	3.1000	1.19722	.37859
AccessibleCarPark	10	2.8000	1.31656	.41633
PersonalAssistance	10	2.5000	1.17851	.37268

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.161	10	.875	-.04545	-.6731	.5821
Entrance	1.449	11	.175	.41667	-.2163	1.0496
DoorType	1.121	11	.286	.33333	-.3210	.9877
AccessibleToilet	1.232	11	.244	.33333	-.2623	.9290
AccessibleChanging	-1.817	11	.097	-.50000	-1.1058	.1058
AccessibleTable	-.897	11	.389	-.25000	-.8633	.3633
Handrails	.538	11	.601	.16667	-.5151	.8485
RoadSurface	2.464	11	.031	.66667	.0710	1.2623
RoadSlope	2.072	11	.063	.66667	-.0415	1.3749
SpaceToTurn	-1.449	11	.175	-.41667	-1.0496	.2163
RampGradient	-.266	11	.795	-.08333	-.7718	.6052
LiftToAll	1.585	9	.147	.60000	-.2564	1.4564
AccessibleCarPark	.721	9	.489	.30000	-.6418	1.2418
PersonalAssistance	.000	9	1.000	.00000	-.8431	.8431

Appendix B

Requirements for the People with Severe Walking Limitations in Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	16	2.6875	1.01448	.25362
Entrance	16	3.7500	.44721	.11180
DoorType	16	3.4375	.62915	.15729
AccessibleToilet	16	3.3750	.71880	.17970
AccessibleChanging	16	2.5000	.81650	.20412
AccessibleTable	15	2.6667	.61721	.15936
Handrails	16	2.8125	.83417	.20854
RoadSurface	15	3.4000	.50709	.13093
RoadSlope	16	3.5625	.51235	.12809
SpaceToTurn	16	2.7500	.93095	.23274
RampGradient	16	3.1250	.71880	.17970
LiftToAll	16	3.6875	.47871	.11968
AccessibleCarPark	15	3.5333	.51640	.13333
PersonalAssistance	16	2.6875	.60208	.15052

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	.739	15	.471	.18750	-.3531	.7281
Entrance	11.180	15	.000	1.25000	1.0117	1.4883
DoorType	5.960	15	.000	.93750	.6022	1.2728
AccessibleToilet	4.869	15	.000	.87500	.4920	1.2580
AccessibleChanging	.000	15	1.000	.00000	-.4351	.4351
AccessibleTable	1.046	14	.313	.16667	-.1751	.5085
Handrails	1.499	15	.155	.31250	-.1320	.7570
RoadSurface	6.874	14	.000	.90000	.6192	1.1808
RoadSlope	8.295	15	.000	1.06250	.7895	1.3355
SpaceToTurn	1.074	15	.300	.25000	-.2461	.7461
RampGradient	3.478	15	.003	.62500	.2420	1.0080
LiftToAll	9.922	15	.000	1.18750	.9324	1.4426
AccessibleCarPark	7.750	14	.000	1.03333	.7474	1.3193
PersonalAssistance	1.246	15	.232	.18750	-.1333	.5083

Requirements for the People using Wheelchair (Manual) in Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	12	2.7500	1.13818	.32856
Entrance	12	3.5833	.51493	.14865
DoorType	12	3.0833	1.16450	.33616
AccessibleToilet	12	3.2500	.96531	.27866
AccessibleChanging	12	2.4167	.90034	.25990
AccessibleTable	11	2.8182	.60302	.18182
Handrails	12	2.3333	.98473	.28427
RoadSurface	12	3.0000	.85280	.24618
RoadSlope	12	3.0000	.85280	.24618
SpaceToTurn	12	3.0000	1.12815	.32567
RampGradient	12	3.0000	1.12815	.32567
LiftToAll	12	3.4167	.66856	.19300
AccessibleCarPark	11	3.1818	.60302	.18182
PersonalAssistance	12	2.5000	.90453	.26112

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	.761	11	.463	.25000	-.4732	.9732
Entrance	7.288	11	.000	1.08333	.7562	1.4105
DoorType	1.735	11	.111	.58333	-.1566	1.3232
AccessibleToilet	2.691	11	.021	.75000	.1367	1.3633
AccessibleChanging	-.321	11	.754	-.08333	-.6554	.4887
AccessibleTable	1.750	10	.111	.31818	-.0869	.7233
Handrails	-.586	11	.570	-.16667	-.7923	.4590
RoadSurface	2.031	11	.067	.50000	-.0418	1.0418
RoadSlope	2.031	11	.067	.50000	-.0418	1.0418
SpaceToTurn	1.535	11	.153	.50000	-.2168	1.2168
RampGradient	1.535	11	.153	.50000	-.2168	1.2168
LiftToAll	4.750	11	.001	.91667	.4919	1.3414
AccessibleCarPark	3.750	10	.004	.68182	.2767	1.0869
PersonalAssistance	.000	11	1.000	.00000	-.5747	.5747

Appendix B

Requirements for the People using Wheelchair (Power) in Built Environment

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	12	2.7500	1.13818	.32856
Entrance	12	3.7500	.45227	.13056
DoorType	12	3.5000	.67420	.19462
AccessibleToilet	12	3.4167	.66856	.19300
AccessibleChanging	12	2.3333	.77850	.22473
AccessibleTable	12	2.7500	.62158	.17944
Handrails	12	2.5833	.79296	.22891
RoadSurface	12	3.3333	.65134	.18803
RoadSlope	12	3.3333	.65134	.18803
SpaceToTurn	12	3.1667	.71774	.20719
RampGradient	12	3.1667	.83485	.24100
LiftToAll	12	3.7500	.45227	.13056
AccessibleCarPark	12	3.1667	.71774	.20719
PersonalAssistance	12	3.0000	.60302	.17408

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	.761	11	.463	.25000	-.4732	.9732
Entrance	9.574	11	.000	1.25000	.9626	1.5374
DoorType	5.138	11	.000	1.00000	.5716	1.4284
AccessibleToilet	4.750	11	.001	.91667	.4919	1.3414
AccessibleChanging	-.742	11	.474	-.16667	-.6613	.3280
AccessibleTable	1.393	11	.191	.25000	-.1449	.6449
Handrails	.364	11	.723	.08333	-.4205	.5872
RoadSurface	4.432	11	.001	.83333	.4195	1.2472
RoadSlope	4.432	11	.001	.83333	.4195	1.2472
SpaceToTurn	3.218	11	.008	.66667	.2106	1.1227
RampGradient	2.766	11	.018	.66667	.1362	1.1971
LiftToAll	9.574	11	.000	1.25000	.9626	1.5374
AccessibleCarPark	3.218	11	.008	.66667	.2106	1.1227
PersonalAssistance	2.872	11	.015	.50000	.1169	.8831

