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Fostering Urban Resilience and Accessibility in Cities: A Dynamic Knowledge Graph Approach

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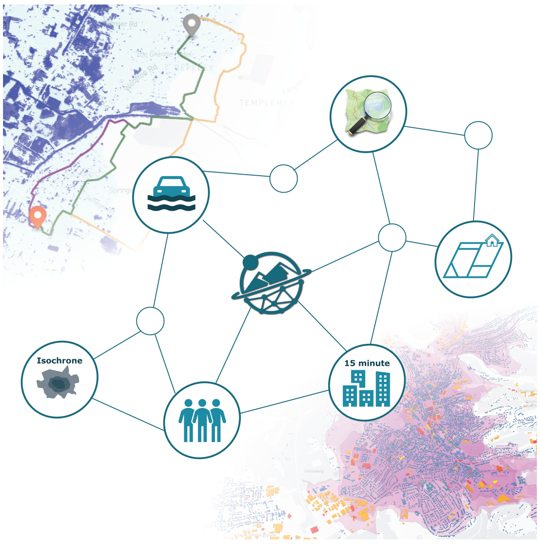
Abstract

This paper explores the utilisation of knowledge graphs to enhance urban resilience and accessibility in city planning. We expand The World Avatar (TWA) dynamic knowledge graph to support comprehensive decision-making in disaster response and urban planning. By employing an agent-based implementation approach and integrating diverse data sources—including flood data, geospatial building information, land plots, and open-source data—through sets of ontologies, we demonstrate disaster response in a coastal town in the UK and various aspects relevant to city planning for a mid-sized town in Germany using TWA. In King's Lynn, our agent-based approach facilitates holistic disaster response by calculating optimal routes, avoiding flooded segments dynamically, assessing infrastructure accessibility before and during a flood, identifying inaccessible population areas, guiding infrastructure restoration, and conducting critical path analysis. In Pirmasens, for city planning purposes, the knowledge graph-driven isochrone generation provides evidence-based insights into current amenity coverage and enables scenario planning for future amenities while adhering to land regulations. Additionally, it facilitates cross-domain correlation analysis and provides demographic insights through the representation of building information, isochrones, and population density using ontologies.



Highlights

- Development of versatile tool for disaster and city planning.
- Disaster response system that focuses on static and dynamic planning through agents interplay.
- Holistic 15-minute city planning by status quo monitoring and scenario planning.
- Cross-domain analyses in planning via the integration of complementary data sources.

Contents

1 Introduction

Global warming and climate change leads to severe weather disasters, giving rise to devastating events such as flooding [61, 65]. Around 23% of the world population are directly exposed to 1-in-100-year floods [64]. These extreme weather disasters accelerate the need for cities to be highly adaptable and responsive to unexpected events. At the same time, other rare and unprecedented global crises like the COVID-19 pandemic have emphasised the importance of a city's hyper-locality attributes [60]. Due to transport lockdown and limitations in mobility, this sped up the development of 15-minute city initiatives. The 15-minute city is a concept which emphasises that all essential services such as healthcare, employment, cultural activities, and shopping should be conveniently located within a 15-minute radius from individuals' residences [46]. These events greatly underscore the importance for cities to emphasise on agility and responsiveness to rapidly changing circumstances to attain holistic living conditions that is capable of fulfilling the residents' needs.

Cities have a wealth of information, yet they often face the hurdle of data silos and insufficient data integration. Many of the existing available data remains fragmented and untapped, *e.g.,* crowd-sourced data, building information, administrative land plots, *etc.* On top of this, current solutions in disaster response and city planning do not leverage on these data enough in their analysis. This unrealised potential in data is hindering the effectiveness of city planning and disaster response.

Effective decision making in disaster scenarios requires overcoming challenges related to the integration and the interoperability of heterogeneous datasets [40]. Many severe weather solutions primarily concentrate on disaster response; however, these solutions fall short in providing capabilities beyond geospatial analysis [35]. This situation can often result in the lack of information transfer between knowledge models which leads to poor scalability and data re-usability in systems, therefore hindering the development of a comprehensive disaster response strategy.

In 15-minute city planning, planning tools for city accessibility exhibit similar challenges in data integration and model re-usability. While there are models and applications developed by researchers that are effective in analysing 15-minute accessibility in cities, however their applicability is often limited to major cities [49] or limited to certain countries [29]. The limited attention given to smaller towns, often coupled with the lack of resources for small towns to engage premium urban planning analysis services pose challenges to the even distribution of essential amenities [38]. This can further accentuate inequality patterns in terms of social and transport mobility in economically disadvantaged or smaller cities [28].

One commonality across both challenges in disaster planning and urban planning is a high barrier of entry caused by the integration of diverse data sources. These data sources commonly come in its own formats, leading to compatibility issues and high set up time. The datasets often comprise a mix of geospatial data and tabular data, covering information about land plots, census data and building information, that can be very different in nature. This gap in data integration creates difficulties and complexities in achieving interoperability, further hindering the full potential of exploiting these data sets [20]. This scenario could lead to researchers producing one-off location and use-case-specific analyses that are difficult to scale and transfer.

The integration of various datasets poses significant difficulties, however both cases of disaster response and city planning necessitate utilising these dataset for cross-domain analysis. A knowledge graph represents individual information in a structured graphical form, capturing relationships between entities [66]. Its unique interoperability and cross-domain functionality solves many constraints in integrating various data types to derive valuable insights, making it an excellent candidate in tackling the challenges in resilience planning and urban planning solutions.

The purpose of this paper is to address the challenge of integrating population, isochrone, flood raster, and building information open-source data for resilience and urban planning. It explores the potential of applying knowledge graphs in representing this information semantically to overcome this challenge. An agent based approach is subsequently employed to utilise these instantiated information on the knowledge graph to perform tasks which includes routing avoiding floods, isochrone generation and critical path analysis.

The sections of this paper are organised as follows: Section 2 details the problem and prior technical efforts; section 3 introduces the methodology used and relevant data sources; section 4 highlights the use cases and results; and section 5 concludes the work.

2 Background

2.1 Urban Resilience

In view of current climate change, disasters have become increasingly unpredictable [33]. Cities must have the capacity to not only withstand and recover from disturbances, while also being able to plan and adapt to the constantly evolving circumstances [15]. The frequency of extreme weather events poses a substantial threat to the daily lives of individuals. This situation highlights the need for government authorities to possess the right tools and resources to act promptly and effectively during life threatening situations. During extreme weather events, such as flooding, proper emergency route planning to rescue and evacuate civilians under distress can prevent the loss of life [39]. Hence, adapting a strategy that incorporates multiple sources of data such as flood, road networks, population and emergency services locations would enhance effective resource allocation and strategical planning.

During flooding events, motorists often attempt to pass through flooded roads because they are unaware of alternative routes, which can be risky and fatal [16]. This situation can be problematic for essential vehicles (*i.e.,* ambulance, rescue trucks) which have to navigate through flooded areas swiftly and safely. The current research done on flood avoiding route planning does not use flood depth estimates in their assessments [14, 67, 76], thereby neglecting a crucial parameter that could potentially enhance the safety and effectiveness of route planning.

Other than that, some current disaster response strategies struggle with insufficient data and lack of data interconnectivity. For example, existing GIS-based emergency evacuation framework planning face challenges in assessing evacuation route planning during floods due to insufficient data [55]. One notable issue is the difficulty in accurately determining the locations of shelter houses to compute accessibility. Additionally, other studies on accessibility to critical amenities during flooding aims to enhance their comprehensiveness in disaster strategy solution by integrating population distribution and evacuation routing capability [3]. Through literature review, these disaster strategies each exhibits deficiencies in certain aspects such as insufficient data or functions. Therefore, there exists a research gap to integrate flood depth data, buildings location, population distribution to build a comprehensive, well-informed disaster response strategy.

2.2 The 15-Minute City

15-minute city is an urban planning concept developed by Carlos Moreno [46] which describes that residents should be able to satisfy their daily needs which include work, home, food, health, education, culture, sports, and leisure within 15 minutes of walking or cycling from their residence. COVID-19 pandemic has prompted a widespread shift towards the concept of 15 minutes cities as cities globally adapt in response to lockdown restrictions [41]. The constraints on mobility resulted in the increasing tendency to centralise essential amenities in close proximity. The primary objective of this movement is to ensure that all residents can conveniently access all these necessary services.

Across the globe, governments are strategically pushing for proximity based planning initiatives [54]. Notably, in Paris, the city's mayor Anne Hidalgo envisions the "Ville Du Quart D'heure" (Quarter-hour city) [62]. Singapore has introduced the "20 Minute Town, 45 Minute City Master Plan" [45], while Melbourne's Victoria government is committed to the concept of "20-Minute Neighbourhood" [68]. In Shanghai, local district authorities are advocating the idea of a "15-Minute Town" [34]. Despite variations in the specified time frames in these concepts, the common thread across these strategies is the focus on proximity-based planning and reduction on car reliance [46].

Gaining widespread attention, 15-minute city has also become a popular topic among researchers. The 20 minute city analysis was performed in Liverpool from a socio-spatial inequalities perspective [11]. The X-Minute City analysed the 500 largest cities in the United States and 43 urban areas of New Zealand in the intervals of 10, 15, 20 minutes [43]. The 20-Minute Neighbourhoods in Toronto assessed the walk-ability of neighbourhoods [69]. Similar qualitative analyses and spatial evaluations were conducted for the 15-minute city model in Oslo and Lisbon [19].

The adoption of proximity based planning can aid policymakers in strategically planning and designing liveable and densified cities that are aligned with the UN Sustainable Development Goals to create inclusive, safe, resilient, and sustainable cities [75]. Not only that, the importance of accessibility extends beyond mere convenience, it plays a crucial role in fostering a more equitable and thriving society, as having higher accessibility and better walkability in a city oftens lead to a higher quality of urban life [81].

However, as observed across the current literatures, researchers often conduct location-specific studies that may become outdated as cities and amenities evolve. While there are online applications to assess accessibility by generating isochrones - a polygon that describes the area of reach within a specified time frame, such as ‘Iso4app‘[36], ‘Geoapify‘[25] and ‘TravelTime‘[73], these existing off-the-shelf solutions do not include the existing building infrastructure in their analyses. To retrieve and integrate the results of the generated isochrones, these services come with pricing plans that allow users to request by API calls specifying accurate locations. For institutions handling sensitive data, such an approach might be unsuitable without disclosing sensitive information externally. Other more comprehensive 15-min city planning apps done by researchers, such as CityAccessMap [49] and 15-Min-City-App [29] focus only on major cities and typically these studies risk becoming obsolete over time as the urban landscape changes.

A research study commissioned by the European Union to evaluate the effectiveness of various accessibility instruments concluded that while isochrones are excellent instruments to identify low accessibility area, there is a notable challenge on the integration of diverse data sources from various sources such as land use [71]. Other urban planning tools that generate isochrones in Germany have been assessed and found to exhibit limitations, particularly in their location-specific focus [32]. These tools face challenges when attempting to scale to measure specific indicators (*i.e.,* accessibility to certain amenities) in diverse regions [32]. These scenarios underscore the need for an enhanced methodology to create a versatile tool adaptable to the dynamic needs of a city, operate independent of location and capable of seamlessly incorporating diverse data into analyses.

2.3 The World Avatar (TWA)

The World Avatar (TWA) project [2] objective is to construct a digital ‘avatar’ of the world. The core concept behind TWA revolves around building an all-encompassing world model to facilitate interoperability between previously isolated yet conceptually connected domains, encompassing both knowledge and data. TWA relies on semantic web technologies and employs a dynamic knowledge graph to semantically describes relationships between concepts and instances. The term ‘dynamic’ signifies that TWA integrates ontologies (*i.e.,* data definitions) with the actual data instances (*i.e.,* from API), and also the computational services (*i.e.,* agents) that operate on the instantiated data [31].

TWA is modular and scalable by design, and new concepts and relationships can be added continuously while maintaining connections to everything existing. It allows decentralisation and enables interoperability across heterogeneous data sources and software. The intelligent agents that are part of TWA act as executable knowledge component, keeping the system current in time and self-evolving. "Agent" commonly refers to software, methods, applications, services, *etc*., that utilise semantic web technologies and operate on the knowledge graph to read, write, estimate, simulate, optimise, query, to fulfil specific objectives [42]. These agents communicate with one another to derive insights [21]. Using this technology stack, TWA is versatile in three aspects: (1) answering cross-domain questions about the current world, (2) controlling real-world entities, and (3) supporting what-if scenario analysis. TWA follows a system of systems approach where individual task-oriented agents and their interplay help to describe a complex behaviour to gain comprehensive understanding and foster informed decisions.

