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Equity-Based Allocation of Mobility Hubs in Seoul

Madiha Bencekri[a], Doyun Lee[b], Sion Kim[a], Seungheon Shin[a], Seungjae Lee[d,*]

[a]Department of Transportation Engineering/Department of Smart Cities, University of Seoul, Korea
[b]Graduate School of Environment Studies, Seoul National University, Korea
[c]Department of Land Economy, University of Cambridge
[d]Department of Transportation Engineering, University of Seoul, Korea
sjlee@uos.ac.kr

Mobility hubs are interconnected nodes where several travel modes, private or public, are integrated. They aim to ensure an efficient inter-modality and to prioritize sustainable transportation. Determining their best location is a new fertile research area attracting considerable attention. Although past studies have addressed the location conundrum using the hub location problem (HLP) models, much of the literature has overlooked the aspect of social equity. In this context, social equity refers to the distribution of advantages and disadvantages of a particular policy across diverse social strata, avoiding any social exclusion and discrimination. This study intends to select mobility hub locations that achieve balanced social justice and optimal coverage. It adopted the single allocation p −median hub with a fixed cost model, where the fixed cost encapsulated equity and coverage indices. For equity, the Gini index was derived using social quantile group data. The meta-heuristic method Genetic Algorithm was exploited to solve the HLP optimization. This model displayed a good performance with a high fitness value of around 7.7e7, selecting nine (9) districts. Results of the first optimization step di underscored that locating mobility hubs within mixed land-use areas inhabited or frequented by low to medium-income strata helps promote equitable access and social justice while enhancing sustainable transportation ridership and coverage.

1. Introduction

Mobility hubs are considered critical cornerstones for sustainable transportation. They provide an interconnection between multiple modes of transportation, facilitating a seamless transition from one mode to another. With the additional incorporation of amenities such as real-time travel information, and retail stores, mobility hubs encourage a shift towards sustainable transportation practices, contributing significantly to the reduction of greenhouse gas emissions and the promotion of sustainable urban development (Banister, 2008). Amidst the touted advantages, a notable void persists in comprehending the intricate interplay between their efficient placement and the holistic integration of social equity. Although previous research has delineated the merits of mobility hubs, few have delved deep into the implications of their location selection, which goes beyond mere efficiency concerns.

An efficient hub ensures the optimal utilization of resources, minimizes travel time, and enhances the overall performance of the transportation system. Apart from the predominant concern, previous research has often overlooked the nuanced impacts of hub location on different social and demographic strata. Selecting the best locations for hub implementation should consider several factors. First, the location should ensure easy accessibility to the target population, including residents and workers. Second, it should be within high transportation demand areas, with a good connectivity level between different modes, such as buses, trains, and shared bikes. Third, hubs should be in an area with adequate space for parking and waiting areas. Finally, they should be in a safe and secure area for all users (Anderson et al., 2017).

In tandem with efficiency and within the accessibility need, social equity principles must be considered one of the essential factors of hub location selection. Past research has indicated the pitfalls of excluding equity considerations, which can lead to systemic inequalities and exacerbate socio-economic disparities, making certain parts of the population more marginalized than others. In this context, social equity refers to ensuring

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that the advantages provided by a mobility hub are accessible and beneficial to all socioeconomic groups. Thus, selecting hubs' locations must be carefully planned to avoid privileging certain groups or regions over others, inadvertently deepening existing socioeconomic divides (Martens, 2016). This study is bridging the gap by implementing a more robust method to reflect the social equity in the location selection of mobility hubs. It adopts a sophisticated and hierarchical methodology to address the issue of social equity in mobility hub location selection (Kirkpatrick et al., 1983), using the robust metaheuristic method Genetic Algorithm (Goldberg, 1989) to minimize travel time for the first stage. And by measuring the equity metric Gini index (Gini, 1921) to reflect social inequity, then using it as a fixed cost in the GIS location optimization technique for the second stage.