B.2 The People with Mobility Difficulties in Public Transport

Requirements for the People with Upper Limb Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	16	2.3125	.87321	.21830
Ramp	16	3.1250	1.02470	.25617
AccessibleToilet	16	2.8750	1.02470	.25617
AccessibleTable	16	2.2500	.93095	.23274
PersonalAssistance	16	2.5625	1.03078	.25769
AccessibleInterchange	16	2.8750	1.02470	.25617
AccessibleTicketMachine	16	2.7500	1.00000	.25000
AccessibleTicketHall	16	3.0000	1.03280	.25820

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.859	15	.404	-.18750	-.6528	.2778
Ramp	2.440	15	.028	.62500	.0790	1.1710
AccessibleToilet	1.464	15	.164	.37500	-.1710	.9210
AccessibleTable	-1.074	15	.300	-.25000	-.7461	.2461
PersonalAssistance	.243	15	.812	.06250	-.4868	.6118
AccessibleInterchange	1.464	15	.164	.37500	-.1710	.9210
AccessibleTicketMachine	1.000	15	.333	.25000	-.2829	.7829
AccessibleTicketHall	1.936	15	.072	.50000	-.0503	1.0503

Requirements for the People with Light Upper Body Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	13	2.2308	.83205	.23077
Ramp	13	2.9231	1.03775	.28782
AccessibleToilet	13	3.0769	1.03775	.28782
AccessibleTable	13	2.2308	.83205	.23077
PersonalAssistance	13	2.6923	1.10940	.30769
AccessibleInterchange	13	3.0769	1.03775	.28782
AccessibleTicketMachine	13	2.7692	1.01274	.28088
AccessibleTicketHall	13	2.9231	1.03775	.28782

Appendix B

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-1.167	12	.266	-.26923	-.7720	.2336
Ramp	1.470	12	.167	.42308	-.2040	1.0502
AccessibleToilet	2.004	12	.068	.57692	-.0502	1.2040
AccessibleTable	-1.167	12	.266	-.26923	-.7720	.2336
PersonalAssistance	.625	12	.544	.19231	-.4781	.8627
AccessibleInterchange	2.004	12	.068	.57692	-.0502	1.2040
AccessibleTicketMachine	.959	12	.357	.26923	-.3428	.8812
AccessibleTicketHall	1.470	12	.167	.42308	-.2040	1.0502

Requirements for the People with Severe Upper Body Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	11	2.3636	.80904	.24393
Ramp	11	3.2727	1.00905	.30424
AccessibleToilet	11	2.9091	1.04447	.31492
AccessibleTable	11	2.2727	.90453	.27273
PersonalAssistance	11	2.7273	1.00905	.30424
AccessibleInterchange	11	3.2727	1.00905	.30424
AccessibleTicketMachine	11	2.9091	1.04447	.31492
AccessibleTicketHall	11	3.2727	1.00905	.30424

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	-.559	10	.588	-.13636	-.6799	.4072
Ramp	2.540	10	.029	.77273	.0948	1.4506
AccessibleToilet	1.299	10	.223	.40909	-.2926	1.1108
AccessibleTable	-.833	10	.424	-.22727	-.8349	.3804
PersonalAssistance	.747	10	.472	.22727	-.4506	.9052
AccessibleInterchange	2.540	10	.029	.77273	.0948	1.4506
AccessibleTicketMachine	1.299	10	.223	.40909	-.2926	1.1108
AccessibleTicketHall	2.540	10	.029	.77273	.0948	1.4506

Requirements for the People with Light Walking Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	11	2.0909	.70065	.21125
Ramp	11	2.3636	.80904	.24393
AccessibleToilet	11	2.4545	1.03573	.31228
AccessibleTable	11	2.0000	.77460	.23355
PersonalAssistance	11	2.4545	1.03573	.31228
AccessibleInterchange	11	2.6364	1.12006	.33771
AccessibleTicketMachine	11	2.3636	.80904	.24393
AccessibleTicketHall	11	2.5455	.93420	.28167

One-Sample Test

	Test Value = 2.5					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
SignLevel	-1.936	10	.082	-.40909	-.8798	.0616
Ramp	-.559	10	.588	-.13636	-.6799	.4072
AccessibleToilet	-.146	10	.887	-.04545	-.7413	.6504
AccessibleTable	-2.141	10	.058	-.50000	-1.0204	.0204
PersonalAssistance	-.146	10	.887	-.04545	-.7413	.6504
AccessibleInterchange	.404	10	.695	.13636	-.6161	.8888
AccessibleTicketMachine	-.559	10	.588	-.13636	-.6799	.4072
AccessibleTicketHall	.161	10	.875	.04545	-.5821	.6731

Requirements for the People with Severe Walking Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	16	2.4375	.96393	.24098
Ramp	16	3.1250	1.02470	.25617
AccessibleToilet	16	2.8750	1.02470	.25617
AccessibleTable	16	2.1875	.75000	.18750
PersonalAssistance	16	2.5000	1.09545	.27386
AccessibleInterchange	16	2.9375	1.12361	.28090
AccessibleTicketMachine	16	2.9375	1.12361	.28090
AccessibleTicketHall	16	3.0625	1.12361	.28090

Appendix B

One-Sample Test

	Test Value = 2.5					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
SignLevel	-.259	15	.799	-.06250	-.5761	.4511
Ramp	2.440	15	.028	.62500	.0790	1.1710
AccessibleToilet	1.464	15	.164	.37500	-.1710	.9210
AccessibleTable	-1.667	15	.116	-.31250	-.7121	.0871
PersonalAssistance	.000	15	1.000	.00000	-.5837	.5837
AccessibleInterchange	1.557	15	.140	.43750	-.1612	1.0362
AccessibleTicketMachine	1.557	15	.140	.43750	-.1612	1.0362
AccessibleTicketHall	2.002	15	.064	.56250	-.0362	1.1612