Ontologies serve as structured representations of knowledge, encapturing concepts, relationships, and properties within a specific domain. They establish a formal framework for organising and sharing information in a machine-readable format. The representation of data through ontologies results in the formation of directed graphs, known as knowledge graphs (KGs), where nodes define entities and data (*i.e.,* concepts or instances) and edges denote their relationships [2]. KGs offer an extensible data structure that is well suited for representing arbitrarily structured data and which can be hosted decentralised, *i.e.,* distributed over the internet, using Semantic Web technology [8]. This implementation is also known as Linked Data [10], where every concept and relation is reference-able to its definition, facilitating information discovery across the web and enhancing machine readability and automation.

Linked Data uses resource description framework (RDF) [37] as the standard language to store data in the form of subject, predicate, and object triples [2]. Subject represents a resource, the predicate indicates a specific property and the object represents a value or another resource [31]. For example in the context of isochrone, concepts like `Isochrone`, `TransportMode`, `Buildings` can be defined in an ontology. While Linked Data connect these concepts through subject-predicate-object triples, such as `Isochrone A - assumesTransportMode - Car` or `Isochrone B - originatesFrom - Building X`.

The ontologies applied in this work include OntoFlood [30], OntoBuiltEnv [30], OntoCityGML [12]. OntoFlood organises flood-related data and its disaster impact [30]. While OntoBuiltEnv organises building related metadata ranging from its building usages, number of rooms, energy ratings, property prices, construction dates, *etc.* [30]. OntoCityGML provides a knowledge graph representation to the geometric representation of urban objects such as building heights, roof type, floor surface, wall surface, material *etc.* [12].

3 Methodology

3.1 Data Sources

In this study, the routing functions, the isochrone generation functions, the critical path analysis and building matching function uses OpenStreeMap (OSM) data, an open-source map collaboratively created by the community [53]. OSM contains a wide range of geographic information about buildings, structures and transportation network in the form of OSM elements (*i.e.*, points, lines and polygons). The features of these OSM elements are conveyed through OSM tags which describe the properties of these elements. OSM serves as the base map for these functions due to its open sourced nature, easy usability and integration with a wide range of open-source library such as pgRouting[58] and osm2pgrouting[57]. Therefore this allows easy scalable solutions across different cities and countries.

To evaluate the population potentially at risk of flooding in King's Lynn, UK, the study utilises the OpenPopGrid, a population distribution dataset derived from the Office for National Statistics 2011 Census and OS OpenData [48]. To evaluate the population coverage of amenities in Pirmasens, Germany, Facebook Data for Good High-Resolution

Population Density Maps is used [72]. Additionally, the land use model is sourced from the municipal government in Pirmasens [18], it contains information about the designated purposes for the land, which can be for residential, industrial, sports, *etc*. The 3D CityGML data and the 1-in-100 years flood raster data were obtained from the industrial partners.

3.2 Ontological Representation

This paper introduces OntoIsochrone - an ontology to connect isochrone, road condition, transport mode and its covered population data. The guiding principle in developing this ontology is to create a semantic representation of isochrones for geospatial analysis, as there has been no prior work done in this area. For example, the `iso:Isochrone` class is the key concept to represent isochrones and the `iso:originatesFrom` relationship connects it with an external geometry class `geo:Geometry` which its instance can be any elements with geographic information. Additionally, since the `iso:Isochrone` class contains geometry information, therefore it is a `rdfs:subClassOf` the `geo:Geometry` class as well. Other relationships to isochrone are semantically defined within OntoIsochrone in **Fig.** 1. The implementation of the semantic representation of isochrone meta properties (*i.e.,* population, area of coverage, *etc.*) facilitates geospatial querying via GeoSPARQL [5]. GeoSPARQL enables the retrieval of geospatial data on the semantic web, allowing the creation of applications that can reason both general and geospatial information to provide cross-domain insight.

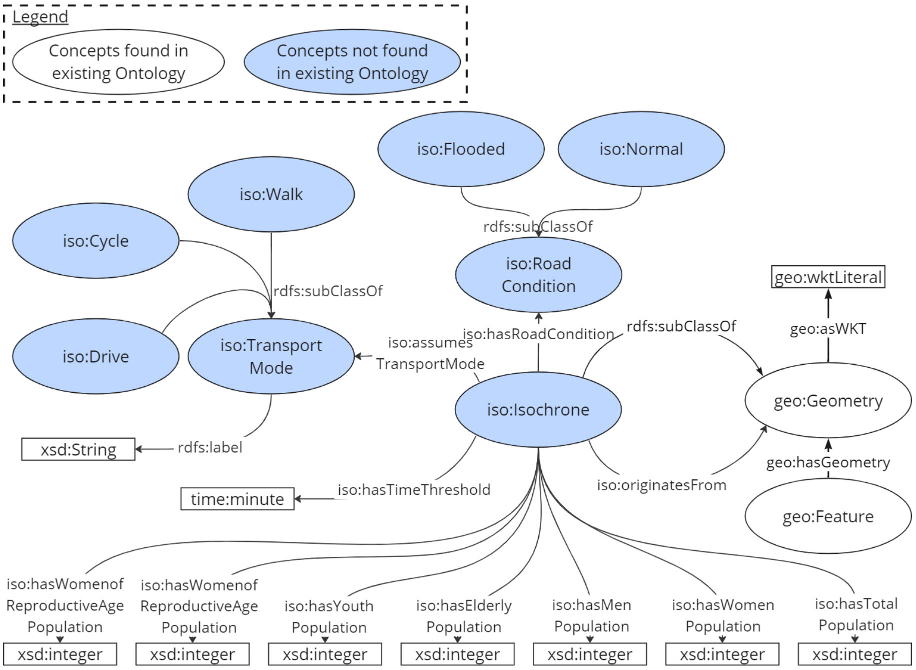


Figure 1: *OntoIsochrone describes the relationships associated with isochrone, this includes transport mode, road condition, demographics population, time threshold and its connection with OpenGis ontology. All referenced namespaces are declared in Appendix A.1.*

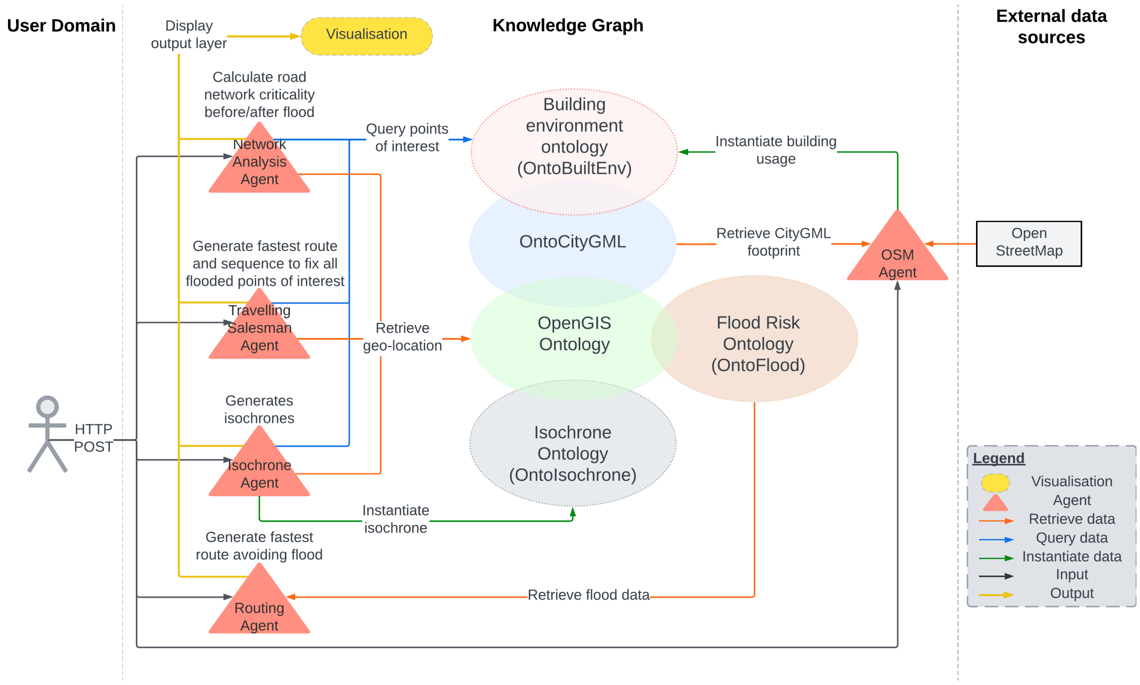


Figure 2: *Agents interplay on how OSM Agent, Routing Agent, Isochrone Agent, Travelling Salesman Agent, Isochrone Agent dynamically derives and instantiate information from and into the knowledge graph.*

3.3 Agent Based Implementation

The work in this paper utilises one input agent (*i.e.,* OSM Agent) and four output agents (*i.e.,* Routing Agent, Isochrone Agent, Travelling Salesman Agent, Network Analysis Agent). Two of these agents (*i.e.,* OSM Agent, Isochrone Agent) instantiate information and results back into the KG. These agents interact with the KG as depicted in **Fig.** 2. The OSM Agent retrieves data from the KG per OntoCityGML, derive building usage information from OpenStreetMap and integrate it into the OntoBuiltEnv ontology. Routing Agent queries for area of flood from OntoFlood and perform routing avoiding flooded area. Travelling Salesman Agent queries for the location of points of interest, evaluates whether these points of interest are flooded, and finds the fastest route to visit these points of interest once. Isochrone Agent queries for the location of points of interest, generates isochrones from that location based on the road conditions and transport mode, subsequently instantiates the isochrone metadata back into the KG. Network Analysis Agent queries for the location of points of interest (*i.e.,* hospitals) and performs road network sensitivity analysis before and during flood to identify the important paths to reach the points of interest. To execute the algorithm of each agents, users initiate these agents through a HTTP POST request which can contain parametric inputs that can be agents configuration or locations.

3.3.1 OpenStreetMap Agent (OSM Agent)

The OSM Agent is designed to incorporate OSM data to augment instantiated 3D CityGML buildings. First, the agent maps the retrieved OSM tags to the OntoBuiltEnv concept which includes healthcare services (*i.e.,* clinics, hospitals, pharmacies), emergency services (*i.e.,* police and fire stations), recreational facilities (*i.e.,* drinking and eating establishments, hotels, sports facilities), residential buildings, industrial buildings, *etc*. This step processes the OSM tags into ontological concepts for improved knowledge re-usability.

Subsequently, the agent proceeds to geometrically identify and match the OSM data with 3D CityGML data by comparing the geometry of the OSM entries to the footprints of the 3D buildings. This procedure links and establishes the semantic connection between identical entities that are present on both datasets (*i.e.,* OSM data, 3D CityGML) which were previously unconnected. Following a successful matching between OSM data and 3D CityGML data, the agent computes the building usage share for each property usage type, as a single building can have multiple property usages. Each 3D CityGML building now has been augmented with the OSM data to provide richer insights on what the buildings is used for. For the untagged buildings to any OSM elements, the OSM Agent assigns building usages based on its corresponding municipal landuse plots (*e.g.,* residential, industrial, religious facility, *etc*.) sourced from the local authority. A detailed UML diagram is provided in **Fig.** 11 in the Appendix.

The results - augmented 3D CityGML buildings with building usages - serve two functions. Firstly, the results facilitate the execution of the Isochrone Agent which needs the accurate geo-location of amenities to run accessibility analyses. Secondly, this augmented information can be reused for other future applications such as to perform electrical demand predictions using the City Energy Analyst based on building usage described in OntoBuiltEnv and its geometrical properties described in OntoCityGML [22].

3.3.2 Routing Agent

The Routing Agent provides context aware routing solutions, meaning the agent derives optimised routing suggestions based on dynamic flood data instantiated via OntoFlood. These flood data can be provided by climate simulations, forecasting or actual flood warnings. By overlaying the flood depth raster and the road network data, road segments that are affected by flood waters can be accurately identified, and excluded from emergency routing decisions.