2. Methodology

To address the nuanced balance between strategic mobility hub placement and the integration of social equity, this study is anchored on a methodological framework comprising sequential steps:

1. Travel Time Minimization: Leveraging the computational capabilities of the Genetic Algorithm (GA) to ensure that hubs are located in areas of high transport connectivity and demand.
2. Social Equity Measurement: Utilizing the Gini index (Gini, 1921), the study quantitatively gauges societal imbalances stemming from prospective hub locations.
3. Spatial Location Optimization: The study then incorporates social equity as a fixed cost in a GIS-based locational optimization paradigm. This approach ensures that the selected locations for mobility hubs not only uphold operational efficiency but also champion principles of social equity.

The used data are sourced from the Seoul Metropolitan Government's online public database. The following table provides a notation for all the involved variables (Table 1).

Table 1: Variables involved in the first stage of optimization.

Type	Variables	Description
Set	λ, γ	The set of possible hub candidates. Note that γ denotes the new set of hub candidates, different from λ of origin-destination nodes.
	G	A fully connected graph. However, this assumption is relaxed, and the subgroups g are considered
Variable	$i, j, k, and\ m$	Nodes
	X	The vector of nodes, with a dimension equal to the total number of nodes (λ). The new vector of hubs with a dimension of γ.
	h_{ij}	The flow between the nodes-pair (i, j), and the flow matrix h is of dimension λ×λ
	h_{ij}	The flow between the nodes-pair (i, j), and the flow matrix h is of dimension λ×λ
	C_{ij}	The transportation cost between the nodes-pair (i, j), and the cost matrix C is of dimension λ×λ
	Y_{ik}	The allocation of a node i to hubs, where $Y_{ik} = 1$ if a node i is allocated to the hub k. The allocation matrix Y is of dimension λ×λ
	G	A fully connected graph. However, this assumption is relaxed, and the subgroups g are considered
	C_{ik}^{g}	The cost between the origin i and the hub k
	C_{mj}^{g}	The cost between the origin j and the hub m
	C_{km}^{f}	The cost between the hubs k & m
	h	The new flow matrix is of dimension (λ+γ)×(λ+γ)
	C	The new cost matrix is of dimension (λ+γ)×(λ+γ)
	Y	The new allocation matrix is of dimension λ×γ
Parameter	α	The discount factor of the transport cost between hubs $k\ and\ m$ $(0 \leq \alpha \leq 1)$
	$(i, j), (k, m)$	Denote non-hub nodes and potential hubs, respectively.

2.1 Hub Location Problem Model

This research adopted the uncapacitated single allocation p −median HLP, referring to selecting p number of hubs within a λ set of possible candidates while allocating the γ non-hub nodes to one hub. Each region chooses one hub, selecting five hubs for every solution. In this case, the link between two hubs is assumed to be less costly than the one involving non-hub nodes, which results in a reduction of 10 % of travel time through the hubs. All possible flows must pass by a hub, and all involved nodes are connected. The methodology and approach of this research are delineated in detail in next sections. For a comprehensive visual overview of the progression and stages of the study, the reader is directed to Figure 1, which encapsulates the flowchart.

