Algorithmic Approach to 15 Minute City

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Contents

1 Introduction

The 15-Minute City was first proposed by Moreno in 2016 as a solution to build safer, more resilient, sustainable and inclusive cities and to harmonise the notion of Smart Cities [MAC⁺21]. Moreno et al. discussed the relationship between the concept of the "15-Minute City" to Urban Planning Pandemic Response, its Emerging Variations (i.e. 20 minute city [CDSKL19]), walkable neighbour [WDL⁺19] smart cities.

Moreno et al. proposed the formal "15-Minute City Concept", arguing that residents should be able to enjoy a higher quality of life where they will be able to effectively fulfil six essential urban social functions to sustain a decent urban life. These include (a) living, (b) working, (c) commerce, (d) healthcare, (e) education and (f) entertainment. The authors then proposed the "modified 15-Minute City" framework, depicting the four identified dimensions that could be incorporated with the already existing one proposed. These are (a) Density, (b) Proximity, (c) Diversity and (d) Digitisation.

Since COVID-19 pandemic, this topic has gained a tremendous amount of attention and has growth exponentially in popularity [LC23, ABCM22] among various research fields in literature, with urban design being the most studied [LC23]. The concept of the 15-Minute City has been studied and shown that it brings benefits to the society (environmental, social, and economical etc.) [ABCM22].

However, many of the studies in 15-Minute City (or t minute city in general) in the literature have used a data-driven approach. Although the 15 minutes threshold is attracted the most attention, the notion of the t-Minute City has also been considered [MAC⁺21]. Some examples are the 20-Minute City in Tempe, Arizona [CDSKL19], the 30-Minute City in Sydney, Australia [SWL20] and Olivari et al. studied 5 to 60 Minute City in Ferrara, Italy [OCNG23]. The lack of algorithmic approaches available regarding t minute city means that many solutions available cannot be generalised and to be reapplied to another location of interest. Moreover, Lima et al. has noted that computational approaches to 15-Minute City design presents significant challenges such as "data availability and quality", "computational cost" and "adaptability" [LC23]. Notably, Weng et al. [WDL⁺19] and Olivari et al.[OCNG23] relied on census data on population density for their respective studies which may not be available for some countries and regions.

2 Previous Work

In this section, we will discuss a number of previous works of 15-Minute City. As this topic have been studied in various research fields in literature, we will break this section into 2 parts - the first part containing works that are more relevant to our focus in this thesis, specifically the methodologies discuessed and used in determining and finding the so-called "15-Minute City". The latter part of this section will covered other studies about the general concept of the "15-Minute City".

2.1 Relevant Works

Table 1: Summary of relevant previous works

Approach	Work	Description
Graph Representation	2.1.1, 2.1.2, 2.1.3	Maps represented by graphs as a mathematical structure
Grid Tessellation	2.1.4, 2.1.5, 2.1.6	Maps divided according to various shapes and 15-MC calculations are applied to each area independently
Flow Data	2.1.7, 2.1.8	Use foot travel data to incorporate human mobility patterns
Walk Score	2.1.9, 2.1.10	Proprietary methodology based on sets of specific factors

Table 1 summarises the common methodologies used in the relevant works. The following are the detailed descriptions of each study and methodology.

2.1.1 Graph Representation of the 15-Minute City: A Comparison between Rome, London, and Paris [BDMM23]

Barbieri et al. defined the general t-minute city (hereafter t-MC) on an urban graph with respect to a given set of services. The urban graph is represented by a planer graph $G(V, E)$ (when a connected graph can be drawn without any edges crossing).

The nodes of G are the intersections of the roads, and the lengths of the edges are proportional to the travel time with a coefficient, which is the speed of the pedestrians. Services $f \in V$ are then placed by adding an extra node to the graph, or use the nearest junction (as per Euclidean distance).