Key functionalities of the Routing Agent are enabled by the open-source dynamic cost-based routing library pgRouting [13]. pgRouting is a well-established tool for solving graph problems and is commonly used in emergency routing and decision planning applications [14, 67]. Additionally, pgRouting has been utilised for locating the nearest shelter during flood emergency events [77], which emphasises its suitability for our research.

In pgRouting, road networks are divided into a graph network $G = (\{V\}, \{E\})$, consisting of a set of nodes (*i.e.,* V) and a set of edges (*i.e.,* E). The cost function on the edges can be modified programmatically and, subsequently, designates certain routes as inaccessible due to flooding. This is achieved by assigning a negative value associated with flooded roads. The Dijkstra's shortest path algorithm is then employed to find the shortest path to reach the destination while avoiding those flooded areas.

Routing Agent retrieves the flood depth raster via OntoFlood and identifies which roads are unusuable for any given maximum inundation depth. Subsequently, the Routing Agent accepts user inputs with a start and end point to compute the fastest route for the maximum allowable wading depth. The resulting route is then displayed via the visualisation interface.

3.3.3 Isochrone Agent

The Isochrone Agent functions by querying the location of the desired points of interest (POIs) from the KG and then generating areas of reach known as isochrone from these location. The advantage of employing ontologies and KG for querying POIs lies in the ability to leverage semantically defined RDF data types. Using ontology concepts and defined classes (*i.e.,* Hospitals, Clinics, PoliceStations, *etc.*) ensures precise POI locations, expedites search processes, achieve model re-usability and eliminates data ambiguity effectively.

The Isochrone Agent algorithm is initiated by receiving inputs from the user specifying the desired time interval and segmentation length. The Isochrone Agent segments the road network based on the specified segment length and breakdown the road network into Delaunay triangulation polygon segments [63]. Subsequently, the Isochrone Agent retrieves the location of POIs from the KG and calculate the travel time to each of these segments using pgRouting's *pgr_drivingDistance* function. Each triangle segments are assigned a calculated travel time from the POIs. Isochrones are formed by selecting the triangles segments which are less than the maximum time threshold specified. Subsequently, Isochrone Agent calculates and maps the isochrone areas onto the population distribution data, thereby calculating the sum of population covered. The resulting isochrones (*i.e.,* represented in the form of polygon) are displayed as an output on the visualisation interface. The isochrone information (*i.e.,* geometry shape, population covered, *etc.*) is then instantiated into the KG via Ontology-Based Data Access (OBDA) mapping [7], thereby exposing these geospatial data stored in relational database to the KG, enabling cross-domain analysis with knowledge graph via GeoSPARQL. A detailed UML diagram is provided in **Fig.** 12 in the Appendix.

Isochrone Agent allows the abstraction of using different modes of transport and road conditions (*e.g.,* Flooded or Normal) by specifying the characteristic of the road parameters in the EdgeTableSQL. EdgeTableSQL in pgRouting [59] is a SQL statement that describes the road cost table used in pgRouting. It defines the allowable road network (*i.e.,* selecting road that is not flooded). At the same time, this approach provides the flexibility to define any vehicle characteristics modelled through time costs. For example, the time cost for walking is represented by the road length divided by the average walking speed, similarly the time cost for driving is represented by the road length divided by the speed limit.

3.3.4 Travelling Salesman Agent

The Travelling Salesman Problem is a computational challenge focused on determining the fastest route to visit all the nodes once in a graph network and return to the starting node [50]. This problem is a commonly studied challenge in the field of operation research in its application for humanitarian relief logistics in disaster operations management [17, 47, 82]. Specialised vehicles such as amphibious vehicle, fire trucks or helicopters are limited resources during disaster, therefore a single vehicle may have to visit multiple locations in scenarios such as disaster rescue or infrastructure restoration. These locations/POIs, represented as nodes in a road network, should ideally be visited once to minimise delays.

The Travelling Salesman Agent identifies the flooded roads, retrieves the locations of POIs (*i.e.,* rescue locations or flooded infrastructure location) from the KG and calculates the fastest route to reach these points while incorporating flood depth into the routing calculation. First, Travelling Salesman Agent queries and extracts crucial location data from the KG. Using the user input location as the starting point, the algorithm dynamically computes the optimal route to reach all points of interest and return to the original position while avoiding flood. The Travelling Salesman Agent evaluates the feasibility of reaching these locations via various modes of transport by using pgRouting's *pgr_tsp* function. If deemed unattainable, the algorithm appropriately flags and displays these unreachable POIs, subsequently omits them from optimal route calculation. The fastest route and the sequence to visit all the points is then displayed as an output via the visualisation interface.

3.3.5 Network Analysis Agent

Roads have varying importance based on their specific position within the transportation network [24]. Researchers have extensively examined road criticality to help in the prioritisation of infrastructure restoration after disasters [24]. One method used for this purpose is the betweenness centrality measure which assesses the significance of roads in a network [56, 70], this metric is often regarded as one of the most important metric for prioritising recovery efforts in transportation infrastructures [9]. Betweenness centrality identifies the importance of a road based on how frequently it appears in the possible shortest paths from a particular node. Roads that are featured more frequently in these shortest paths are considered more important.

The Network Analysis Agent assesses the accessibility of critical amenities (*e.g.,* hospitals) by measuring the betweenness centrality metric before and during a flood. The Network Analysis Agent first retrieve the critical amenities location from the KG, then computes the betweenness centrality metric for the road network from the critical amenities location. The changes in percentage in the betweenness centrality metric before and during a flood is displayed as an output via the visualisation interface. Through this direct comparison, critical pathways can be pinpointed by identifying the roads with the most significant percentage decrease in betweenness centrality before and during a flood.

4 Use Cases

To demonstrate TWA's potential as a versatile flood disaster response tool, King's Lynn a mid-size coastal town in the East of England, has been selected for a proof of concept for the Urban Resilience use case (refer to section 4.1). The selection of King's Lynn is strategic, considering the town's vulnerability to coastal flooding and the wealth of available open data in the UK.

Additionally, to illustrate TWA's capabilities as a planning tool for 15-minute city planning, a small town of 40,000 people - Pirmasens in Rhineland-Palatinate, Germany, has been chosen (refer to section 4.2). Facing a dwindling population, the local municipal government in Pirmasens is actively seeking improved methods for accurate resource allocation. The overarching goal is to ensure that the town's amenities can adequately cater to all residents. This requires streamlining and integrating fragmented data sources to enable the municipality to make well-informed decisions for optimised resource distribution.

4.1 Urban Resilience

In King's Lynn, 8% of the town's population is aged 75 years or above and approximately 7.7% of the total town's population physically challenged in their day-to-day life [52]. This highlights the need of ensuring rapid, efficient, and specialised assistance for these vulnerable demographics during severe weather and disaster events. During such situations, rapid deployment of healthcare and rescue services is required. Loss of local medical services and amenities combined with restricted accessibility to the people at risk are factors that will drastically increase the mortality rate [1]. Therefore, advanced preparedness and anticipatory actions are required to provide a quicker and more effective response during sudden disaster.

4.1.1 Context-aware Routing

In the event of floods, specialised vehicles such as helicopters, boats, ambulances, fire truck, and high-water trucks are limited resources. These vehicles each have distinct operational speed, allowable water wading depth and deployment time. It is essential to effectively coordinate and allocate resources according to various vehicles and the locations requiring rescue.

One way to achieve this is by integrating flood depth level dynamically into routing calculations. **Figure** 3 illustrates the effectiveness of this approach, showcasing the selection of a route that circumvents flooded areas, leading to a swift and efficient emergency response by a fire truck.

Best available route: 3.184 km, by vehicle with deep wading depth

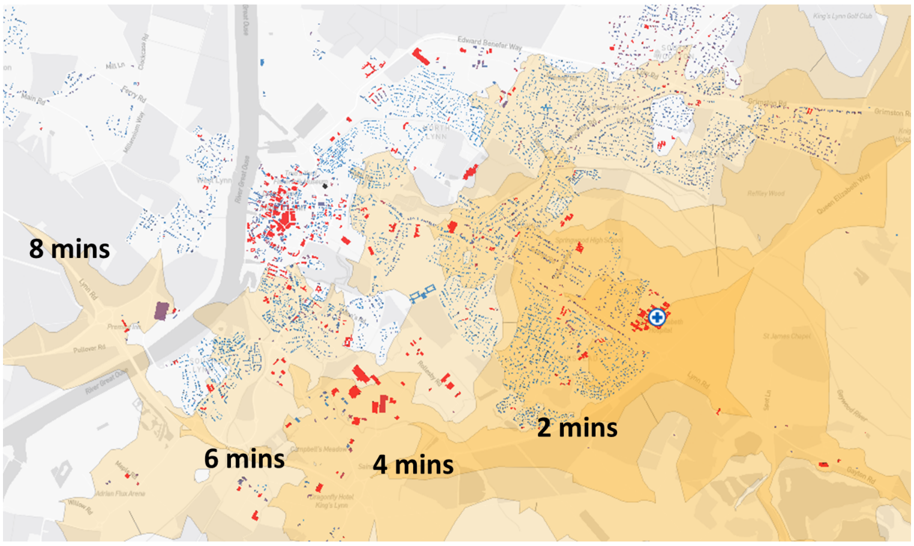
Figure 3: *Optimal route selection under flooded conditions where orange, green, and purple lines represent the fastest paths taken by vehicles with 10cm, 30cm, and 90cm wading depth capabilities, respectively.*

4.1.2 Accessibility Analysis (Healthcare)

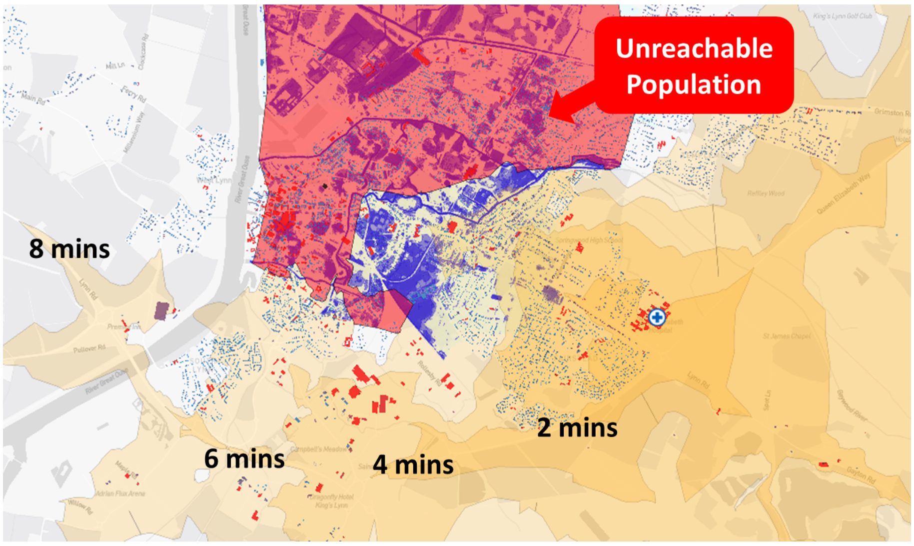
The key in reducing the consequences of disasters is by having the ability to respond and prepare for them effectively [4]. This includes evaluating the loss of physical access to critical infrastructure and identifying the population that will likely be impacted. The Isochrone Agent addresses this by identifying the area of reach from any points of interest under flooded conditions. Isochrones help to identify who is covered by certain critical infrastructure and what share of population is potentially unreachable.

The agent retrieves the locations of critical infrastructure such as hospitals, police stations, fire stations, *etc*. Subsequently, the agent generates polygons with the reachable area from each location of interest within a certain time threshold, so-called isochrone maps.

For example, an isochrone map that depicts the service area under normal conditions from the hospital in King's Lynn is shown in **Fig.** 4(a). During severe weather, certain areas might become inaccessible due to flood. Insights on the segment and the share of population which are likely unreachable within a 10-minute timeframe can be derived through the consideration of the population density as seen in **Fig.** 4(b). By gaining an understanding of the operational region of essential infrastructures, it becomes possible to pinpoint inaccessible areas. This knowledge can then be used to determine strategic measures needed in emergency service planning to guarantee comprehensive coverage, avoiding blind spots. Currently, the flood scenario in **Fig.** 4(b) uses a 1-in-100 years flood scenario. This approach could be applied to multiple projected flood scenarios.