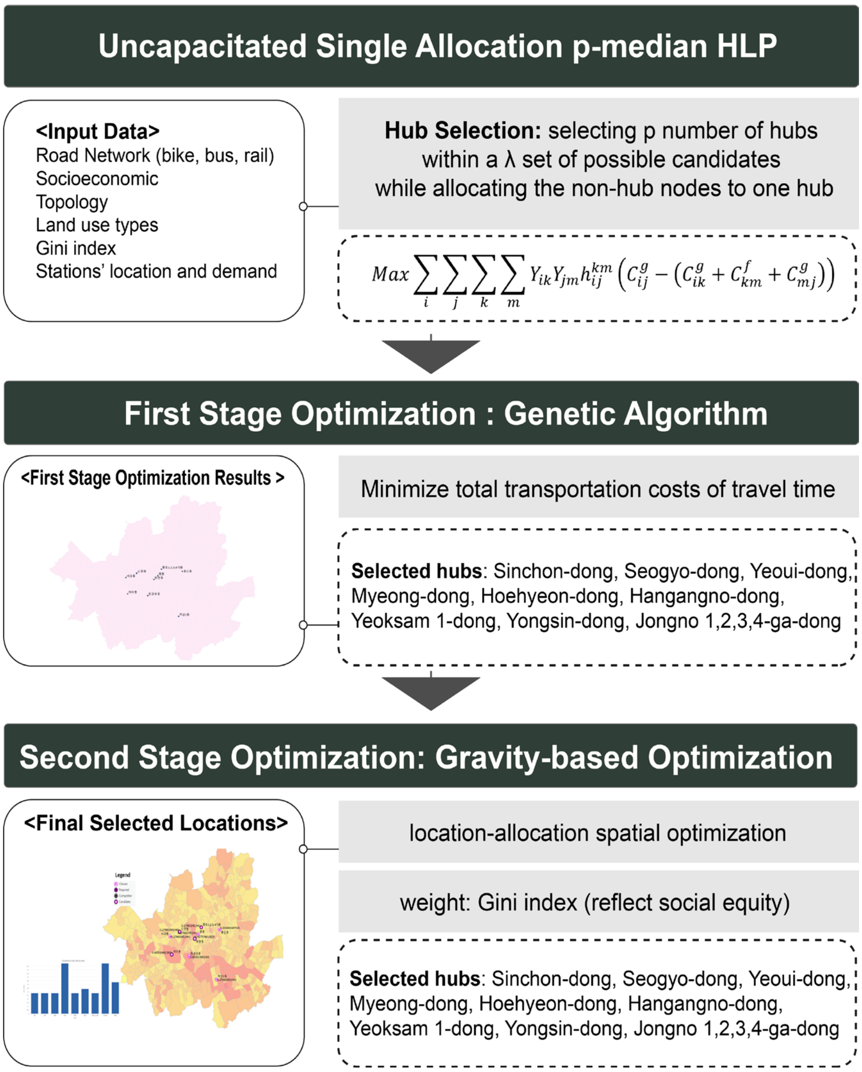

Figure 1: Research Flowchart

This research has implemented the formulation of Farahani et al. (2013) and Hsieh and Kao (2019), to develop its adopted objective function as shown in Eq(1), where variables are explained in Table 1.

$$Max \sum_i \sum_j \sum_k \sum_m Y_{ik} Y_{jm} h_{ij}^{km} \left(C_{ij}^{g} - \left(C_{ik}^{g} + C_{km}^{f} + C_{mj}^{g} \right) \right) \quad (1)$$

Subject to:

- $\sum_k X_k = p$, where p is the exact number of selected hubs.
- $\sum_k Y_{ik} = 1 \ \forall i$, which means each non-hub is allocated to one hub.
- $Y_{ik} \leq X_k \ \forall i, k$, which means that nodes are only located in the selected hubs.
- $X_k = \begin{cases} 1 \\ 0 \end{cases} \forall k, \ where\ 1\ if\ k\ is\ a\ hub\ and\ 0\ if\ not$
- $Y_{ik} = \begin{cases} 1 \\ 0 \end{cases} \forall i, k, where\ 1\ \text{node}\ i\ \text{is allocated to the hub}\ k\ 0\ if\ not$
- α "1, which reflects the assumption that the travel between hubs is much less critical than the hub-node one (it is assumed to be 10 % in this study).
- (k, m) are selected hubs for which $X_k = X_m = 1$, the constraint is $C_{ik} Y_{ik} \leq C_{im} \ \forall k, m$, and it means that users are more likely to use the hub if the nodes are close to their origins or destinations.

- The assumption that each travel must pass through a hub is relaxed as the objective is to minimize the cost; hence trips between non-hub nodes are allowed when the cost is less than when a hub is involved. Then $C_{ij}^{g} > C_{ik}^{g} + C_{km}^{f} + C_{mj}^{g}$
- There is at least one node to function as the base, which means $\exists\ k \in \varphi,\ X_k = 1$, where φ is a set of large nodes.

2.2 Equity Index Development

To accurately reflect social inequity, this study employs the Gini index, which serves as a comprehensive measure of inequality in the distribution of income or consumption expenditure (Gini, 1921). The Gini index is a valuable instrument in the equity-based allocation of mobility hubs due to its capability to quantify the degree of inequality within a distribution, with a range of 0 to 1 where 0 signifies perfect equality and 1 symbolizes absolute social disparities. In this study, the Gini index is computed using the Lorenz curve, a graph illustrating the income or consumption distribution (Gastwirth, 1972). The mathematical formula in Eq(2) represents the Gini index.

$$G_{ik} = \frac{\sum_k (Q_i - Q_k)}{2n \sum Q_k} \tag{2}$$

In the provided formula, "k" represents the number of nodes, "i" denotes the number of hubs, and "n" signifies the total number of 'dong' or neighborhoods within Seoul.