Requirements for the People with Wheelchair (Manual) Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	16	2.4375	.96393	.24098
Ramp	16	3.1250	1.02470	.25617
AccessibleToilet	16	2.8750	1.02470	.25617
AccessibleTable	16	2.1875	.75000	.18750
PersonalAssistance	16	2.5000	1.09545	.27386
AccessibleInterchange	16	2.9375	1.12361	.28090
AccessibleTicketMachine	16	2.9375	1.12361	.28090
AccessibleTicketHall	16	3.0625	1.12361	.28090

One-Sample Test

	Test Value = 2.5					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
SignLevel	-.259	15	.799	-.06250	-.5761	.4511
Ramp	2.440	15	.028	.62500	.0790	1.1710
AccessibleToilet	1.464	15	.164	.37500	-.1710	.9210
AccessibleTable	-1.667	15	.116	-.31250	-.7121	.0871
PersonalAssistance	.000	15	1.000	.00000	-.5837	.5837
AccessibleInterchange	1.557	15	.140	.43750	-.1612	1.0362
AccessibleTicketMachine	1.557	15	.140	.43750	-.1612	1.0362
AccessibleTicketHall	2.002	15	.064	.56250	-.0362	1.1612

Requirements for the People with Wheelchair (Power) Limitations in Public Transport

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SignLevel	12	2.6667	.98473	.28427
Ramp	12	3.5000	.90453	.26112
AccessibleToilet	12	3.0000	1.04447	.30151
AccessibleTable	12	2.2500	.86603	.25000
PersonalAssistance	12	3.0000	1.04447	.30151
AccessibleInterchange	12	3.3333	.98473	.28427
AccessibleTicketMachine	12	2.8333	1.02986	.29729
AccessibleTicketHall	12	3.3333	.98473	.28427

One-Sample Test

	Test Value = 2.5					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SignLevel	.586	11	.570	.16667	-.4590	.7923
Ramp	3.830	11	.003	1.00000	.4253	1.5747
AccessibleToilet	1.658	11	.125	.50000	-.1636	1.1636
AccessibleTable	-1.000	11	.339	-.25000	-.8002	.3002
PersonalAssistance	1.658	11	.125	.50000	-.1636	1.1636
AccessibleInterchange	2.932	11	.014	.83333	.2077	1.4590
AccessibleTicketMachine	1.121	11	.286	.33333	-.3210	.9877
AccessibleTicketHall	2.932	11	.014	.83333	.2077	1.4590

Appendix C SWRL Rules for Difficulty Category Inference

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasNoUpperBodyLimitation(?p, ?ubl)
^ UpperLimbLimitation(?ull) ^
LightWalkingLimitation(?lowerLimbLimitation) ^ Person(?p) ^
hasLowerLimbLimitation(?p, ?lowerLimbLimitation) ^
UpperBodyLimitation(?ubl) -> CategoryNNL(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasNoUpperBodyLimitation(?p, ?ubl)
^ hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
Person(?p) ^ SevereWalkingLimitation(?lll) ^ UpperBodyLimitation(?ubl)
-> CategoryNNS(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasNoUpperBodyLimitation(?p, ?ubl)
^ ManualWheelchairLimitation(?lll) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ Person(?p) ^ UpperBodyLimitation(?ubl) ->
CategoryNNWM(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasNoUpperBodyLimitation(?p, ?ubl)
^ hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
PowerWheelchairLimitation(?lll) ^ Person(?p) ^ UpperBodyLimitation(?ubl
-> CategoryNNWP(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ UpperLimbLimitation(?ull) ^
hasUpperBodyLimitation(?p, ?upperBodyLimitation) ^
LightWalkingLimitation(?lowerLimbLimitation) ^
LightUpperBodyLimitation(?upperBodyLimitation) ^ Person(?p) ^
hasLowerLimbLimitation(?p, ?lowerLimbLimitation) -> CategoryNLL(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ UpperLimbLimitation(?ull) ^
hasUpperBodyLimitation(?p, ?upperBodyLimitation) ^
SevereWalkingLimitation(?lowerLimbLimitation) ^
LightUpperBodyLimitation(?upperBodyLimitation) ^ Person(?p) ^
hasLowerLimbLimitation(?p, ?lowerLimbLimitation) -> CategoryNLS(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ UpperLimbLimitation(?ull) ^
hasUpperBodyLimitation(?p, ?upperBodyLimitation) ^
LightUpperBodyLimitation(?upperBodyLimitation) ^ Person(?p) ^
ManualWheelchairLimitation(?lowerLimbLimitation) ^
hasLowerLimbLimitation(?p, ?lowerLimbLimitation) -> CategoryNLWM(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ UpperLimbLimitation(?ull) ^
hasUpperBodyLimitation(?p, LightUpperBodyLimitation) ^ Person(?p) ^
hasLowerLimbLimitation(?p, PowerWheelchairLimitation) ->
CategoryNLWP(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ LightWalkingLimitation(?lll) ^ Person(?p) ^
SevereUpperBodyLimitation(?ubl) ^ hasUpperBodyLimitation(?p, ?ubl) ->
CategoryNSL(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ Person(?p) ^ SevereWalkingLimitation(?lll)
^ SevereUpperBodyLimitation(?ubl) ^ hasUpperBodyLimitation(?p, ?ubl) ->
CategoryNSS(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ ManualWheelchairLimitation(?lll) ^
hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
Person(?p) ^ SevereUpperBodyLimitation(?ubl) ^
hasUpperBodyLimitation(?p, ?ubl) -> CategoryNSWM(?p)
```

```
hasNoUpperLimbLimitation(?p, ?ull) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ PowerWheelchairLimitation(?lll) ^ Person(?p
^ SevereUpperBodyLimitation(?ubl) ^ hasUpperBodyLimitation(?p, ?ubl) ->
CategoryNSWP(?p)
```

```
hasNoUpperBodyLimitation(?p, ?ubl) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ LightWalkingLimitation(?lll) ^ Person(?p) ^
hasUpperLimbLimitation(?p, ?ull) ^ UpperBodyLimitation(?ubl) ->
CategoryUNL(?p)
```

```
hasNoUpperBodyLimitation(?p, ?ubl) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ SevereWalkingLimitation(?lll) ^ Person(?p)
^ hasUpperLimbLimitation(?p, ?ull) ^ UpperBodyLimitation(?ubl) ->
CategoryUNS(?p)
```