Given a list of N_i services of type i, $C_k^i = (C_1^i, C_2^i, ..., C_{N_i}^i)$ are the nodes that reach f^i in less than 15 min. The set of vertices that form a 15-MC with respect to services of type i is given by the union of all these vertices

$$C^i = \bigcup_{k=1}^{N_i} C_k^i \subseteq V$$

If services f_i, f_j of the same type are far enough, it is possible that $C_i \cap C_j = \emptyset$. The authors noted that these "gaps" can be recognised as "the places where it is necessary to intervene to reconnect". Then for K types of services, the set of the 15-minute vertices is

$$C = \bigcap_{i=1}^{K} C^i = \bigcap_{i=1}^{K} \left(\bigcup_{j=1}^{N_i} C_k^j \right) \subseteq V$$

Finally, the authors define G_C as the graph induced on G by the vertices C, the 15-MC graph is the subgraph G_C of the urban graph G. To formalise, the set C depends on the travel time t, the service matrix $\mathbf{s}$, and the travel speed v, the graph of the 15-MC can be defined as

$$G_C = G_C(C, E_C; t, \mathbf{s}, v) \subseteq G$$

A metric/ratio $\gamma(r, x_0; t, \mathbf{s}, v)$ was also defined as a function of the radius r with respect to a given origin x_0, which can be used to characterise the 15-MC and compare different cities or areas of the same city, where

$$\gamma(r, x_0; t, \mathbf{s}, v) \equiv |C(r, x_0; t, \mathbf{s}, v)| / |E|$$

A possible generalisation of the index was then suggested which takes into account the properties or weights $w(e), e \in E$ of each edge, such as the length of the path, the population density or the slope of the streets

$$\gamma = \frac{\sum_{c \in C} w(c)}{\sum_{e \in E} w(e)}$$

If $w(\cdot)$ is the population density, the edges of the parks and archaeological area have $w = 0$, and the index γ is not biased.

For the case study, the authors used a "shortest path search algorithm" for graph search [Dij59].

Note: This paper transform map data into a planar graph, the algorithm starts from services rather than houses which reduces computational complexity. The authors referenced an article about Dijkstra algorithm for graph search but their implementation was not mentioned.

2.1.2   Exploring the 15-minute neighbourhoods [CCRZ22]

According to the authors (Caselli et al.), "in the proposed study, the 15-Minute City theme is addressed with an analytical model designed and developed using GIS to assess existing conditions of accessibility to neighbourhood services for all the resident social groups."

The GIS-model is implemented by improving and integrating a Territorial Information system (managed with ArcGIS software). Extracting the pedestrian paths feature class to generate a link-node graph with all walking routes available. The model also considers that users "might choose to walk along road margins or cross in the proximity of road intersections."

The paper studied the area covered that can be travelled to "neighbour cores" within 15 minutes by the following calculation:

$$\text{Length}(km)/(3km/h \times 60min) + \text{DF}(min)$$

where DF is the delay factor at crossings (20 and 30 seconds for non-signalised and 40 and 60 seconds for signalised).

The authors then compare this area with its population distribution to study the proportion of population covered by the 15-MC.

Notes: The authors did not define the neighbour cores, only by saying "urban nodes well served by necessities shops and services, such as supermarkets, grocery stores, bars, drugstores, and banks." However, using such nodes to calculate for 15-Minute City contributes to faster running time. The actual 15-Minute City search approach was not mentioned.

2.1.3   The inclusive 15-Minute City: Walkability analysis with sidewalk networks [RSRBH23]

The paper proposed a framework for assessing multi-factor walkability on a sidewalk network model.

The sidewalk network model is defined as a graph where the nodes are intersections or crosswalks, the edges have 3 types: sidewalks, crosswalks, and

pedestrian-only paths and 4 attributes: length, width, slope, and pedestrian hazard. The pedestrian-only paths includes pedestrianised streets, living streets, and paths through parks and plazas. Pedestrian hazard is a metric to describe how dangerous each sidewalk segment by using a fine-grained map of estimated pedestrian safety in Barcelona [BRSR$^+$21] and by exploiting Deep Learning tools. The resulting network is denser than the road network (approximately 4 to 1 in both nodes and edges). Each node of the graph has also been assigned a population according to census data.