(a) Normal road conditions



(b) Flooded conditions with 30 cm wading depth vehicle

Figure 4: *Demonstration of the capability of TWA to create isochrone maps for access times from hospitals. (a) represents the isochrone maps in 2-minute interval from Queen's Elizabeth Hospital. (b) represents the isochrone maps under flooded condition and outlines the area of unreachable population in 8 minutes.*

4.1.3 Travelling Salesman Problem

Flooded roads block off available paths and increase travel time to critical infrastructure (*i.e.,* power stations). Failures of multiple infrastructures caused by disaster events often cannot be restored at the same time because of the limitation of the recovery resources, such as recovery vehicles [44]. The objective in reducing the travel time to restore these critical infrastructures in case of failure can be modelled as a Travelling Salesman Problem.

The application of Travelling Salesman Agent supports the fastest restoration of failed power stations submerged due to flooding by minimising the travel time. UK Power Network's power stations [74] are first identified if flooded. Travelling Salesman Agent then calculates the fastest route to restore these flooded power stations while incorporating flood depth and vehicle water depth wading capability, as seen in **Fig.** 5. The optimised route is determined and the sequence for visiting these power stations is outlined. Each station is visited once only to reduce delay before returning to the starting node which typically represents a resource depot [78].

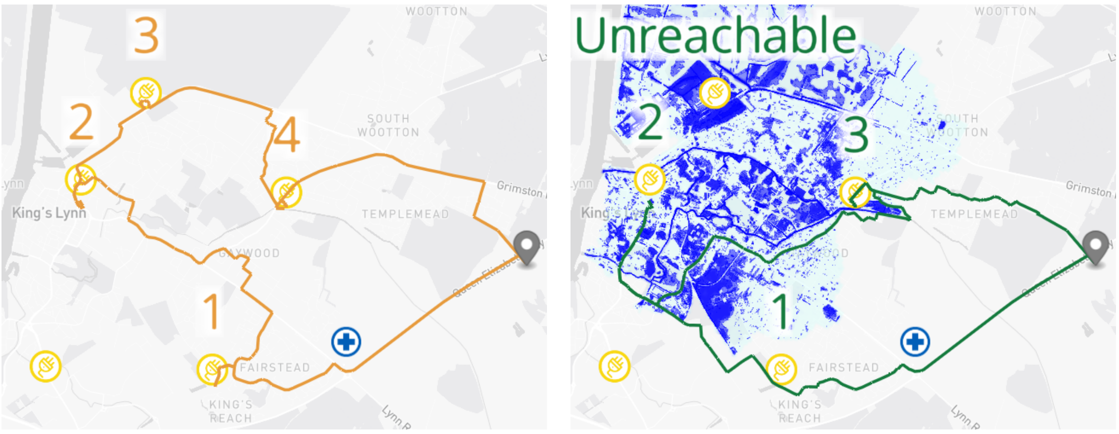
This strategy ensures a reactive response that minimises recovery time during a disaster. On top of that, additional information such as the hierarchical importance of specific infrastructures and the consideration of cascading network effects, can be integrated into the travelling salesman analysis for a more holistic approach. Similarly, this approach can also be applied for relief goods distribution or mobile medical care [66].

4.1.4 Critical Path Analysis

In post disaster situations with a large portion of damaged transportation network, such as roads and bridges, the task of coordinating recovery resources systematically and building a reconstruction plan robustly can be challenging [26]. Administrators often need to organise limited resources in planning their subsequent and rapid reconstruction as poor transportation network could severely limit the recovery efforts [23]. Critical path analysis can provide a guideline on how to prioritise re-construction efforts after a disaster. It can determine which roads or pathways should be repaired first, ensuring a smooth, continuous, and efficient overall disaster response. Furthermore, this ability allows us to identify which road should be prioritised to be kept clear from traffic or, if possible, even flood waters to streamline disaster response.

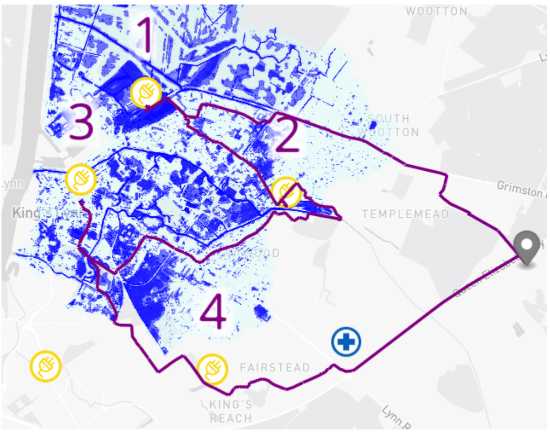
Using this approach, the Network Analysis Agent queries and retrieves accurate geo-locations of critical infrastructure (*i.e.,* hospitals, police stations) from the KG. Subsequently, the agent conducts a sensitivity analysis in both before and during flood, as depicted in **Fig.** 6(a). Infering from this analysis, the paths that experience a huge decrease in the betweenness centrality metric (*i.e.,* represented in red) should be prioritised for restoration. On the other hand, the paths that experience an increase in the betweenness centrality metric (*i.e.,* represented in orange) become more relevant and these paths should be kept clear from flood or traffic during flood event. In **Fig.** 6(b) paths that are rendered totally unusable by flood were outlined, the most important paths can be identified and prioritised for restoration.

Overall, the proposed Network Analysis Agent can effectively guide rescue and repair efforts during and after a disaster to ensure continuous accessibility to essential services. As a result, an improved city planning that integrates strong, robust transportation network systems and flood resilience can be attained.



(a) Normal road conditions

(b) Flooded conditions: Deployment of 30cm wading depth vehicle



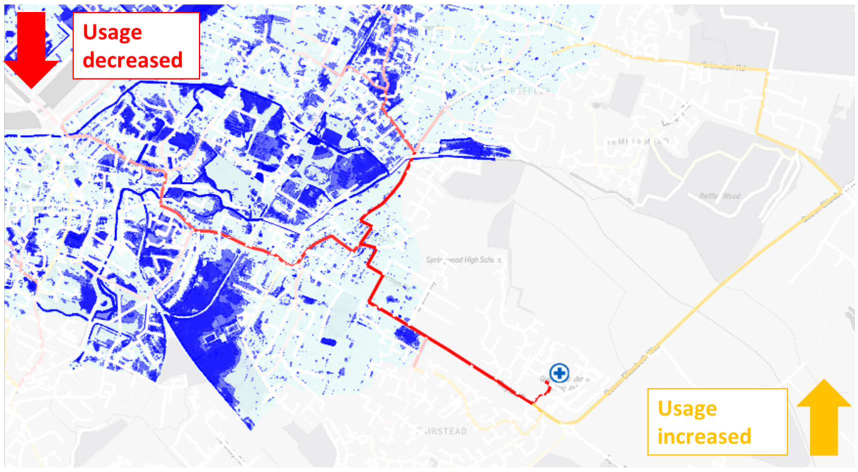
(c) Flooded conditions: Deployment of 90cm wading depth vehicle

Figure 5: *Fastest route to restore power stations during normal road conditions and flooded conditions.*

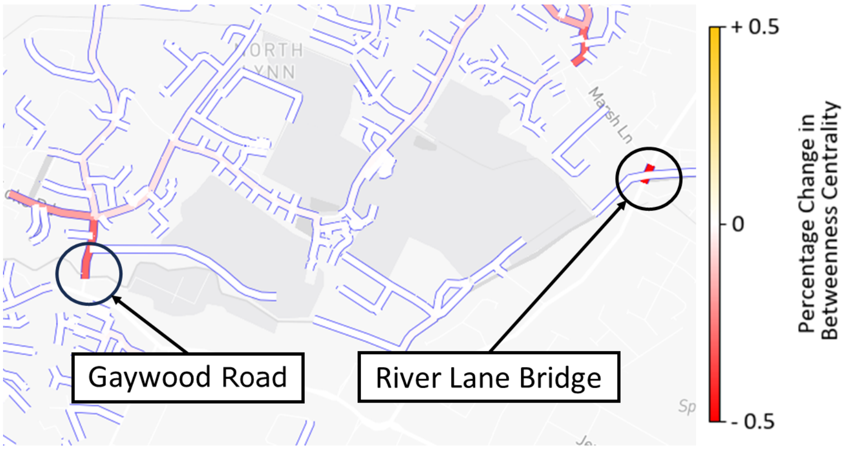
4.2 Improving the Livability of Cities

4.2.1 Status Quo Assessment

TWA aims to provide status quo assessments that offer city officials a means to analyse the current amenities coverage of their cities. Isochrone Agent can retrieve the accurate locations of buildings with a certain usage (category), allowing it to generate isochrones based on the gathered information. The critical points of interests used by the Isochrone Agent which are crucial for a 15-minute city, include healthcare services (*e.g.,* clinics, hospitals, pharmacies), emergency services (*e.g.,* police and fire stations), recreational facilities (*e.g.,* drinking and eating establishments, hotels, sports facilities), residential buildings, industrial buildings, transportation facilities, educational institutions, retail establishments, offices, and banks. Through this accessibility analysis, local municipal governments have the ability to evaluate the current coverage of city services for its residents,



(a) Changes in betweenness centrality before and during flood



(b) Flooded unusable roads (*i.e.,* outlined by blue) with high reduction in betweenness centrality metric (*i.e.,* coloured with brighter red), indicating the more important roads to be prioritised

Figure 6: *The percentage change in betweenness centrality is visually represented using red and orange hues. The red lines denote paths that experience a reduction in the betweenness centrality metric, signifying a diminished role in the total shortest paths prior to the flood. Conversely, the orange lines denote paths experiencing an increase in the betweenness centrality metric, highlighting paths that have become more prominent during flood in the overall of the total shortest paths originating from the critical POI.*

for example the area of coverage by all the pharmacies in Pirmasens as shown in **Fig.** 7.

Similarly isochrones can be generated for various transport modes such as walking, cycling and driving from various amenities that includes, but are not limited to, banks, schools, and hospitals, as shown in **Fig.** 8. By doing so, gaps and blind spots in the coverage area of these amenities can be effectively identified.

On top of that, accessibility can be assessed to evaluate if the entire population are equally covered. City officials can investigate whether certain essential service coverage corre-

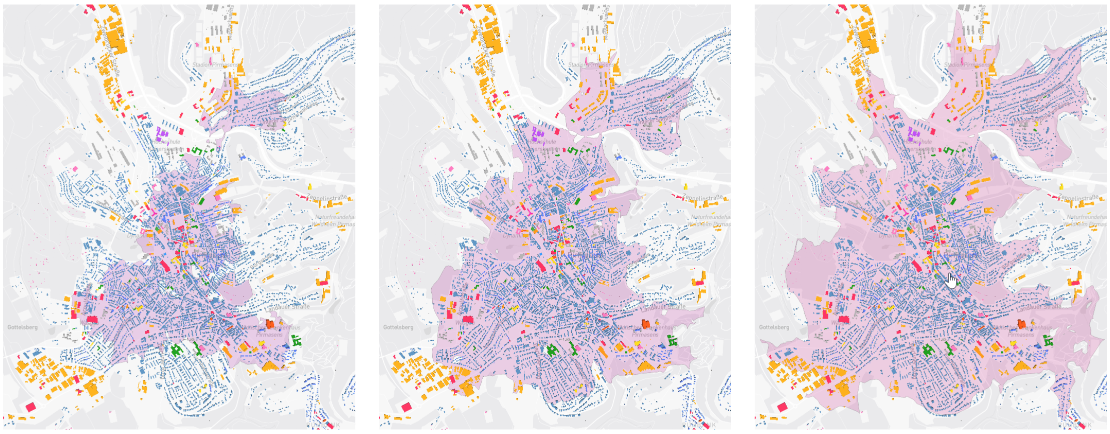

(a) 5 minutes (b) 10 minutes (c) 15 minutes

Figure 7: *Isochrones via cycling from all pharmacies in Pirmasens.*

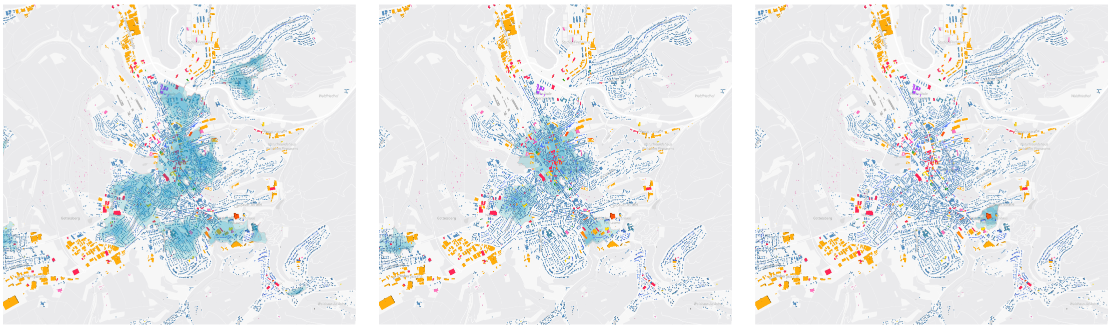
lates with certain socio-economic parameters such as wealth, age or ethnicity. This assist governments in discovering whether a particular demographic group is lacking in accessibility to services which contribute towards social inequities within the urban fabric. It provide tools for the administrators to draw findings from the correlation analysis from parameters such as the housing prices as described through OntoBuiltEnv and accessibility as described through OntoIsochrone in the knowledge graph domain. Studies have found that the accessibility to local amenities such as dining, shopping, health services, *etc*., can have different impacts on the property prices [6, 83, 84].