In this study, the Gini index is computed using data stratified by districts, illustrating the income distribution in each district of Seoul (Figure 2). The income distribution is divided into ten deciles, each decile (D1 to D10) representing 10% of the income distribution. Here, D1 represents the lowest income decile, and D10 represents the highest income decile (Atkinson, 1970). As of 2021, the average decile for all of Seoul is 7, and all districts in Seoul fall into the 5^{th} decile or higher. Daechi 1-dong in Seoul stands uniquely at the top, falling into the 10^{th} decile. Looking at it by borough, Gangnam-gu and Seocho-gu average in the 9^{th} decile while Yongsan-gu, Mapo-gu, Yangcheon-gu, and Songpa-gu average in the 8^{th} decile.

2.3 Spatial Location Optimization

This study conducted a location-allocation spatial optimization using ArcGIS as a second step. The adopted impedance or weight is the Gini index to reflect social equity in hub selection. The demand points, which are the districts of Seoul, are weighted by their travel demand. To solve the location-allocation problem, this research adopted the maximization of the market share solution method, which is gravity-based Optimization. In this case, the gravity models determine the proportion of the demand allocated to each candidate. The objective is to find the best sites that maximize the total demand while serving various social groups.

The location-allocation spatial Optimization conducted using ArcGIS in this study introduced an innovative approach to hub selection by factoring in the Gini index, a common measure of inequality. By using the Gini index as the impedance or weight, the study incorporated an element of social equity in the decision-making process, ensuring that the resulting transportation hubs not only serve areas of high demand but also cater to the needs of various social groups across Seoul. The maximization of the market share solution method adopted in this research further facilitated an equitable distribution of resources. This gravity-based optimization process determined the proportion of the demand allocated to each candidate hub, intending to maximize the total demand served while ensuring social equity.

3. Results and Discussion

3.1 Equity Analysis

The Gini index, which measures income inequality, reveals that most districts fall between 0.252 and 0.441, averaging 0.391 (Figure 2a). Districts like Gangnam-gu and Jongno-gu have higher Gini indexes, signifying greater income disparities and subsequent socioeconomic challenges, like limited opportunity access and potential unrest (Figure 2b). In terms of selecting mobility hub locations, areas with higher Gini values, such as Yeouido and Jamsil 6-dong, need special focus. Such areas display stark differences between rich and poor residents, leading to potential social tension and limited resource access for the less affluent. Prioritizing these areas for mobility hubs can bridge the transportation gap for all socio-economic groups and foster a sense of community. Hence, for equitable urban development and to combat transport-related exclusions, it's crucial to consider the Gini index when planning transportation systems, especially in areas with higher inequality.