This network is then simplified by a percolation analysis according to the sidewalks' properties (i.e., width, slope, or hazard).

The authors then noted that the analysis on the 1260m that can be travelled in 15 min at a walking speed of 1.4 m/s, in accordance with literature [BW17]. Using government data, the authors selected a list of services.

To find such a set of links, we extended the classic Dijkstra algorithm to

1. explore all nodes within the threshold time from a single source, and

2. to record all edges that can be traversed within the threshold, not only the ones that form part of a shortest path.

A formal description can be found in Section S3 of the Supplementary Materials, while the implementation was done in Python, using the igraph library [igr].

The authors then studied the impact of population size of the largest and second largest connected component of Barcelona's sidewalk networks by changing the parameters of percolation analysis.

Notes: *This model takes hazard as a factor. The percolation analysis is a main focus of the study. The Supplementary notes also included the modification of Dijkstra algorithm.*

2.1.4   Urban accessibility in a 15-Minute City a measure in the city of Naples, Italy [GGZC22]

The authors (Gaglione et al.) in this paper proposed a 4 steps methodology through a GIS environment to define the areas accessible in 15 minutes.

1. With a systemic approach, 17 variables have been identified by

   - The characteristics of the population.
   - The characteristics of urban fabrics, in particular their shape.

- The physical characteristics relating to safety, amenities and pleas-antness of the pedestrian. network.

2. The relationships among different groups of characteristics were identified through a (Pearson) correlation analysis to remove some variables.

3. Relating the demand (users) to the supply (local urban services). The authors used a proximity analysis by calculating the Euclidean distances from the centroids of the census sections to the related closer local urban services, then study how users can move along the pedestrian network by labelling 13 characteristics on each pedestrian path. "On the basis of the travel times defined on each link of the pedestrian network and the distribution and location of all the local services examined, urban areas accessible in 15 minutes have been defined."

4. The population density is then compared with the 15-minute accessible areas. Individual age groups are also studied in this context.

The authors then explored the effect of choosing different grid size, shapes etc. in terms of the results of the minute city.

Notes: *The authors did not specify walking speeds or any algorithms used in calculating travel times.*

2.1.5 Are Italian cities already 15-minute? [OCNG23]

The authors (Olivari et al.) of this paper proposed a data-driven approach solution by defining the NExt proXimity Index (NEXI), which "exploits the data to answer the question: "Which parts of your city or town already follow the 15-minute model?"

With a selected list of service categories, and the nodes of the road network (the intersection points of the network geometries) and the points of interest (the geographical location of the various services). For each node the algorithm computes the time needed to reach – at an average walking speed - the closest point of interest of any given category, being constrained to move only on roads accessible to pedestrians. More in details, the time needed to reach the points of interest is computed as $t = l/s$, where:

- l is the length of the shortest route to the PoI (Point of Interest), on a road network made only of walkable roads,

- s is the approximate walking speed of an average person, that is 5 km/h.

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If all categories can be reached within 15 minutes, the node is then considered to be a 15-minute node. Using a 5 km/h speed, the maximum reachable distance in 15 minutes is 1250m. "if the average time to reach all the categories from the nodes in that area is lower or equal to 15 minutes".

The algorithm computes the level of proximity of a given area as the mean of the levels of proximity of the nodes inside that area. Therefore, an area is 15-minute if the average time to reach all the categories from the nodes in that area is lower or equal to 15 minutes. The authors used hexagons with a diameter of 250 meters as the smallest resolution unit.

3 indices are proposed by the authors:

1. The NEXI-Minutes assigns to each category for each area a value of time which is the average time to reach each category.