```
Person(?p) ^ hasNoUpperBodyLimitation(?p, ?ubl) ^
ManualWheelchairLimitation(?lll) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ hasUpperLimbLimitation(?p, ?ull) ^
UpperBodyLimitation(?ubl) -> CategoryUNWM(?p)
```

```
hasNoUpperBodyLimitation(?p, ?ubl) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ PowerWheelchairLimitation(?lll) ^ Person(?p
^ hasUpperLimbLimitation(?p, ?ull) ^ UpperBodyLimitation(?ubl) ->
CategoryUNWP(?p)
```

```
hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
LightWalkingLimitation(?lll) ^ Person(?p) ^
hasUpperLimbLimitation(?p, ?ull) ^ hasUpperBodyLimitation(?p, ?ubl) ^
LightUpperBodyLimitation(?ubl) -> CategoryULL(?p)
```

```
hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
SevereWalkingLimitation(?lll) ^ Person(?p) ^
hasUpperLimbLimitation(?p, ?ull) ^ hasUpperBodyLimitation(?p, ?ubl) ^
LightUpperBodyLimitation(?ubl) -> CategoryULS(?p)
```

Appendix C

```
ManualWheelchairLimitation(?lll) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ Person(?p) ^
hasUpperLimbLimitation(?p, ?ull) ^ hasUpperBodyLimitation(?p, ?ubl) ^
LightUpperBodyLimitation(?ubl) -> CategoryULWM(?p)
```

```
hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
PowerWheelchairLimitation(?lll) ^ Person(?p) ^
hasUpperLimbLimitation(?p, ?ull) ^ hasUpperBodyLimitation(?p, ?ubl) ^
LightUpperBodyLimitation(?ubl) -> CategoryULWP(?p)
```

```
hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
LightWalkingLimitation(?lll) ^ Person(?p) ^
SevereUpperBodyLimitation(?ubl) ^ hasUpperBodyLimitation(?p, ?ubl) ^
hasUpperLimbLimitation(?p, ?ull) -> CategoryUSL(?p)
```

```
hasLowerLimbLimitation(?p, ?lll) ^ UpperLimbLimitation(?ull) ^
Person(?p) ^ SevereWalkingLimitation(?lll) ^
SevereUpperBodyLimitation(?ubl) ^ hasUpperBodyLimitation(?p, ?ubl) ^
hasUpperLimbLimitation(?p, ?ull) -> CategoryUSS(?p)
```

```
ManualWheelchairLimitation(?lll) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ Person(?p) ^ SevereUpperBodyLimitation(?ubl
^ hasUpperBodyLimitation(?p, ?ubl) ^ hasUpperLimbLimitation(?p, ?ull) -
CategoryUSWM(?p)
```

```
hasUpperLimbLimitation(?p, ?ull) ^ hasLowerLimbLimitation(?p, ?lll) ^
UpperLimbLimitation(?ull) ^ PowerWheelchairLimitation(?lll) ^ Person(?p
^ SevereUpperBodyLimitation(?ubl) ^ hasUpperBodyLimitation(?p, ?ubl) ->
CategoryUSWP(?p)
```

Appendix D OWL2-RL Rulesets in MODO

```
Prefices
{
  rdf   : http://www.w3.org/1999/02/22-rdf-syntax-ns#
  modo   : http://purl.org/net/ontology/modo#
  owl   : http://www.w3.org/2002/07/owl#
}
Axioms
{
 // ============================================================================
 // RDF axiomatic triples
 // ============================================================================
 // The following RDF axiomatic triples were taken from here:
 // http://www.w3.org/TR/rdf-mt/#RDFINTERP
 // ============================================================================
  <rdf:type> <rdf:type> <rdf:Property>
 <rdf:subject> <rdf:type> <rdf:Property>
 <rdf:predicate> <rdf:type> <rdf:Property>
 <rdf:object> <rdf:type> <rdf:Property>
 <rdf:first> <rdf:type> <rdf:Property>
 <rdf:rest> <rdf:type> <rdf:Property>
 <rdf:value> <rdf:type> <rdf:Property>
 <rdf:_1> <rdf:type> <rdf:Property>
 <rdf:nil> <rdf:type> <rdf:List>}
Rules
{
 // ============================================================================
 // NNL NNS NNWM NNWP
 // ============================================================================
Id:category_nnl
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNNL>

Id:category_nns
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:SevereWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNNS>

Id:category_nnwm
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:ManualWheelchairLimitation>
  -------------------------------
```

```
  x <rdf:type> <modo:CategoryNNWM>

Id:category_nnwp
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:PowerWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNNWP>

 // ==========================================================================
 // NLL NLS NLWM NLWP
 // ==========================================================================

Id:category_nll
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNLL>

Id:category_nls
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:SevereWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNLS>


Id:category_nlwm
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:ManualWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNLWM>

Id:category_nlwp
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:PowerWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNLWP>


 // ==========================================================================
 // NSL NSS NSWM NSWP
 // ==========================================================================

Id:category_nsl
  x <rdf:type> <modo:Person>
```

```
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNSL>

Id:category_nss
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:SevereWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNSS>

Id:category_nswm
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:ManualWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNSWM>

Id:category_nswp
  x <rdf:type> <modo:Person>
  x <modo:hasNoUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:PowerWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryNSWP>

 // ==========================================================================
 // UNL UNS UNWM UNWP
 // ==========================================================================

Id:category_unl
  x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryUNL>

Id:category_uns
  x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:SevereWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryUNS>


Id:category_unwm
  x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
```

```
   x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
   x <modo:hasLowerLimbLimitation> <modo:ManualWheelchairLimitation>
   -------------------------------
   x <rdf:type> <modo:CategoryUNWM>

Id:category_unwp
   x <rdf:type> <modo:Person>
   x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
   x <modo:hasNoUpperBodyLimitation> <modo:UpperBodyLimitation>
   x <modo:hasLowerLimbLimitation> <modo:PowerWheelchairLimitation>
   -------------------------------
   x <rdf:type> <modo:CategoryUNWP>

// ============================================================================
// ULL ULS ULWM ULWP
// ============================================================================

Id:category_ull
   x <rdf:type> <modo:Person>
   x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
   x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
   x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
   -------------------------------
   x <rdf:type> <modo:CategoryULL>