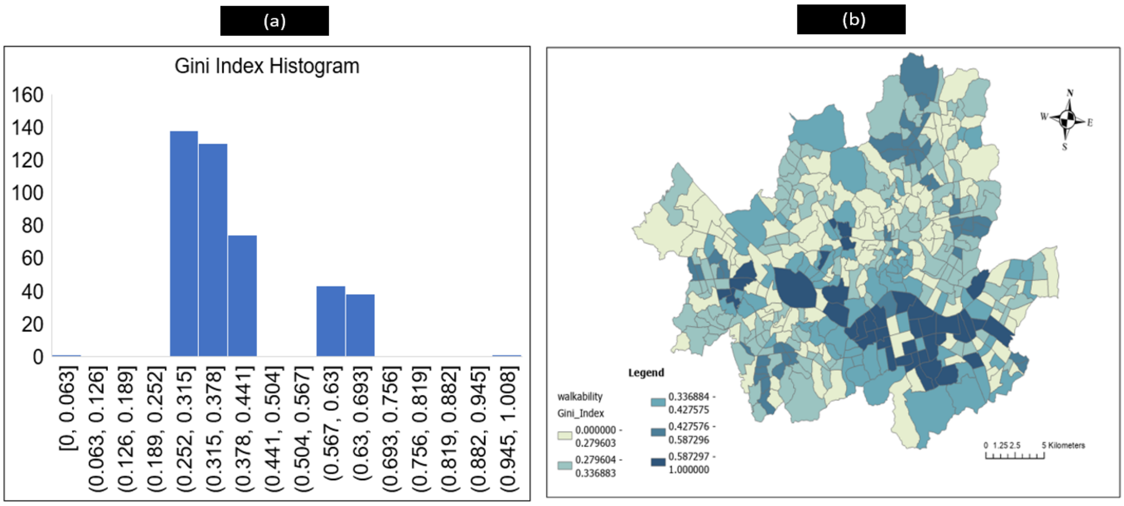

Figure 2: Gini Index Distribution in Seoul

3.2 First Stage Optimization

According to GA's results (Figure 3a and Figure 3b), several locations were selected by region. The algorithm's objective function was to minimize total transportation costs of travel time. Thereby GA tends to select subdistricts with high traffic volume. The selected hub locations are presented, first in Figure 3a overlayed with active population (between 15 and 65 years old), as active population is considered source of travel demand. Second, in Figure 3b overlayed with the Gini index, showing the region with most social disparities. Several hubs were chosen as a product of this Optimization due to their strategic importance in high demand and concentration of commercial and business activities. These hubs were: Sinchon-dong, Seogyo-dong, Yeoui-dong, Myeong-dong, Hoehyeon-dong, Hangangno-dong, Yeoksam 1-dong, Yongsin-dong, and Jongno 1,2,3,4-ga-dong. Each of these selected hubs is known for their unique characteristics. For instance, Sinchon-dong is a well-known university town that hosts a youthful and vibrant population, resulting in a high demand for transportation. Seogyo-dong is the heart of the trendy Hongdae area, which is known for its active nightlife, shopping, and entertainment scenes. Yeoui-dong and Yeoksam 1-dong are crucial business districts hosting several multinational companies and high-rise office buildings. Myeong-dong and Hoehyeon-dong are key shopping and tourist districts. And Jongno 1,2,3,4-ga-dong constitutes a historical, cultural, and touristic center.

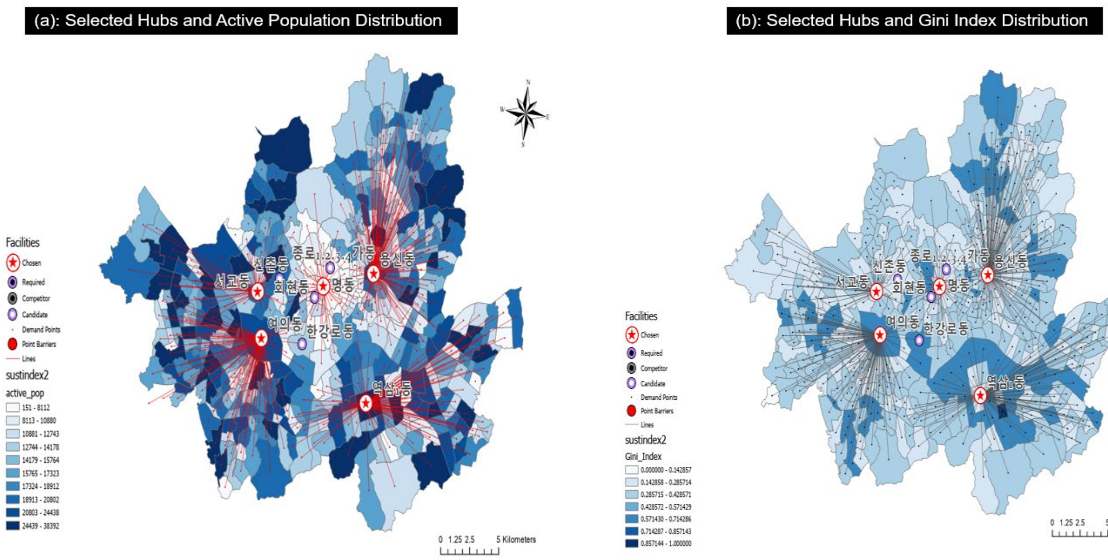

Figure 3: Selected Hubs and the Distribution of Active Population (between 15-65 years old) and Gini Index