2. The NEXI-Global takes inspiration from the Walk Score methodology, measuring the global proximity to all service categories on a scale that goes from $0 - 100$, where 0 means that none of the categories is at least within a 30-minute walk, while 100 means that all categories are within a 15-minute walk and all values in between describe an intermediate situation.

3. A discomfort index which takes population into account, where

$$\text{Discomfort} = (100 - \text{Global}) \times \text{Population}$$

Notes: *This paper takes the population distribution into account, only considering walking (but can be changed easily by varying the speed parameter). It does not use graph representation and there are no mentions of graph search algorithm. Though the authors mentioned that the algorithm could be sped up by using "parallelisable algorithm".*

2.1.6   Travel-time in a grid: modelling movement dynamics in the "minute city" [PAMC24]

The authors claimed to "provide initial insights and recommendations for developing more robust 15-Minute City models" and emphasised "the importance of technical modelling steps in determining the mapping outputs which support the assessments of 15-minute cities." In the paper, they experimented on evaluating grid-based methods and identified four noteworthy variables:

1. Grid tessellation choices

2. Software application pick

3. Speed selection for travel-time calculations

4. Classification rules' adoption for mapping urban functions against mapped amenities

"The absence of standardised modelling protocols imposes significant limitations on the application of MC models, hinders synchronic comparisons, and can indirectly foster the formulation of exclusive policies and inconsistent planning decisions. Hence, it is crucial to undertake concerted efforts towards standardisation, including by bridging the gap between the planning practice and software development communities, to effectively address the existing challenges in MC modelling and representation. This entails establishing shared modelling protocols, algorithms (across various software applications), and standardised data inputs, all of which can substantially enhance the consistency and reliability of grid-based MC assessments focused on travel-time estimates. Ultimately, advancing research, fostering collaboration, and promoting knowledge sharing, can elevate the quality of evidence generated through spatial analysis, leading to better-informed decisions in MC planning."

Note: *The authors concluded the article with the paragraph above, which highlights the importance of having a standardised method in calculating 15-Minute City. The results of the thesis can be used to be a harmonised solution to this.*

2.1.7 Towards a 15-minute city: A network-based evaluation framework. [ZZK⁺23]

In the context of 15-Minute City, it is suggested that the allocation of facilities should account for how people access and use local service and amenities rather than merely considering population size [CLZ20].

The authors in this paper proposed a methodological framework for evaluating 15-Minute City based on network science approaches. The paper proposes a network-based approach to evaluating 15-Minute City. This approach differs from mostly used accessibility measurements by accounting for human mobility patterns.

The network-based evaluation framework contains 3 parts:

1. Optimal mobility network is estimated based on the spatial distribution of urban amenities and population using a maximum flow algorithm.

2. The actual origin-destination network is obtained using mobile phone signalling data.

3. The differences between actual origin-destination network and the optimal network are measured to provide insights on the extent to which human mobility patterns, as a reflection on the usage patterns of urban amenities, match or do not match the schemes of urban planning and construction.

The authors then applied the framework model to a case study in Nanjing, China.

2.1.8 Measuring polycentricity via network flows, spatial interaction and percolation [SWL20]

This paper studied polycentricity based on inflow and outflow trip data and considered 3 network-based centricity metrics. In particular, accessibility-based centricity index computes the total number of jobs available and the number of works available within a time threshold from a location. The time threshold was set to 30 in the study to align with the polycentricity-inspired masterplan proposed by The Greater Sydney Commission (GSC) in 2018 which applies to the Sydney-GMR (Sydney Greater Metropolitan Region), noting that "access to jobs, goods and services is provided to the community in three largely self-contained regions."

2.1.9 Walk Score [Wal]

Walk Score is a measure of how walkable an address is based on the distance and availability of nearby amenities, such as grocery stores, restaurants, schools, parks, etc. The higher the Walk Score, the more walkable the location is.