These accessibility studies enable local municipal government to build the right infrastructure at the right location, reaching the intended demographics and filling previous coverage gaps. An interesting observation in the analysis is that contrary to conventional beliefs, residing in the city center does not necessarily guarantee proximity to essential amenities as shown in **Fig.** 9, which the accessibility to pharmacies is used as an example. The coverage of 15 minutes walking isochrone from all pharmacies in Pirmasens does not overlap at the city center. This challenges the common assumption that central locations inherently provide convenient walking access to most amenities. Hence, such observations underscore the need for a comprehensive urban planning tool that allows current status quo monitoring.

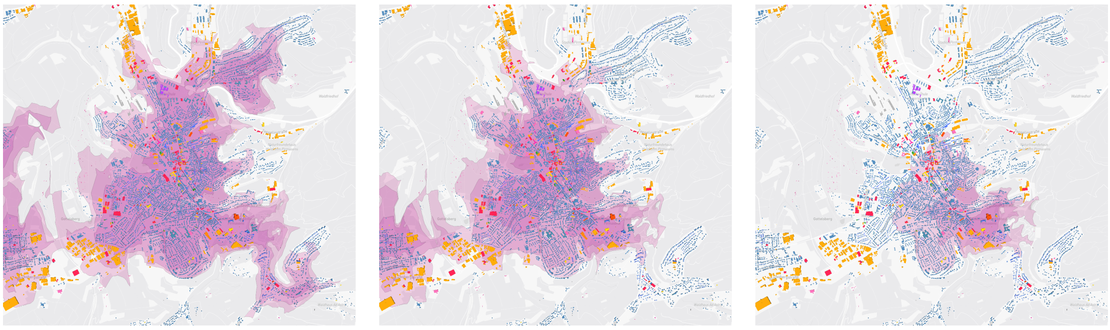
4.2.2 Scenario Planning

TWA has the ability to address hypothetical scenarios that can be applied for strategic infrastructure development. Some of the questions TWA can answer include: (1) Where to place the next amenities? (2) Which land plot can it be built on? (3) What will be the new population coverage?

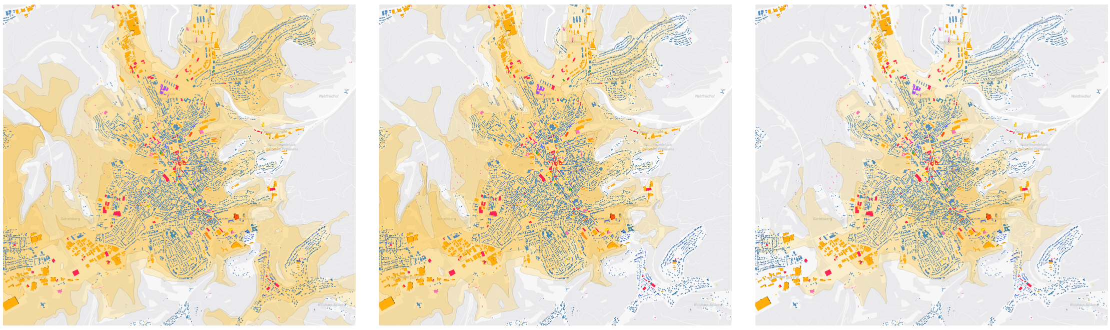
By strategically placing and validate the placements with underlying zoning regulations, TWA can assist governments in effective services planning. Some important aspects include planning on emergency services through determining the best locations for critical infrastructures (*i.e.,* fire stations, police stations, emergency medical services) to minimise



(a) School (Walk) (b) Bank (Walk) (c) Hospital (Walk)



(d) School (Cycle) (e) Bank (Cycle) (f) Hospital (Cycle)

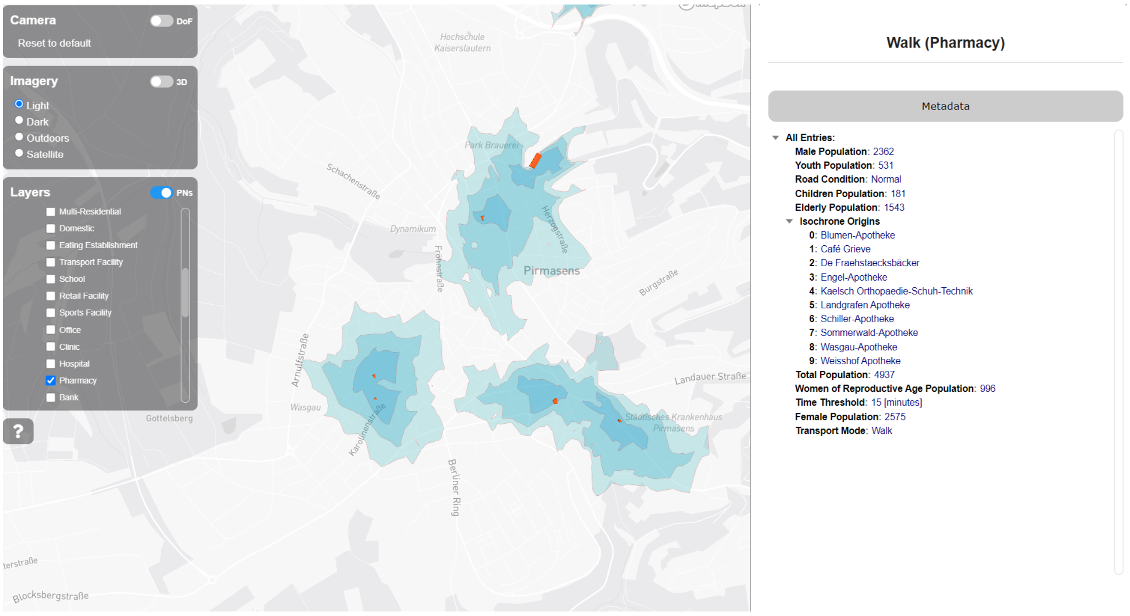


(g) School (Drive) (h) Bank (Drive) (i) School (Drive)

Figure 8: *Isochrones illustrating 5, 10, and 15 minutes travel time boundaries from the schools, banks, and hospitals, each color-coded to represent specific modes of transportation: blue for walking, purple for cycling, and yellow for driving.*

response times. Additionally, TWA can also analyses residents access to green spaces and recreational areas to identify areas in need of additional green infrastructure.

Overlaying information on the accessibility analysis with population density often time can help spatial planners in designing solution-oriented upgrading programmes to pin-point residential area with poor access [27]. As seen in **Fig.** 10 which uses pharmacy as an example the placement of pharmacy was optimised based on the allowed zone and population distribution. Through the integration of land plots in TWA, TWA possess the capability to improve coverage while adhering to the land plot regulations. Due to the limitations of open data, currently population distribution estimates by demograph-

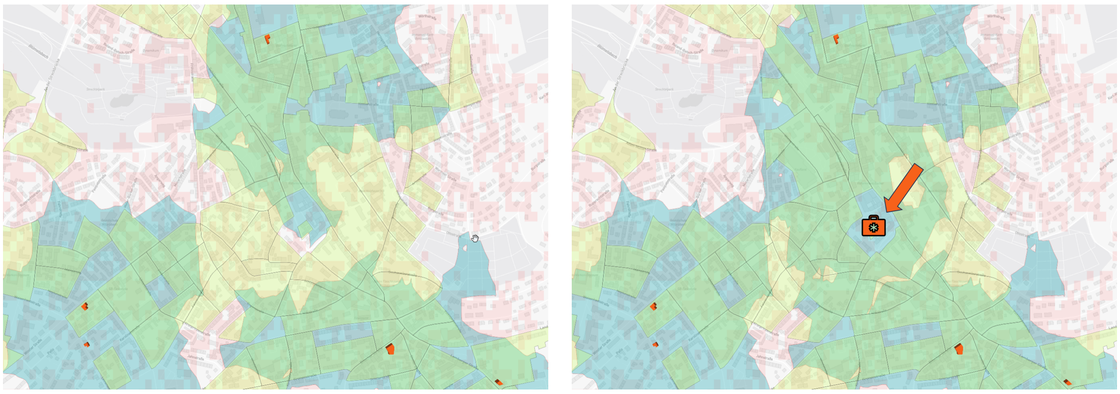


Walk (Pharmacy)

- **All Entries:**
  - **Male Population**: 2362
  - **Youth Population**: 531
  - **Road Condition**: Normal
  - **Children Population**: 181
  - **Elderly Population**: 1543
  - **Isochrone Origins**
    - **0**: Blumen-Apotheke
    - **1**: Café Grieve
    - **2**: De Fraehstaecksbäcker
    - **3**: Engel-Apotheke
    - **4**: Kaelsch Orthopaedie-Schuh-Technik
    - **5**: Landgrafen Apotheke
    - **6**: Schiller-Apotheke
    - **7**: Sommerwald-Apotheke
    - **8**: Wasgau-Apotheke
    - **9**: Weisshof Apotheke
  - **Total Population**: 4937
  - **Women of Reproductive Age Population**: 996
  - **Time Threshold**: 15 [minutes]
  - **Female Population**: 2575
  - **Transport Mode**: Walk

Figure 9: *User Interface of TWA Visualisation Framework which details the metadata of isochrones (i.e., population covered by demographics, the building names of isochrone origination source, etc.)*

ics are based on the census data [72]. When more granular population distribution by socio-economic attributes is provided, better cross-domain insights can be achieved. This include measuring the accessibility of medical healthcare services to reach the intended group such as elderly population, children or where to place the mobile vaccination centre.



(a) 15 minutes walk isochrone from pharmacies in Pirmasens

(b) Improvement in pharmacy accessibility via walking through the addition of a pharmacy at the allowable land plot zone in city centre

Figure 10: *Infrastructure planning through the multi-factor considerations where red grids represents population distribution, yellow polygons represents allowable zones for pharmacies to be built, blue represents 15 minutes walk isochrone from pharmacies.*

4.3 Core Capability of TWA

TWA exhibits versatility by supporting both dynamic and static planning, as demonstrated in the use cases outlined in Section 4.1 and Section 4.2. It supports dynamic planning through context aware routing: TWA interacts with users to acquire location information, enabling the specification of origin and destinations for routing while dynamically considering factors such as flood avoidance. Two key agents, namely Routing Agent and Travelling Salesman Agent, intelligently recompute optimal routes based on the user input locations. These functionalities can enhance the agility and responsiveness of emergency response teams in disaster situations.