3.3 Second stage optimization

In the second step of optimization, involving GIS optimization using equity index as a weight, a set of five districts was selected, one by region. The final selection includes Seogyo-dong, Yeoui-dong, Myeong-dong, Yeoksam 1-dong, and Yongsin-dong (Figure 3). Except for Myeong-dong, all four districts have a high active population (Figure 3a). are of particular significance in ensuring social equity. Also, except for the Yeoui-dong, all other four selected districts are within low Gini-index areas (Figure 3b), which reflect fewer social inequalities and a more balanced income level. The Myeong-dong is a famous shopping district, that can contribute to economic equity by enhancing accessibility for small business owners and market vendors who rely on foot traffic for their livelihoods. The choice of a hub in Yeoksam 1-dong, a prominent part of the affluent Gangnam district, caters to the high job density in the area, supporting a fair distribution of employment opportunities.

4. Conclusions

The study intended to ensure social equity while creating mobility hubs. The strategic selection of these hubs ensures the efficient flow of traffic and minimizes overall travel costs, reflecting the effectiveness of the GA in identifying areas of high demand and importance. Including a hub in the culturally rich Jongno 1,2,3,4-ga-dong aids in cultural equity by improving access to historical and cultural sites for residents and tourists alike. Thus, by incorporating social equity measures in the location-allocation process, this study contributes to a more nuanced and holistic approach to urban planning and transportation management in Seoul, a city grappling with diverse socioeconomic issues.

For future endeavours, it would be valuable to explore other equity metrics beyond the Gini index and delve deeper into the nuanced interplay between transportation and socio-economic dynamics in rapidly urbanizing cities. Additionally, the limitations faced in this study, such as potential data constraints, offer a platform for the next wave of research to build upon.

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References

Anderson K., Blanchard S.D., Cheah D., Levitt D., 2017, Incorporating equity and resiliency in municipal transportation planning: Case study of mobility hubs in Oakland, California, Transportation Research Record, 2653(1), 65-74.

Atkinson A.B., 1970, On the measurement of inequality, Journal of Economic Theory, 2(3), 244-263.

Banister D., 2008, The sustainable mobility paradigm, Transport Policy, 15(2), 73-80.

Delbosc A., Currie G., 2011, The spatial context of transport disadvantage, social exclusion and well-being, Journal of Transport Geography, 19(6), 1130-1137.

Farahani R.Z., Hekmatfar M., Arabani A.B., Nikbakhsh E., 2013, Hub location problems: A review of models, classification, solution techniques, and applications, Computers & Industrial Engineering, 64(4), 1096-1109.

Gini C., 1921, Measurement of inequality of incomes, The Economic Journal, 31(121), 124-125.

Goldberg D.E., 1989, Genetic algorithms in search, optimization and machine learning, Addison Welssey Publishing Company, Reading, MA.

Hsieh S.Y., Kao S.S., 2019, A survey of hub location problems, Journal of Interconnection Networks, 19(01), 1940005.

Jang S., An Y., Yi C., Lee S., 2017, Assessing the spatial equity of Seoul's public transportation using the Gini coefficient based on its accessibility, International Journal of Urban Sciences, 21(1), 91-107.

Kirkpatrick S., Gelatt Jr C.D., Vecchi M.P., 1983, Optimization by simulated annealing, Science, 220(4598), 671-680.

Lucas K., 2012, Transport and social exclusion: Where are we now?, Transport Policy, 20, 105-113.

Martens K., 2016, Transport justice: Designing fair transportation systems, Routledge, London, United Kingdom.

Mihyeon Jeon C., Amekudzi A., 2005, Addressing sustainability in transportation systems: definitions, indicators, and metrics, Journal of Infrastructure Systems, 11(1), 31-50.

O'kelly M.E., 1986, The location of interacting hub facilities, Transportation Science, 20(2), 92-106.

Sen A., Sen M.A., Foster J.E., Amartya S., Foster J.E., 1997, On economic inequality, Oxford University Press, Oxford, United Kingdom,