According to the Walk Score methodology, for each address, hundreds of walking routes to nearby amenities are analysed. Points are awarded based on the distance to amenities in each category. Amenities within a 5 minute walk (0.25 miles) are given maximum points. A decay function is used to give points to more distant amenities, with no points given after a 30 minute walk. Walk Score also measures pedestrian friendliness by analysing population density and road metrics such as block length and intersection density. Data sources include Google, Factual, Great Schools, Open Street Map, the U.S. Census, Localise, and places added by the Walk Score user community.

The Walk Score calculation can be summarised into 4 steps

1. Assigning raw weights for selected amenities

2. Calculating distances from each location (community, data from government) to the selected amenities

3. Computing the total scores based on the distances and modifying the scores according to decay factors (e.g. street intersections and block length)

4. Normalising scores to 0–100

Walk Score ranges from 0 to 100, with the following descriptions:

- 90–100: Walker's Paradise. Daily errands do not require a car.

- 70–89: Very Walkable. Most errands can be accomplished on foot.

- 50–69: Somewhat Walkable. Some errands can be accomplished on foot.

- 25–49: Car-Dependent. Most errands require a car.

- 0–24: Car-Dependent. Almost all errands require a car.

Notes: *The Walk Score algorithm is not open source. However, it considers walking distance between 5 to 30 minutes. Its calculation has been validated [CDM11]*

2.1.10 The 15-Minute Walkable Neighbourhoods: Measurement, Social Inequalities and Implications for Building Healthy Communities in Urban China [WDL⁺19]

In this paper, the authors (Weng et al.) noted some of the limitations of the Walk Score calculation, such as

1. It targets at overall population and the walking demands of different pedestrian groups have not been included in the assessment.

2. The decay effect of amenity varies greatly among population groups and categories of amenities.

3. Actual traffic situation has not been considered when calculating distances based on Euclidean distance.

They proposed a modified method to measure 15-min walkable neighbourhoods based on the Walk Score metric, taking into account pedestrians' characteristics and amenity attributes (scale and category). 6 categories of amenities were studied, including education, medical care, municipal administration, finance and telecommunication, commercial services, and elderly care. They delivered the questionnaire to 132 respondents to conclude the parameters considered in

the metric. They also used a decay factor to account for different age groups etc in terms of walking speed.

Notes: *This paper did not consider any algorithm and modification is heavily based on a questionnaire.*

2.2 Other works

2.2.1 A Grammar-Based Optimisation Approach for Designing Urban Fabrics and Locating Amenities for 15-Minute Cities [LBD22]

This paper uses a geometric grammar based approach to explore computation to support decision-making concerning the layout of urban fabrics and the location of amenities in a neighbourhood. They used an inductive method for qualitative content analysis. However, the authors noted that this solution "does not address irregular or non-orthogonal urban block patterns, and the influence of nearby amenities located outside the studied fabric was not considered."

2.2.2 The Quest for Proximity: A Systematic Review of Computational Approaches towards 15-Minute Cities [LC23]

The authors developed a comprehensive overview of the use of computational tools to support the analysis and design of 15-Minute Cities using a systematic literature review. They noted that the topic of 15-minute city has growth exponentially in popularity and especially in the field of urban design. They concluded that computational approaches to 15-minute city design presents significant challenges such as "Data availability and quality", "Computational cost" and "Adaptability".

2.2.3 The 15-minute city: Urban planning and design efforts toward creating sustainable neighbourhoods [KGSS23]

The authors collected 103 documents, dealing with underlying principles, sustainability advantages, and critics of the 15-minute city concept. They defined 7 dimensions constitute the 15-minute city: (1) proximity, (2) density, (3) diversity, (4) digitalisation, (5) human scale urban design, (6) flexibility, (7) connectivity. The authors summarised the sustainability contributions in social, economical and environmental aspects in the society by 15-Minute City and also the barrier of implementations.