Id:category_uls
   x <rdf:type> <modo:Person>
   x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
   x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
   x <modo:hasLowerLimbLimitation> <modo:SevereWalkingLimitation>
   -------------------------------
   x <rdf:type> <modo:CategoryULS>

Id:category_ulwm
   x <rdf:type> <modo:Person>
   x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
   x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
   x <modo:hasLowerLimbLimitation> <modo:ManualWheelchairLimitation>
   -------------------------------
   x <rdf:type> <modo:CategoryULWM>

Id:category_ulwp
   x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
   x <modo:hasUpperBodyLimitation> <modo:LightUpperBodyLimitation>
   x <modo:hasLowerLimbLimitation> <modo:PowerWheelchairLimitation>
   -------------------------------
   x <rdf:type> <modo:CategoryULWP>
// ============================================================================
 // USL USS USWM USWP
 // ============================================================================

Id:category_usl
   x <rdf:type> <modo:Person>
```

```
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:LightWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryUSL>

Id:category_uss
  x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:SevereWalkingLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryUSS>


Id:category_uswm
  x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:ManualWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryUSWM>

Id:category_uswp
  x <rdf:type> <modo:Person>
  x <modo:hasUpperLimbLimitation> <modo:UpperLimbLimitation>
  x <modo:hasUpperBodyLimitation> <modo:SevereUpperBodyLimitation>
  x <modo:hasLowerLimbLimitation> <modo:PowerWheelchairLimitation>
  -------------------------------
  x <rdf:type> <modo:CategoryUSWP>
}
```

Appendix E SPARQL Query to publish the Data

```
PREFIX taco: < http: //purl.org/net/ontology/taco#>
PREFIX paco: < http: //purl.org/net/ontology/paco#>
PREFIX schema: < http: //schema.org/>
PREFIX geo: < http: //www.w3.org/2003/01/geo/wgs84_pos#>
PREFIX spatialrelations: < http: //data.ordnancesurvey.co.uk/ontology/spatialrelations/>
PREFIX rdf: < http: //www.w3.org/1999/02/22-rdf-syntax-ns#>