The static planning aspect of TWA is characterised through its ability to perform accessibility analysis and critical path analysis. In terms of emergency response, Isochrone Agent can effectively identify the area of reach from critical infrastructures and at the same time, identify blind spots and the area out of reach. While Network Analysis Agent can identify important paths in a road network before and during disaster. TWA can be applied in (1) correlation analyses to evaluate if household income correlates with factors such as accessibility to hospitals, schools (2) demographic insights through gaining a comprehensive understanding of population distribution by considering parameters like age, race, and income in specific geographic area. Few examples of such analyses are as below, whereby the SPARQL queries can be found in Appendix A.2:

1. What is the average estimated building price within a 2-minute driving radius of the hospital in King's Lynn?
   Answer: Average £308,234 (based on 299 buildings in area)
2. Find all buildings with a gross floor area between 80-120 m^2 within 2 minutes driving from the hospital in King's Lynn?
   Answer: 108 buildings (count shown instead of individual instances for readability)
3. What is the total number of elderly population per pharmacy within 10 minutes of walking?
   Answer: 106 elderly people per pharmacy
4. What is the name of the 3 tallest schools in Pirmasens?
   Answer: (1) Grundschule Wittelsbach - 27.03m, (2) Landgraf Ludwig Realschule plus - 24.53m, (3) Matzenbergschule - 24.34m
5. What is the area not covered by pharmacies in Pirmasens?
   Answer: Observed in **Fig.** 9

Through TWA, these competency questions are able to answer some of the pressing policy planning challenges, for example walkable cities for children that necessitates designing urban environments that are inclusive and conducive to walking, particularly for children residing in proximity to schools. Another applicable scenario include environmental agencies which vision is to achieve accessibility for all residential houses to be located within 10 minutes walking from parks [51]. Addressing these challenges in policy planning is a crucial stride in the direction of creating a 15-minute city.

While one might argue that Geographic Information Systems (GIS) can easily address individual use cases, however leveraging solely on GIS often leads to less optimal outcomes due to restricted data silos that only encode just one domain/perspective [35]. The distinctive advantage of leveraging a knowledge graph lies in its capability for cross-domain analysis while at the same time transcends geo-location dependencies. By serving as a gateway to various data sources, the knowledge graph approach facilitates scalability across diverse data sets, effectively overcoming data ambiguity. This results in a robust system characterised by high re-usability and extendability.

5 Conclusions

Knowledge graph driven technology like TWA has the ability to connect, and integrate flood data, OpenStreetMap data, land plot data, and 3D CityGML buildings data, through ontologies. These ontologies create semantic representations to facilitate machine-readability and automation, enabling cross-domain analyses to support emergency response and urban planning.

TWA presents itself as a versatile tool to address challenges in disaster response and urban planning using an agent-based approach. Through series of agents, it possesses the capability for dynamic planning via informed routing avoiding floods and travelling salesman problem to restore critical infrastructures. Simultaneously, TWA supports static planning through accessibility analyses under flood situations using isochrones, as well as critical path analyses to streamline recovery efforts using betweenness centrality metric.

In urban planning, TWA extends its capability to support 15-minute city planning. This involve using isochrone to measure the reach and population coverage of essential amenities by different timescales and different transport modes such as walking, cycling, driving. This ability is further extended to scenario planning which enables the optimisation of amenities placements to improve areal coverage while complying with land use regulations. At the same time, the application of ontologies to represents building information, isochrones, populations, facilitates cross-domain correlation analysis and provides valuable demographic insights.

Future work includes simulating and incorporating traffic flow under flood conditions to enhance the accuracy of informed routing as flooding will often lead to traffic congestion due to lesser accessible roads. Potential future applications include using TWA to perform route avoidance for other disaster such as forest fires or plumes. There are ongoing research effort investigating methods to implement dynamic plume model in routing avoiding forest fire [79, 80]. With TWA's fully developed plume dispersion modelling considering real-time weather data [21], TWA could be a suitable ecosystem to integrate an end-to-end solution that combines hazard simulation results to support routing during disasters.

City planning projects involve significant investments, therefore there should be an effort to emphasise on reusing and extending existing data structures. Knowledge graph reuse ontologies and eliminate data ambiguity. The practical deployment of TWA in both King's Lynn, United Kingdom and Pirmasens, Germany, showcase its location independence as an open data model. At the same time, TWA's versatility is demonstrated through its ability in effectively tackling two different scenarios: urban resilience and 15-minute city.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to enhance the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data and code availability

All the codes developed are available on The World Avatar GitHub repository

https://github.com/cambridge-cares/TheWorldAvatar.

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Nomenclature

API	Application Programming Interface
GeoSPARQL	Geographic Query Language for RDF Data
GML	Geography Markup Language
KG	Knowledge Graph

OBDA	Ontology-Based Data Access
OSM	OpenStreetMap
OS	Ordnance Survey
POI	Point of Interest
RDF	Resource Description Framework
SPARQL	SPARQL Protocol and RDF Query Language
SQL	Structured Query Language
TWA	The World Avatar

A Appendix

A.1 Namespaces

rdfs: <`http://www.w3.org/2000/01/rdf-schema#`>
geo: <`http://www.opengis.net/ont/geosparql#`>
geof: <`http://www.opengis.net/def/function/geosparql/`>
om: <`http://www.ontology-of-units-of-measure.org/resource/om-2/`>
dabgeo: <`http://www.purl.org/oema/infrastructure/`>
obe: <`https://www.theworldavatar.com/kg/ontobuiltenv/`>
xsd: <`https://www.w3.org/2001/XMLSchema#`>
iso: <`https://www.theworldavatar.com/kg/ontoisochrone#`>
obe: <`https://www.theworldavatar.com/kg/ontobuiltenv/`>
bldg: <`http://www.opengis.net/citygml/building/2.0/`>

A.2 Competency Questions SPARQL Queries

The following SPARQL queries can be used to answer the stated competency questions. It is important to note that Ontop is employed for the processing of GeoSPARQL queries. Hence, the placeholder `<ontop>` needs to be substituted with the actual Ontop endpoint before executing the queries.

Listing 1: *What is the average estimated building price within a 2-minute driving radius of the hospital in King's Lynn?*

```
SELECT (COUNT(?bldg) as ?buildings) (AVG(?price) as ?average)
WHERE {
?bldg obe:hasMarketValue ?mv .
?mv om:hasValue ?value .
?value om:hasUnit om:poundSterling ;
       om:hasNumericalValue ?price .
SERVICE <{ontop}> {
    ?bldg a dabgeo:Building ;
          geo:hasGeometry/geo:asWKT ?bldg_loc .
    ?iso a iso:Isochrone ;
        iso:hasRoadCondition ?rc ;
        iso:hasTimeThreshold "2"^^<http://www.w3.org/2006/time#minute> ;
        iso:originatesFrom ?poi ;
        geo:hasGeometry ?geometry .
    ?rc a iso:Normal .
    ?poi a obe:Hospital .
    ?geometry geo:asWKT ?polygon .
    FILTER ( geof:sfWithin(?bldg_loc, ?polygon) )
    }
}
```

Listing 2: *Find all buildings with a gross floor area between 80-120 m^2 within 2 minutes driving from the hospital in King's Lynn?*

```
SELECT ?bldg
WHERE {
?bldg rdf:type dabgeo:Building ;
      obe:hasTotalFloorArea ?area .
?area om:hasValue ?value .
```

```
?value om:hasUnit om:squareMetre ;
       om:hasNumericalValue ?num_val .
FILTER (?num_val >= 80 && ?num_val <= 120)
SERVICE <{ontop}> {
    ?bldg geo:hasGeometry/geo:asWKT ?bldg_loc .
    ?iso a iso:Isochrone ;
        iso:hasRoadCondition ?rc ;
        iso:hasTimeThreshold "2"^^<http://www.w3.org/2006/time#minute> ;
        iso:originatesFrom ?poi ;
        geo:hasGeometry ?geometry .
    ?rc a iso:Normal .
    ?poi a obe:Hospital .
    ?geometry geo:asWKT ?polygon .
    FILTER ( geof:sfWithin(?bldg_loc, ?polygon) )
    }
}
```

Listing 3: *What is the total number of elderly population per pharmacy within 10 minutes of walking?*

```
SELECT ?elderlyPopulationPerPharmacy
WHERE {
  SERVICE <{ontop}> {
    SELECT (ROUND(?elderlyPopulation/?pharmacyCount) as ?elderlyPopulationPerPharmacy)
        WHERE {
      {
        SELECT (COUNT(DISTINCT ?building) as ?pharmacyCount) WHERE {
          ?isochrone a iso:Isochrone .
          ?isochrone iso:originatesFrom ?building.
          ?building a obe:Pharmacy.
        }
      }
      {
        SELECT ?elderlyPopulation WHERE {
          ?isochrone a iso:Isochrone .
          ?isochrone iso:originatesFrom ?building.
          ?building a obe:Pharmacy.
          ?isochrone iso:hasTimeThreshold "10"^^<http://www.w3.org/2006/time#minute>.
          ?isochrone iso:assumesTransportMode ?transportMode.
          ?transportMode a iso:Walk.
          ?isochrone iso:hasElderlyPopulation ?elderlyPopulation.
        }
        GROUP BY ?elderlyPopulation
      }
    }
  }
}
```

Listing 4: *What is the name of the 3 tallest schools in Pirmasens?*

```
SELECT DISTINCT ?name ?height WHERE {
  SERVICE <{ontop}> {
    SELECT DISTINCT ?name ?height WHERE {
      ?building a obe:School.
      ?building obe:hasPropertyUsage ?propertyUsage.
      ?propertyUsage obe:hasUsageLabel ?name.
      ?building bldg:lod0FootPrint ?footprintID;
                bldg:measuredHeight ?height.
    }
    ORDER BY DESC(?height)
    LIMIT 3
  }
}
```