2.2.4 The Theoretical, Practical, and Technological Foundations of the 15-Minute City Model: Proximity and Its Environmental, Social and Economic Benefits for Sustainability [ABCM22]

15-Minute City has four main cornerstones (proximity, diversity, density, and digitisation). The authors in this paper explored the proximity dimensions of the 15-Minute City and how it could influence mixed land use to yield environmental, social, and economic benefits.

2.2.5 Urban Transition and the Return of Neighbourhood Planning. Questioning the Proximity Syndrome and the 15-Minute City [MB22]

The authors of this paper developed an evidence-based approach to a deeper analysis of policy design and implementation of the 15 minute city. They concluded that the implementation and effectiveness of the 15 minute city depend on the concrete and contextual conformation of each city. The authors ended the paper stating that city development "needs some design framework and structure capable of addressing transformations, and their space and time location and sequences" on top of the "15 minute device" and that "it needs a syntax for an urban planning course of action that is incremental and adaptive but not limited to the contingent, blurred, and agnostic appeal of a catchy label."

3 Problem Statement

In the previous section 1, serveral studies have discussed the needs for standardisation in terms of the methodology used in computing the 15-Minute City. In particular, Pezzica et al. argued that "the absence of standardised modelling protocols imposes significant limitations on the application of MC models, hinders synchronic comparisons, and can indirectly foster the formulation of exclusive policies and inconsistent planning decisions" [PAMC24]. Lima et al. noted that "introducing computational approaches to 15-minute city design presents significant challenges and potential bottlenecks. On the other hand, exploring these challenges as opportunities for inserting new research is also possible since the theme is rising", some of these challenges are "Data availability and quality", "Computational cost" and "Adaptability" [LC23]. Furthermore, Marchigiani et al. found that the approach to 15-Minute City needs to be changed and adapted to each location case by case [MB22].

With these in mind, the aim of this thesis is to provide a general, adaptable algorithm to identify the 15-Minute City, where a person can travel to all their needs within 15 minutes from their home. Formally, the algorithm has the

following properties.

1. Inputs

   - A graph data structure $G(V, E)$ representing the area of which 15-Minute City is computed, where V is the set of vertices representing road junctions, E is the set of weighted, undirected edges such that $E \subseteq V \times V$ and the weights of the edges are proportional to the length of the roads.
   - A list of services of n types, define f^i as the list of vertices in the graph representation the locations of each service type $i = 1, ..., n$.

2. Output

   - Returns the area within which a person can travel to any of these services within 15 minutes.

4 Algorithms

Breadth-First Search (BFS) and Depth-First Search (DFS), along with Prim's algorithm, Kruskal's algorithm, and Dijkstra's algorithm, are fundamental graph algorithms used in various applications across computer science and related fields. Here's a brief overview of their use cases.

4.1 Breadth-first Search (BFS)

Breadth-first Search algorithm is a single-source graph search algorithm where the graph contains unweighted, undirected edges. The algorithm searches the graph from the source node level by level, that means the algorithm will search all nodes adjacent to the source node, before moving on to searching all nodes adjacent to these nodes. The visited nodes will be marked so that the algorithm will not be stuck in a cycle. The algorithm can be used to determine the connected components of a graph and search for cycles. An example of an application of this algorithm is maze solving, where it can be used to find the shortest path through a maze from the source node (i.e. entrance/exit).

4.2 Depth-First Search (DFS)

Depth-First Search algorithm is another popular single-source graph search algorithm for graphs with unweighted, undirected edges. Depth-First Search starts from the source node, travels along one of its edges and visits the adjacent node,

the algorithm then repeats the process to this adjacent node and so on. Once the algorithm gets to the final node (i.e. there are no edges connected to this node where the adjacent node has not been visited), the algorithm travels to the previous level and checks if that node has an alternate adjacent node through a different edge. This process is then repeated until all nodes have been visited which can be reached to from our source node. Similar to Breadth-first Search algorithm, this algorithm can be used to detect connected components of a graph and search for cycles.