INSERT {

  paco: AccessibleToilet_Floor_1_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: AccessibleToilet_Floor_3_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Building32_University_of_Southampton spatialrelations: within paco:
UniversityOfSouthampton.
  paco: CentralEntranceDoor_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: CentralEntrance_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Door_Room1_Floor1_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Door_Room3049_Floor3_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: FemaleToilet_Floor_1_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: FemaleToilet_Floor_3_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Floor_1_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Floor_2_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Floor_3_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Floor_4_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: MaleToilet_Floor_1_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: MaleToilet_Floor_3_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: NorthEntranceDoor_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: NorthEntrance_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: NorthLift_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Ramp_SouthEntrance_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Room1_Floor1_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Room3049_Floor3_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: Sign_SouthEnrance_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: SouthEntranceDoor_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: SouthEntrance_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: SouthLift_B32 spatialrelations: within paco: UniversityOfSouthampton.
  paco: UniversityOfSouthampton spatialrelations: contains paco: AccessibleToilet_Floor_1_B32,
  paco: AccessibleToilet_Floor_3_B32,
  paco: Building32_University_of_Southampton,
  paco: CentralEntranceDoor_B32,
  paco: CentralEntrance_B32,
  paco: Door_Room1_Floor1_B32,
  paco: Door_Room3049_Floor3_B32,
  paco: FemaleToilet_Floor_1_B32,
  paco: FemaleToilet_Floor_3_B32,
  paco: Floor_1_B32,
  paco: Floor_2_B32,
  paco: Floor_3_B32,
  paco: Floor_4_B32,
  paco: MaleToilet_Floor_1_B32,
  paco: MaleToilet_Floor_3_B32,
```

paco: NorthEntranceDoor_B32,
paco: NorthEntrance_B32,
paco: NorthLift_B32,
paco: Ramp_SouthEntrance_B32,
paco: Room1_Floor1_B32,
paco: Room3049_Floor3_B32,
paco: Sign_SouthEnrance_B32,
paco: SouthEntranceDoor_B32,
paco: SouthEntrance_B32,
paco: SouthLift_B32;
a paco: Place,
schema: Place,
rdfs: Resource,

owl: NamedIndividual,
owl: Thing;
owl: sameAs paco: UniversityOfSouthampton;
owl: topObjectProperty paco: AccessibleToilet_Floor_1_B32,

paco: AccessibleToilet_Floor_3_B32,
paco: Building32_University_of_Southampton,
paco: CentralEntranceDoor_B32,
paco: CentralEntrance_B32,
paco: Door_Room1_Floor1_B32,
paco: Door_Room3049_Floor3_B32,
paco: FemaleToilet_Floor_1_B32,
paco: FemaleToilet_Floor_3_B32,
paco: Floor_1_B32,
paco: Floor_2_B32,
paco: Floor_3_B32,
paco: Floor_4_B32,
paco: MaleToilet_Floor_1_B32,
paco: MaleToilet_Floor_3_B32,
paco: NorthEntranceDoor_B32,
paco: NorthEntrance_B32,
paco: NorthLift_B32,
paco: Ramp_SouthEntrance_B32,
paco: Room1_Floor1_B32,
paco: Room3049_Floor3_B32,
paco: Sign_SouthEnrance_B32,
paco: SouthEntranceDoor_B32,
paco: SouthEntrance_B32,
paco: SouthLift_B32.

}

Bibliography

1. Aguirre, J., Grau, B., and Eckert, K. Results of the Ontology Alignment Evaluation Initiative. *Procceeding of 7th ISWC workshop on ontology matching (OM)*, (2012).

2. Alonso, K., Aginako, N., Lozano, J., and Olaizola, I. Ontology based middleware for ranking and retrieving information on locations adapted for people with special needs. *Computers Helping People with Special Needs*, (2012), 351–354.

3. Auer, S., Bizer, C., Kobilarov, G., Lehmann, J., Cyganiak, R., and Ives, Z. DBpedia: A Nucleus for a Web of Open Data. In Springer Berlin Heidelberg, 2007, 722–735.

4. Aumueller, D., Do, H.-H., Massmann, S., and Rahm, E. Schema and ontology matching with COMA++. *Proceedings of the 2005 ACM SIGMOD international conference on Management of data - SIGMOD '05*, (2005), 906.

5. Ayhan, M.B. A Fuzzy AHP Approach for Supplier Selection Problem: A Case Study in a Gearmotor Company. *Internation Journal of Managing Value and Supply Chains (IJMVSC) 4*, 3 (2013), 11–23.

6. Azevedo, F., Vale, Z., and Oliveira, P. A decision-support system based on particle swarm optimization for multiperiod hedging in electricity markets. *IEEE Transactions on Power Systems 22*, 3 (2007), 995–1003.

7. Baron, L., Achiche, S., and Balazinski, M. Fuzzy decision support system knowledge base generation using a genetic algorithm. *International Journal of Approximate Reasoning 28*, 2–3 (2001), 125–148.

8. Beale, L., Field, K., Briggs, D., Picton, P., and Matthews, H. Mapping for Wheelchair Users: Route Navigation in Urban Spaces. *The Cartographic Journal 43*, 1 (2006), 68–81.

9. Bekiaris, E., Panou, M., and Mousadakou, A. Elderly and disabled travelers needs in infomobility services. *Universal Acess in Human Computer Interaction. Coping with Diversity (2007)*, (2007), 853–860.

10. Bhargava, H. and Power, D.J. Decision support systems and web technologies: a status report. *Proceedings of the 7th Americas Conference on Information Systems AMCIS 01*, (2001), 3–5.

11. Bhargava, H.K., Power, D.J., and Sun, D. Progress in Web-based decision support technologies. *Decision Support Systems 43*, 4 (2007), 1083–1095.

12. Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Chen, Q. and Weston, L. *Development of an urban accessibility index: Literature review*. 2000.

13. Bizer, C., Heath, T., and Berners-Lee, T. Linked data-the story so far. *International Journal on Semantic Web*

and Information Systems (IJSWIS) 5, 3 (2009), 1–22.

14. Blichfeldt, B.S. and Nicolaisen, J. Disabled travel: not easy, but doable. *Current Issues in Tourism 14*, 1 (2011), 79–102.

15. Blomqvist, E. The use of Semantic Web technologies for decision support–a survey. *Semantic Web*, (2012), 1–24.

16. Buhalis, D. and Darcy, S. *Accessible Tourism: Concepts and Issues*. Channel View Publications, 2010.

17. Caldiera, V. and Rombach, H. The goal question metric approach. *Encyclopedia of software engineering 2*, (1994), 1–10.

18. Cardonha, C. and Gallo, D. A crowdsourcing platform for the construction of accessibility maps. *Proceedings of the 10th International Cross-Disciplinary Conference on Web Accessibility - W4A '13*, (2013), 1.

19. Carmien, S., Dawe, M., Fischer, G., Gorman, A., Kintsch, A., and Sullivan, J.F. Socio-technical environments supporting people with cognitive disabilities using public transportation. *ACM Transactions on Computer-Human Interaction 12*, 2 (2005), 233–262.

20. Catak, F., Karabas, S., and Yildirim, S. Fuzzy Analytic Hierarchy Based DBMS Selection In Turkish National Identity Card Management Project. *International Journal of Information 2*, 4 (2012), 29–38.

21. Cebeci, U. Fuzzy AHP-based decision support system for selecting ERP systems in textile industry by using balanced scorecard. *Expert Systems with Applications 36*, 5 (2009), 8900–8909.

22. Chen, Z. *Computational intelligence for decision support*. CRC Press, 2010.