A.3 Agent UML Diagrams

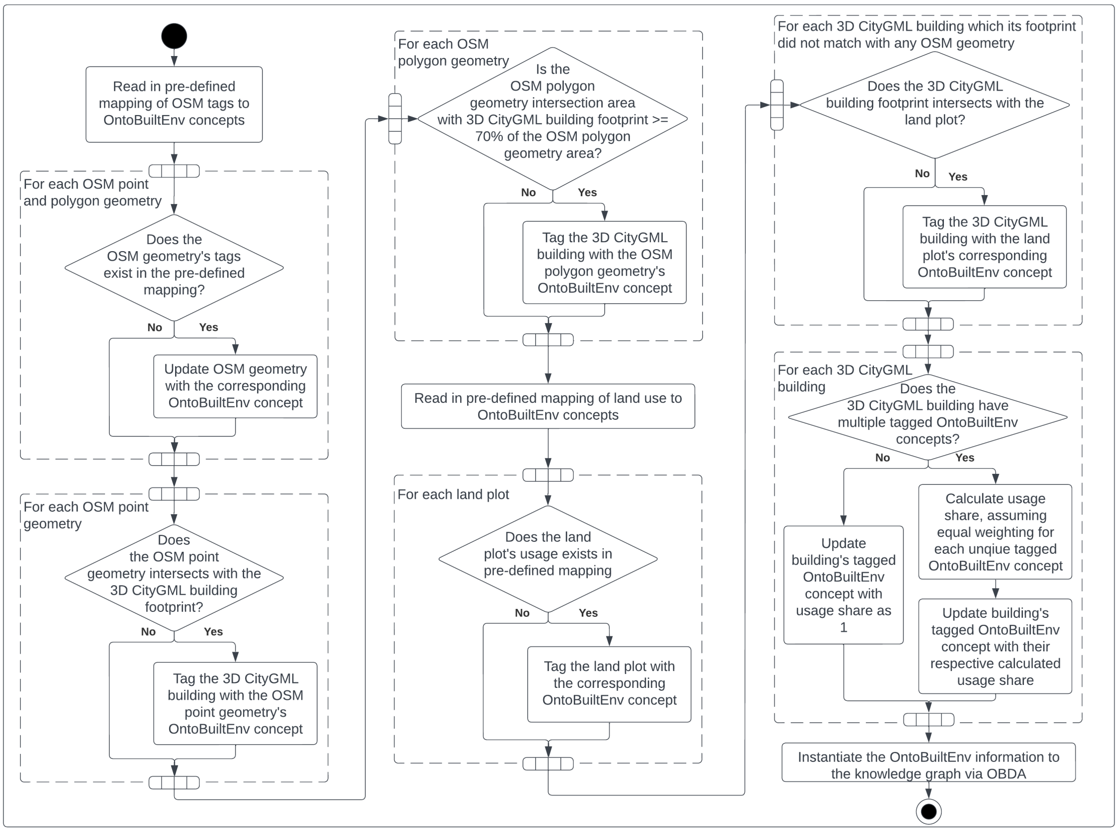

Figure 11: *OSMAgent UML diagram*

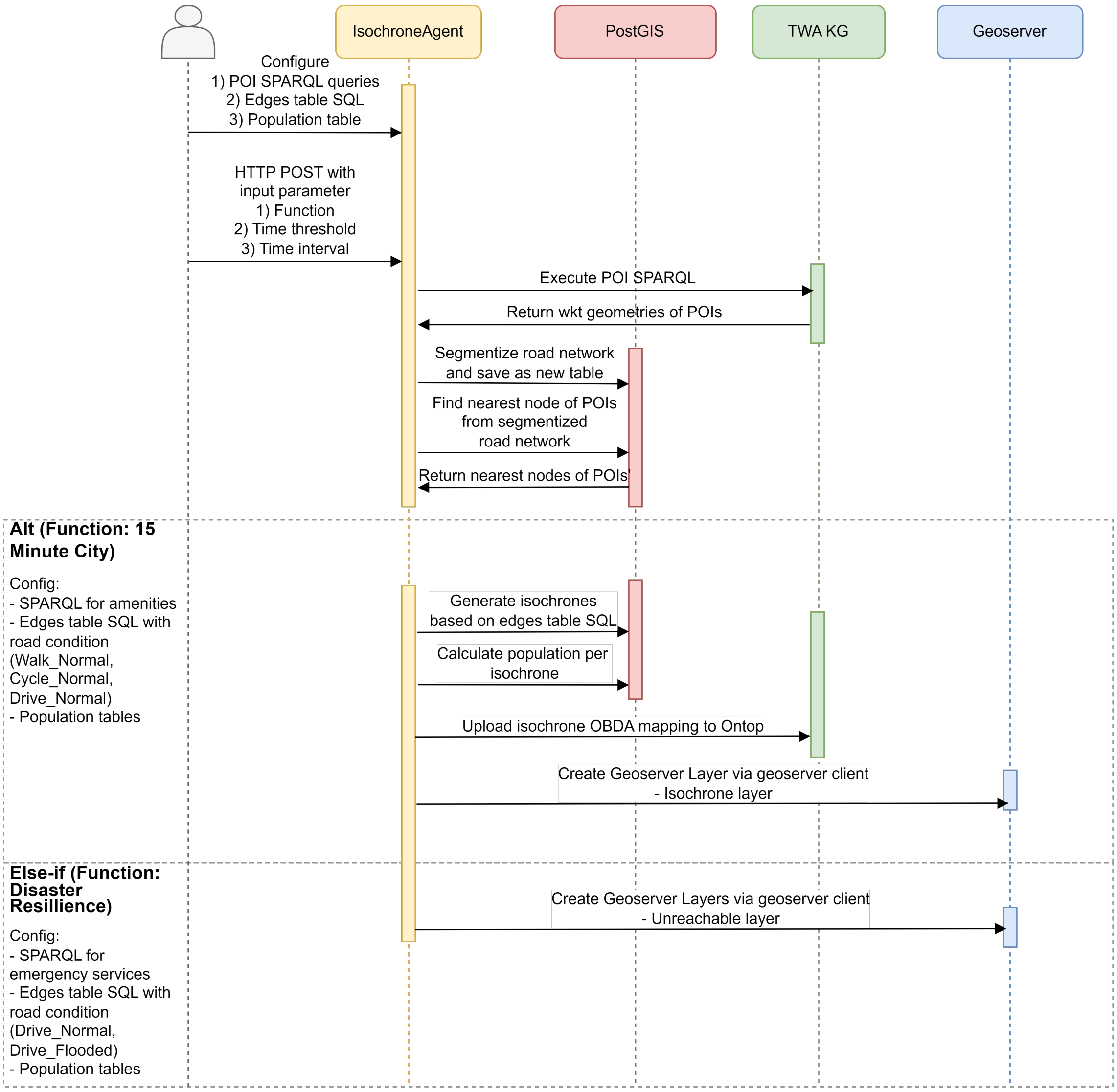

Figure 12: *Isochrone Agent UML diagram*

References

[1] M. Akbari, A. Farshad, and M. Asadi-Lari. The devastation of Bam: an overview of health issues 1 month after the earthquake. *Public Health*, 118(6):403–408, 2004. doi:10.1016/j.puhe.2004.05.010.

[2] J. Akroyd, S. Mosbach, A. Bhave, and M. Kraft. Universal digital twin-a dynamic knowledge graph. *Data-Centric Engineering*, 2:e14, 2021. doi:10.1017/dce.2021.10.

[3] Y. Alabbad, J. Mount, A. M. Campbell, and I. Demir. Assessment of transportation system disruption and accessibility to critical amenities during flooding: Iowa case study. *Science of The Total Environment*, 793:148476, 2021. doi:10.1016/j.scitotenv.2021.148476.

[4] D. E. Alexander. Disaster and emergency planning for preparedness, response, and recovery. Oxford Research Encyclopedia of Natural Hazard Science, 2015. doi:10.1093/acrefore/9780199389407.013.12.

[5] R. Battle and D. Kolas. Geosparql: enabling a geospatial semantic web. *Semantic Web Journal*, 3(4):355–370, 2011.

[6] E. Beracha, B. T. Gilbert, T. Kjorstad, and K. Womack. On the relation between local amenities and house price dynamics. *Real Estate Economics*, 46(3):612–654, 2018. doi:10.1111/1540-6229.12170.

[7] K. Bereta, G. Xiao, and M. Koubarakis. Ontop-spatial: Ontop of geospatial databases. *Journal of Web Semantics*, 58:100514, 2019. doi:10.1016/j.websem.2019.100514.

[8] T. Berners-Lee, J. Hendler, and O. Lassila. The semantic web. *Scientific American*, 284(5):34–43, 2001.

[9] U. Bhatia, D. Kumar, E. Kodra, and A. R. Ganguly. Network science based quantification of resilience demonstrated on the indian railways network. *PloS one*, 10(11): e0141890, 2015. doi:10.1371/journal.pone.0141890.

[10] C. Bizer, T. Heath, and T. Berners-Lee. Linked data: The story so far. In *Semantic services, interoperability and web applications: emerging concepts*, pages 205–227. IGI global, 2011. doi:10.4018/978-1-60960-593-3.

[11] A. Calafiore, R. Dunning, A. Nurse, and A. Singleton. The 20-minute city: An equity analysis of Liverpool City Region. *Transportation Research Part D: Transport and Environment*, 102:103111, 2022. doi:10.1016/j.trd.2021.103111.

[12] A. Chadzynski, N. Krdzavac, F. Farazi, M. Q. Lim, S. Li, A. Grisiute, P. Herthogs, A. von Richthofen, S. Cairns, and M. Kraft. Semantic 3D City Database—An enabler for a dynamic geospatial knowledge graph. *Energy and AI*, 6:100106, 2021. doi:10.1016/j.egyai.2021.100106.

[13] S. Choosumrong, V. Raghavan, and E. Realini. Implementation of dynamic cost based routing for navigation under real road conditions using FOSS4G and OpenStreetMap. *Proceedings of GIS-IDEAS 2010, Hanoi, Vietnam, 9-11 December 2010*, pages 53–58, 2010.

[14] S. Choosumrong, C. Humhong, V. Raghavan, and G. Fenoy. Development of optimal routing service for emergency scenarios using pgRouting and FOSS4G. *Spatial Information Research*, 27:465–474, 2019. doi:10.1007/s41324-019-00248-2.

[15] J. Coaffee and P. Lee. *Urban resilience: planning for risk, crisis and uncertainty*. Planning, Environment, Cities. Red Globe Press, 1st edition, May 2016. ISBN 9781137288837.

[16] A. R. Coles. Identification and evaluation of flood-avoidance routes in Tucson, Arizona. *International journal of disaster risk reduction*, 48:101597, 2020. doi:10.1016/j.ijdrr.2020.101597.

[17] G. C. Crişan, C.-M. Pintea, and V. Palade. Emergency management using geographic information systems: application to the first romanian traveling salesman problem instance. *Knowledge and Information Systems*, 50:265–285, 2017. doi:10.1007/s10115-016-0938-8.

[18] Das Landesamt für Vermessung und Geobasisinformation (LVermGeo) Rheinland-Pfalz. Digitales Landschaftsmodell (DLM), 2023. URL `https://lvermgeo.rlp.de/de/produkte/geotopografie/digitale-landschaftsmodelle-dlm/`. Accessed: December 12, 2023.

[19] M. Di Marino, E. Tomaz, C. Henriques, and S. H. Chavoshi. The 15-minute city concept and new working spaces: a planning perspective from Oslo and Lisbon. *European Planning Studies*, 31(3):598–620, 2023. doi:10.1080/09654313.2022.2082837.

[20] L. Ding, G. Xiao, A. Pano, M. Fumagalli, D. Chen, Y. Feng, D. Calvanese, H. Fan, and L. Meng. Integrating 3D City Data through Knowledge Graphs. *arXiv preprint arXiv:2310.11555*, 2023. doi:10.48550/arXiv.2310.11555.

[21] A. Eibeck, M. Q. Lim, and M. Kraft. J-Park Simulator: An ontology-based platform for cross-domain scenarios in process industry. *Computers & Chemical Engineering*, 131:106586, 2019. doi:10.1016/j.compchemeng.2019.106586.

[22] J. A. Fonseca, T.-A. Nguyen, A. Schlueter, and F. Marechal. City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts. *Energy and Buildings*, 113:202–226, 2016. doi:10.1016/j.enbuild.2015.11.055.

[23] D. Freckleton, K. Heaslip, W. Louisell, and J. Collura. Evaluation of resiliency of transportation networks after disasters. *Transportation Research Record*, 2284(1): 109–116, 2012. doi:10.3141/2284-13.

[24] U. Gangwal, A. Siders, J. Horney, H. A. Michael, and S. Dong. Critical facility accessibility and road criticality assessment considering flood-induced partial failure. *Sustainable and Resilient Infrastructure*, 8(sup1):337–355, 2023. doi:10.1080/23789689.2022.2149184.

[25] Geoapify GmbH. Geoapify, 2023. URL `https://www.geoapify.com/`. Accessed: November 30, 2023.

[26] P. Ghannad, Y.-C. Lee, and J. O. Choi. Prioritizing postdisaster recovery of transportation infrastructure systems using multiagent reinforcement learning. *Journal of Management in Engineering*, 37(1):04020100, 2021. doi:10.1061/(ASCE)ME.1943-5479.0000868.

[27] R. Gutting, M. Gerhold, and S. Rößler. Spatial accessibility in urban regeneration areas: A population-weighted method assessing the social amenity provision. *Urban Planning*, 6:189–201, 11 2021. doi:10.17645/up.v6i4.4425.

[28] L. A. Guzman, J. Arellana, D. Oviedo, and C. A. M. Aristizábal. COVID-19, activity and mobility patterns in Bogotá. Are we ready for a ‘15-minute city’? *Travel Behaviour and Society*, 24:245–256, 2021. doi:10.1016/j.tbs.2021.04.008.

[29] Here Technologies. 15-Minute City Map, 2020. URL `https://app.developer.here.com/15-min-city-map/`. Accessed: November 28, 2023.

[30] M. Hofmeister, J. Bai, G. Brownbridge, S. Mosbach, K. F. Lee, F. Farazi, M. Hillman, M. Agarwal, S. Ganguly, J. Akroyd, and M. Kraft. Semantic Agent Framework for Automated Flood Assessment Using Dynamic Knowledge Graphs, 2023. Submitted for publication. Preprint available at `https://como.ceb.cam.ac.uk/preprints/309/`.

[31] M. Hofmeister, G. Brownbridge, M. Hillman, S. Mosbach, J. Akroyd, K. F. Lee, and M. Kraft. Cross-domain flood risk assessment for smart cities using dynamic knowledge graphs. *Sustainable Cities and Society*, page 105113, 2023. doi:10.1016/j.scs.2023.105113.

[32] A. Hull, C. Silva, and L. Bertolini. *Accessibility instruments for planning practice*. Cost Office Brussels, 2012.

[33] N. E. Hultman and A. S. Bozmoski. The changing face of normal disaster: risk, resilience and natural security in a changing climate. *Journal of International Affairs*, pages 25–41, 2006.