4.3 Prim's Algorithm

Prim algorithm is used for finding the minimum spanning tree (MST) within a weighted, undirected graph. A minimum spanning tree is a subset of the edges of a connected, weighted and undirected graph that connects all the nodes together, without any cycles and with the least possible total edge weight. Prim's algorithm starts from the source node, it keeps a record of the nodes it has selected. It then repeatedly search for the edge with the smallest weight that connects a node from the selected set and a node from outside of this set. Prim is a greedy algorithm and an example of an application is used in network design problems to find the minimum cost to connect all nodes in a network.

4.4 Kruskal's Algorithm

Kruskal's algorithm is similar to Prim algorithm that it is a greedy algorithm which finds a minimum spanning tree in a weighted, undirected graph. The algorithm finds and records the minimum weighted edge, and selects the 2 nodes connected by the edge. It then searches and records for the next smallest weighted edge and select the nodes connected by it. The algorithm repeats the process until all nodes have been selected and the edges recorded form the minimum spanning tree. Kruskal's algorithm can be used in clustering problems where the objective is to group similar items together while minimising the total dissimilarity.

4.5 Dijkstra's Algorithm

Dijkstra's algorithm is a search algorithm which finds the shortest path from a single source node to all other nodes in a non-negative weighted graph.

Dijkstra's algorithm begins from the source node, in every iteration, Dijkstra's algorithm considers all of the current node's neighbours and update their tentative distances through the current node. If this distance is smaller than the

previously assigned distance then update the assigned distance to the new one. The current node is then marked as visited and its tentative distance is then fixed. The algorithm then repeat the same steps on each of the neighbour nodes in the ascending order of their temporary tentative distances, until all nodes in the graph have been visited. Two applications for this algorithm would be network routing to find the shortest paths in computer networks and GPS navigation to find the shortest route between two locations.

5   Proposed solution

Our first proposed solution is to represent the area of interest as a graph. Barbieri et al. proposed to use a planar graph [BDMM23]. However, it is not clear if a planar graph would be able to represent bridges/tunnels etc effectively, as the definition of a planar graph is that it can be drawn on the plane in such a way that its edges intersect only at their endpoints.

Adapting the notations used by Barbieri et al. [BDMM23],, for n types of services. For each service type, the locations of each service can be denoted as $f_j^i, j = 1..., m$, where m denotes the number of services of service type i in the graph.

Subsequently, define $C^i = \bigcup\limits_{j=1}^{m} C_j^i$ the nodes that can be reached by f^i in less than 15 minutes. More specifically, C_j^i is the set of nodes which can be reached by f_j^i in less than 15 minutes.

$$C^i = \bigcup_{j=1}^{m} C_j^i \subseteq V$$

If services

$$f_k^i$$

, f_l^i of the same type i are far enough, it is possible that $C_k \cap C_l = \emptyset$. This represents a gap in the graph where its nodes cannot reach to service type i within 15 minutes.

Finally, we can define the 15-Minute City as the nodes which can reach to all service types within 15 minutes, namely

$$C = \bigcap_{i=1}^{n} \bigcup_{j=1}^{m} C_j^i = \bigcap_{i=1}^{n} C^i \subseteq V$$

5.1 Rewrite notations

Given n types of services, define $F_v \in \{0,1\}^n$ for node v as

$$F_v(i) = \begin{cases} 1 & \text{if node } v \text{ can reach to service } i \text{ in 15 minutes} \\ 0 & \text{otherwise} \end{cases}$$

The output of the algorithm is a set $X \subseteq V$ of nodes where

$$\forall v \in X, \;\; F_v = \mathbf{1}$$

5.2 Search for nodes within 15 minutes

As we have discussed in 4.5, Dijkstra's algorithm can be used to find the shortest route between 2 locations. Therefore, this can be considered as a motivation/inspiration as part of the solution in finding 15-Minute City.

5.3 Modified Algorithm

5.4 Complexity

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