23. Chou, S. and Chang, Y. A decision support system for supplier selection based on a strategy-aligned fuzzy SMART approach. *Expert Systems with Applications 34*, 4 (2008), 2241–2253.

24. Courtney, J.F. Decision making and knowledge management in inquiring organizations: toward a new decision-making paradigm for DSS. *Decision Support Systems 31*, 1 (2001), 17–38.

25. Crossland, M.D., Wynne, B.E., and Perkins, W.C. Spatial decision support systems: An overview of technology and a test of efficacy. *Decision Support Systems 14*, 3 (1995), 219–235.

26. Crowley, D.N., Dabrowski, M., and Breslin, J.G. Decision Support using Linked, Social, and Sensor Data. *19th Americas Conference on Information Systems (AMCIS)*, (2013).

27. Ding, C., Wald, M., and Wills, G. Linked data for accessibility: from techniques to users. *Proceedings of the 11th International Conference e-Society 2013*, IADIS (2013), 514–516.

28. Ding, C., Wald, M., and Wills, G. Travelling for all. *Proceedings of the 11th International Conference e-Society 2013*, IADIS (2013), 519–522.

29. Ding, C., Wald, M., and Wills, G. A Survey of Open Accessibility Data. *Proceedings of 13th International Web for All Conference - W4A '14*, ACM (2014), 73–80.

30. Ding, C., Wald, M., and Wills, G. Open Accessibility Data Interlinking. *Proceedings of The 14th International Conference on Computers Helping People with Special Needs (ICCHP)*, (2014), 73–80.

31. Do, H.-H. and Rahm, E. COMA: a system for flexible combination of schema matching approaches. *Proceedings of the 28th international conference on Very Large Data Bases*, (2002), 610–621.

32. Doan, A. and Madhavan, J. Learning to match ontologies on the semantic web. *The VLDB Journal—The International Journal on Very Large Data Bases*, Springer-Verlag New York, Inc. (2003), 303–319.

33. Doan, A., Madhavan, J., Domingos, P., and Halevy, A. Ontology Matching : A Machine Learning Approach. *Handbook on ontologies in information systems*, (2004), 397--416.

34. Draper, B. a., Baek, K., Bartlett, M.S., and Beveridge, J.R. Recognizing faces with PCA and ICA. *Computer Vision and Image Understanding 91*, 1–2 (2003), 115–137.

35. Du, J., Jiang, R., and Hu, Y. Multi-criteria axiom ranking based on analytic hierarchy process. *Communications in Computer and Information Science 406*, (2013), 118–131.

36. Ebner, H. and Palmér, M. LDCache - A cache for linked data-driven web applications. *CEUR Workshop Proceedings*, (2014), 67–73.

37. El-Hachem, J., Shaban-Nejad, A., Haarslev, V., DubŽ, L., and Buckeridge, D.L. An OWL 2-Based Knowledge Platform Combining the Social and Semantic Webs for an Ambient Childhood Obesity Prevention System. *Procedia Computer Science 10*, (2012), 110–119.

38. Euzenat, J. and Shvaiko, P. *Ontology matching*. Springer Heidelberg, 2007.

39. Fenton, N. and Pfleeger, S. *Software metrics: a rigorous and practical approach*. 1998.

40. Field, M.J. and Jette, A.M. *Transportation Patterns and Problems of People with Disabilities*. National Academies Press (US), 2007.

41. Geurs, K.T. and van Wee, B. Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography 12*, 2 (2004), 127–140.

42. Ghorbel, M., Kadouche, R., and Mokhtari, M. User & service modelling in assistive environment to enhance accessibility of dependent people. *The first International Conference on ICT & Accessibility*, (2007).

43. Gkemou, M., Bekiaris, E., and Isacker, K. Van. An end-user evaluation point of view towards OSS assistive technology. *Universal Access in Human-Computer Interaction. Design for All and eInclusion*, (2011), 225–234.

44. Gray, A.J.G., Sadler, J., Kit, O., et al. A semantic sensor web for environmental decision support applications. *Sensors (Basel, Switzerland) 11*, 9 (2011), 8855–87.

45. Guarino, N., Oberle, D., Staab, S., and Studer, R. Handbook on Ontologies. (2009), 1–17.

46. Gunawardana, A. and Shani, G. A survey of accuracy evaluation metrics of recommendation tasks. *The Journal of Machine Learning Research 10*, (2009), 2935–2962.

47. Guriano, N. Understanding, Building, and Using Ontologies/A Commentary to “Using Explicit Ontologies in KBS Development.” *International Journal of Human and Computer Studies*, (1997).

48. Halevy, A., Ives, Z., Mork, P., and Tatarinov, I. Piazza: Data management infrastructure for semantic web applications. *Proceedings of the 12th international conference on World Wide Web*, (2003).

49. Hausenblas, M. Linked data applications. *First Community Draft, DERI*, July (2009).

50. Henricksen, K. and Indulska, J. Developing context-aware pervasive computing applications: Models and approach. *Pervasive and Mobile Computing 2*, 1 (2006), 37–64.

51. Ho, W., Xu, X., and Dey, P.K. Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *European Journal of Operational Research 202*, 1 (2010), 16–24.

52. Holland, J. *Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence.* 1975.

53. Holone, H. and Misund, G. People helping computers helping people: Navigation for people with mobility problems by sharing accessibility annotations. *Computers Helping People with Special Needs*, (2008).

54. Ian Horrocks and Peter F. Patel-Schneider. Knowledge Representation and Reasoning on the Semantic Web: OWL. (2010).

55. Jain, P., Hitzler, P., Sheth, A., Verma, K., and Yeh, P. Ontology alignment for linked open data. *International Semantic Web Conference*, Springer Berlin Heidelberg (2010), 402–417.

56. Kadouche, R. and Mokhtari, M. Personalization in smart homes for disabled people. *2008 Second International Conference on Future Generation Communication and Networking 2*, IEEE (2008), 411–415.

57. Kämpgen, B., Riepl, D., and Klinger, J. SMART Research using Linked Data–Sharing Research Data for Integrated Water Resources Management in the Lower Jordan Valley. *Mayor2.Dia.Fi.Upm.Es*, , 1–12.

58. Karimi, H., Zhang, L., and Benner, J. Personalized accessibility maps (PAMs) for communities with special needs. *International Symposium on Web and Wireless Geographical Information Systems*, Springer Berlin Heidelberg (2013), 199–213.

59. Kawanaka, S., Kobayashi, M., Takagi, H., and Asakawa, C. Accessibility commons: a metadata repository for web accessibility. *ACM SIGWEB Newsletter*, Summer (2009), 1–7.

60. Khalili, A., Loizou, A., and Van Harmelen, F. Adaptive Linked Data-driven Web Components: Building Flexible and Reusable Semantic Web Interfaces. .

61. Korn, P., Bekiaris, E., and Gemou, M. Towards Open Access Accessibility Everywhere : The ÆGIS Concept. *Universal Access in Human-Computer Interaction. Addressing Diversity*, (2009), 535–543.

62. Kuo, R.J. and Lin, L.M. Application of a hybrid of genetic algorithm and particle swarm optimization algorithm for order clustering. *Decision Support Systems 49*, 4 (2010), 451–462.

63. Kwan, M. Geographical Analysis in the Twenty-first Century. *Geographical Analysis 35*, 4 (2003).

64. Lee, C.-S., Wang, M.-H., and Chen, J.-J. Ontology-based intelligent decision support agent for CMMI project monitoring and control. *International Journal of Approximate Reasoning 48*, 1 (2008), 62–76.

65. Li, N., Raskin, R., Goodchild, M., and Janowicz, K. An Ontology-Driven Framework and Web Portal for Spatial Decision Support. *Transactions in GIS 16*, 3 (2012), 313–329.

66. Li, Y., Draffan, E.A., Glaser, H., et al. RailGB : Using Open Accessibility Data to Help People with Disabilities. *Proceedings of the Semantic Web Challenge co-located with ISWC2012*, (2012), 1–8.