[34] Information Office Of Shanghai Municipality. 15-minute Community Living Circle in Shanghai, November 2023. URL `https://ghzyj.sh.gov.cn/ldft/20210715/cc2adc4ffff244418d2a99fd6d7756ad.html`. Accessed: November 29, 2023.

[35] K. Janowicz, P. Hitzler, W. Li, D. Rehberger, M. Schildhauer, R. Zhu, C. Shimizu, C. Fisher, L. Cai, G. Mai, et al. Know, Know Where, KnowWhereGraph: A densely connected, cross-domain knowledge graph and geo-enrichment service

stack for applications in environmental intelligence. *AI Magazine*, 43(1):30–39, 2022. doi:10.1002/aaai.12043.

[36] K-SOL S.r.l. ISO4App, 2023. URL `https://www.iso4app.net/`. Accessed: November 30, 2023.

[37] G. Klyne. Resource description framework (RDF): Concepts and abstract syntax. *http://www. w3. org/TR/rdf-concepts/*, 2004.

[38] P. Knox and H. Mayer. *Small town sustainability: Economic, social, and environmental innovation*. Walter de Gruyter, 2013. doi:10.1515/9783038210283.

[39] B. Kolen, M. Kok, I. Helsloot, and B. Maaskant. EvacuAid: a probabilistic model to determine the expected loss of life for different mass evacuation strategies during flood threats. *Risk Analysis*, 33(7):1312–1333, 2013. doi:10.1111/j.1539-6924.2012.01932.x.

[40] W. Li, S. Wang, X. Chen, Y. Tian, Z. Gu, A. Lopez-Carr, A. Schroeder, K. Currier, M. Schildhauer, and R. Zhu. Geographvis: a knowledge graph and geovisualization empowered cyberinfrastructure to support disaster response and humanitarian aid. *ISPRS International Journal of Geo-Information*, 12(3):112, 2023. doi:10.3390/ijgi12030112.

[41] Y. Li, Y. Chai, Z. Chen, and C. Li. From lockdown to precise prevention: Adjusting epidemic-related spatial regulations from the perspectives of the 15-minute city and spatiotemporal planning. *Sustainable Cities and Society*, 92:104490, 2023. doi:10.1016/j.scs.2023.104490.

[42] M. Q. Lim, X. Wang, O. Inderwildi, and M. Kraft. The world avatar—A world model for facilitating interoperability. In *Intelligent Decarbonisation: Can Artificial Intelligence and Cyber-Physical Systems Help Achieve Climate Mitigation Targets?*, pages 39–53. Springer, 2022. doi:10.1007/978-3-030-86215-2_4.

[43] T. Logan, M. Hobbs, L. Conrow, N. Reid, R. Young, and M. Anderson. The x-minute city: Measuring the 10, 15, 20-minute city and an evaluation of its use for sustainable urban design. *Cities*, 131:103924, 2022. doi:10.1016/j.cities.2022.103924.

[44] C. Ma, J. Zhang, Y. Zhao, M. F. Habib, S. S. Savas, and B. Mukherjee. Traveling repairman problem for optical network recovery to restore virtual networks after a disaster. *Journal of Optical Communications and Networking*, 7(11):B81–B92, 2015. doi:10.1364/JOCN.7.000B81.

[45] O. R. Manifesty and J. Y. Park. A Case Study of a 15-Minute City Concept in Singapore's 2040 Land Transport Master Plan: 20-Minute Towns and a 45-Minute City. *International Journal of Sustainable Transportation Technology*, 5(1):1–11, 2022. doi:10.31427/IJSTT.2022.5.1.1.

[46] C. Moreno, Z. Allam, D. Chabaud, C. Gall, and F. Pratlong. Introducing the "15-Minute City": Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities*, 4(1):93–111, 2021. doi:10.3390/smartcities4010006.

[47] M. Mosayebi, M. Sodhi, and T. A. Wettergren. The traveling salesman problem with job-times (tspj). *Computers & Operations Research*, 129:105226, 2021. doi:10.1016/j.cor.2021.105226.

[48] A. Murdock, A. Harfoot, D. Martin, S. Cockings, and C. Hill. OpenPopGrid: an open gridded population dataset for England and Wales. *GeoData, University of Southampton*, 2015.

[49] L. Nicoletti, M. Sirenko, and T. Verma. City Access Map, 2022. URL `https://www.cityaccessmap.com/`. Accessed: November 28, 2023.

[50] C. E. Noon and J. C. Bean. An efficient transformation of the generalized traveling salesman problem. *INFOR: Information Systems and Operational Research*, 31(1): 39–44, 1993. doi:10.1080/03155986.1993.11732212.

[51] NParks. Singapore, Our City in Nature, 2020. URL `https://www.nparks.gov.sg/about-us/city-in-nature`. Accessed: Dec 14, 2023.

[52] U. K. Office for National Statistics. Population Census, 2021. URL `https://www.ons.gov.uk/census/maps/choropleth/population/age`. Accessed: July 27, 2023.

[53] OpenStreetMap contributors. Planet dump retrieved from https://planet.osm.org . `https://www.openstreetmap.org`, 2017.

[54] E. Papadopoulos, A. Sdoukopoulos, and I. Politis. Measuring compliance with the 15-minute city concept: state-of-the-art, major components and further requirements. *Sustainable Cities and Society*, page 104875, 2023. doi:10.1016/j.scs.2023.104875.

[55] G. Parajuli, S. Neupane, S. Kunwar, R. Adhikari, and T. D. Acharya. A GIS-Based Evacuation Route Planning in Flood-Susceptible Area of Siraha Municipality, Nepal. *ISPRS International Journal of Geo-Information*, 12(7):286, 2023. doi:10.3390/ijgi12070286.

[56] S. Petricola, M. Reinmuth, S. Lautenbach, C. Hatfield, and A. Zipf. Assessing road criticality and loss of healthcare accessibility during floods: the case of Cyclone Idai, Mozambique 2019. *International Journal of Health Geographics*, 21(1):14, 2022. doi:10.1186/s12942-022-00315-2.

[57] pgRouting. osm2pgrouting, 2023. URL `https://pgrouting.org/docs/tools/osm2pgrouting.html`. Accessed: January 30, 2023.

[58] pgRouting. pgRouting, 2023. URL `https://pgrouting.org/`. Accessed: January 30, 2023.

[59] pgRouting. Graph with Cost, 2023. URL `https://docs.pgrouting.org/latest/en/pgRouting-concepts.html#graph-with-cost`. Accessed: December 7, 2023.

[60] C. Pisano. Strategies for post-COVID cities: An insight to Paris En Commun and Milano 2020. *Sustainability*, 12(15):5883, 2020. doi:10.3390/su12155883.

[61] N. L. Poff. Ecological response to and management of increased flooding caused by climate change. *Philosophical transactions of the royal society of London. Series A: mathematical, physical and engineering sciences*, 360(1796):1497–1510, 2002. doi:10.1098/rsta.2002.1012.

[62] G. Pozoukidou and Z. Chatziyiannaki. 15-Minute City: Decomposing the new urban planning eutopia. *Sustainability*, 13(2):928, 2021. doi:10.3390/su13020928.

[63] D. Praliaskouski. Isochrones are not Alpha Shapes, 2018. URL `https://www.patreon.com/posts/isochrones-are-20933638`. Accessed: Dec 4, 2023.

[64] J. Rentschler, M. Salhab, and B. A. Jafino. Flood exposure and poverty in 188 countries. *Nature communications*, 13(1):3527, 2022. doi:10.1038/s41467-022-30727-4.

[65] Q. Schiermeier et al. Increased flood risk linked to global warming. *Nature*, 470 (7334):316–316, 2011. doi:10.1038/470316a.

[66] A. Sheth, S. Padhee, and A. Gyrard. Knowledge graphs and knowledge networks: the story in brief. *IEEE Internet Computing*, 23(4):67–75, 2019. doi:10.48550/arXiv.2003.03623.

[67] P. S. Singh, R. B. Lyngdoh, D. Chutia, V. Saikhom, B. Kashyap, and S. Sudhakar. Dynamic shortest route finder using pgRouting for emergency management. *Applied Geomatics*, 7:255–262, 2015. doi:10.1007/s12518-015-0161-4.

[68] State Government of Victoria. 20-Minute Neighbourhoods, 2023. URL `https://www.planning.vic.gov.au/guides-and-resources/strategies-and-initiatives/20-minute-neighbourhoods`. Accessed: November 28, 2023.

[69] A. Sulaiman and M. T. Abulajiang. In Search of 20-Minute Neighborhoods: Toronto's Pedestrian Network using Walkability to Nearest Amenities: Walkable City. *ScienceOpen Preprints*, 2023. doi:10.14293/S2199-1006.1.SOR-.PPJI638.v1.

[70] S. Tachaudomdach, A. Upayokin, N. Kronprasert, and K. Arunotayanun. Quantifying road-network robustness toward flood-resilient transportation systems. *Sustainability*, 13(6):3172, 2021. doi:10.3390/su13063172.

[71] M. Te Brömmelstroet, C. Silva, L. Bertolini, et al. COST Action TU1002-Assessing usability of accessibility instruments. *Brussels: COST*, 2014.

[72] T. G. Tiecke, X. Liu, A. Zhang, A. Gros, N. Li, G. Yetman, T. Kilic, S. Murray, B. Blankespoor, E. B. Prydz, et al. Mapping the world population one building at a time. *arXiv preprint arXiv:1712.05839*, 2017. doi:10.48550/arXiv.1712.05839.

[73] TravelTime. TravelTime, 2023. URL `https://traveltime.com/`. Accessed: November 30, 2023.

[74] UK Power Networks. UK Power Networks Open Data. `https://ukpowernetworks.opendatasoft.com/explore/?disjunctive.theme&disjunctive.keyword&sort=explore.popularity_score`, 2023. Accessed: Dec 20, 2023.

[75] United Nations. Cities - United Nations Sustainable Development Action 2015, January 7 2015. URL `https://www.un.org/sustainabledevelopment/cities/`. Sustainable Development Goals.

[76] B. Veerubhotla, V. Bothale, B. Kumar, N. Urkude, and R. Shukla. Route Analysis for Decision Support System in Emergency Management Through GIS Technologies. *International Journal of Advanced Engineering and Global Technology*, 03, 02 2015.

[77] P. Wang. Web-based public participation GIS application: a case study on flood emergency management. *Student thesis series INES*, 2013. URL `https://www.lunduniversity.lu.se/lup/publication/3358659`.

[78] S. Wang, B. R. Sarker, L. Mann Jr, and E. Triantaphyllou. Resource planning and a depot location model for electric power restoration. *European Journal of Operational Research*, 155(1):22–43, 2004. doi:10.1016/S0377-2217(02)00803-2.

[79] Z. Wang and S. Zlatanova. Safe route determination for first responders in the presence of moving obstacles. *IEEE Transactions on Intelligent Transportation Systems*, 21(3):1044–1053, 2019. doi:10.1109/TITS.2019.2900858.

[80] Z. Wang, S. Zlatanova, A. Moreno, P. Van Oosterom, and C. Toro. A data model for route planning in the case of forest fires. *Computers & Geosciences*, 68:1–10, 2014. doi:10.1016/j.cageo.2014.03.013.

[81] M. Weng, N. Ding, J. Li, X. Jin, H. Xiao, Z. He, and S. Su. The 15-minute walkable neighborhoods: Measurement, social inequalities and implications for building healthy communities in urban China. *Journal of Transport & Health*, 13:259–273, 2019. doi:10.1016/j.jth.2019.05.005.

[82] X. Xu, L. Zhang, M. Trovati, F. Palmieri, E. Asimakopoulou, O. Johnny, and N. Bessis. PERMS: An efficient rescue route planning system in disasters. *Applied Soft Computing*, 111:107667, 2021. doi:10.1016/j.asoc.2021.107667.

[83] F. Yuan, Y. D. Wei, and J. Wu. Amenity effects of urban facilities on housing prices in China: Accessibility, scarcity, and urban spaces. *Cities*, 96:102433, 2020. doi:10.1016/j.cities.2019.102433.

[84] C. Zhang, M. Xiong, and X. Wei. Influence of accessibility to urban service amenities on housing prices: Evidence from Beijing. *Journal of Urban Planning and Development*, 148(1):05021063, 2022. doi:10.1061/(ASCE)UP.1943-5444.0000795.