67. Litman, B.T. *Measuring Transportation: Traffic, Mobility and Accessibility*. 2011.

68. Litman, T. Evaluating Accessibility for Transportation Planning Measuring People ' s Ability To Reach Desired Goods and Activities. *Victoria Transport Policy Institute website. Accessed: May*, January 2008 (2012).

69. Lopez, V., Sabou, M., and Motta, E. PowerMap : Mapping the Real Semantic Web on the Fly. *International Semantic Web Conference*, Springer Berlin Heidelberg (2006), 414–427.

70. Ma, J., Lu, J., and Zhang, G. Decider: A fuzzy multi-criteria group decision support system. *Knowledge-Based Systems 23*, 1 (2010), 23–31.

71. Masuwa-Morgan, K.. and Burrell, P. Justification of the need for an ontology for accessibility requirements (Theoretic framework). *Interacting with Computers 16*, 3 (2004), 523–555.

72. Oertel, B., Hasse, C., and Scheermesser, M. Accessibility of Tourism Web sites within the European Union.

Proceedings of the 11th International Conference on Information and Communication Technologies in Tourism (ENTER 2004), ISBN 3, (2004), 211.

73. Oliver, M. and Sapey, B. *Social work with disabled people*. Palgrave Macmillan, 2006.

74. Önüt, S., Efendigil, T., and Soner Kara, S. A combined fuzzy MCDM approach for selecting shopping center site: An example from Istanbul, Turkey. *Expert Systems with Applications 37*, 3 (2010), 1973–1980.

75. Packer, T.L., McKercher, B., and Yau, M.K. Understanding the complex interplay between tourism, disability and environmental contexts. *Disability and rehabilitation 29*, 4 (2007), 281–92.

76. Palazzi, C., Teodori, L., and Roccetti, M. Path 2.0: A participatory system for the generation of accessible routes. *2010 IEEE International Conference on Multimedia and Expo (ICME)*, 1 (2010), 1707–1711.

77. Pawlak, Z. Rough set approach to knowledge-based decision support. *European Journal of Operational Research 99*, 1 (1997), 48–57.

78. Peter, N. *Documentation Economic Impulses of Accessible Tourism for All,Study commissioned by the Federal Ministry of Economics and Labour (BMWA)*. Berlin, Germany, 2004.

79. Prandi, C. Accessibility and Smart Data : the Case Study of mPASS. *Proceedings of 13th International Web for All Conference - W4A '14*, (2014), 9–10.

80. Pühretmair, F. It's time to make eTourism accessible. *Computers helping people with special needs*, (2004), 272–279.

81. Pühretmair, F. and Miesenberger, K. Accessible information space to promote accessible tourism. *Computers helping people with special needs*, (2006), 329–336.

82. Saaty, R.W. The analytic hierarchy process-what it is and how it is used. *Mathematical Modelling 9*, 3–5 (1987), 161–176.

83. Sabou, M., Braşoveanu, A., and Arsal, I. Supporting tourism decision making with linked data. *Proceedings of the 8th International Conference on Semantic Systems*, (2012).

84. Sanayei, A., Farid Mousavi, S., and Yazdankhah, A. Group decision making process for supplier selection with VIKOR under fuzzy environment. *Expert Systems with Applications 37*, 1 (2010), 24–30.

85. Schmöcker, J.-D., Quddus, M. a., Noland, R.B., and Bell, M.G.H. Mode choice of older and disabled people: a case study of shopping trips in London. *Journal of Transport Geography 16*, 4 (2008), 257–267.

86. Shaw, G. and Coles, T. Disability, holiday making and the tourism industry in the UK: a preliminary survey. *Tourism Management*, (2004).

87. Shi, Y. and Eberhart, R. Empirical study of particle swarm optimization. *Evolutionary Computation, 1999. CEC 99. Proceedings of the 1999 Congress on*, (1999).

88. Shim, J.P., Warkentin, M., Courtney, J.F., Power, D.J., Sharda, R., and Carlsson, C. Past, present, and future of decision support technology. *Decision support systems 33*, 2 (2002), 111–126.

89. Shvaiko, P. Ontology Matching : State of the Art and Future Challenges. *IEEE Transactions on Knowledge and Data Engineering*, (2013), 158–176.

90. Simperl, E., Acosta, M., and Norton, B. A Semantically Enabled Architecture for Crowdsourced Linked Data Management. *CrowdSearch*, (2012).

91. Sobek, A. and Miller, H. U-Access: a web-based system for routing pedestrians of differing abilities. *Journal of Geographical Systems 8*, 3 (2006), 269–287.

92. Steinfeld, A., Aziz, R.D., and Dehsen, L. Von. The value and acceptance of citizen science to promote transit accessibility. *Technology and Disability 22*, (2010), 73–81.

93. Takagi, H., Kawanaka, S., Kobayashi, M., Itoh, T., and Asakawa, C. Social accessibility. *Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility - Assets '08*, ACM Press (2008), 193.

94. Tektonidis, D. and Koumpis, A. Accessible Internet-of-Things and Internet-of-Content Services for All in the Home or on the Move. *International Journal of Interactive Mobile Technologies (iJIM) 6*, 4 (2012), 25–33.

95. Tim Berners-Lee. Linked Data - Design Issues. 2009. http://www.w3.org/DesignIssues/LinkedData.html.

96. Transport for London. Measuring Public Transport Accessibility Levels PTALs Summary. 2010.

97. Unger, C., Forascu, C., Lopez, V., et al. Question answering over linked data (QALD-5). *CEUR Workshop Proceedings 1391*, (2015).

98. Unger, C., Freitas, A., and Cimiano, P. An Introduction to Question Answering over Linked Data. *Reasoning Web: Reasoning on the Web in the Big Data Era 8714*, (2014), 100–140.

99. Vanderheiden, G. Fundamental principles and priority setting for universal usability. *Proceedings on the 2000 conference on Universal Usability - CUU '00*, (2000), 32–37.

100. Vanderheiden, G. and Treviranus, J. Creating a global public inclusive infrastructure. *Universal Access in Human-Computer Interaction. Design for All and eInclusion*, (2011), 517–526.

101. Vanderheiden, G.C., Treviranus, J., Usero, J. a. M., Bekiaris, E., Gemou, M., and Chourasia, a. O. Auto-Personalization: Theory, Practice and Cross-Platform Implementation. *Proceedings of the Human Factors*

and Ergonomics Society Annual Meeting 56, 1 (2012), 926–930.

102. Völkel, T. and Weber, G. RouteCheckr: personalized multicriteria routing for mobility impaired pedestrians. *Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility*, (2008), 185–192.

103. Wache, H., Vogele, T., Visser, U., et al. Ontology-Based Information Integration: A Survey of Existing Approaches. *International Joint Conference on Artificial Intelligence; Workshop: Ontologies and Information Sharing*, (2001), 108–117.

104. Westcott, J. *Improving information on accessible tourism for disabled people*. 2004.

105. Wiethoff, M. and Sommer, S. Specification of information needs for the development of a mobile communication platform to support mobility of people with functional limitations. *Proceedings of Universal Access in HumanComputer Interaction Ambient Interaction*, (2007), 595–604.

106. Wooldridge, M., Jennings, N., and Kinny, D. The Gaia methodology for agent-oriented analysis and design. *Autonomous Agents and multi-agent systems 3*, 3 (2000), 285–312.

107. World Health Organization. *International classification of functioning, disability and health (ICF)*. World Health Organization, Geneva, 2001.

108. Yu, L., Wang, S., and Lai, K.K. An intelligent-agent-based fuzzy group decision making model for financial multicriteria decision support: The case of credit scoring. *European Journal of Operational Research 195*, 3 (2009), 942–959.