Original Research Article

Modeling Efficiency and Equity in Disability-Based Accessibility Resource Allocation Using Linear Programming

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ABSTRACT

Communication accessibility is essential for the social participation of people with disabilities. However, limited public funding makes it difficult to prioritize accessibility investments. This study proposes a quantitative framework to examine how resources may be allocated for communication accessibility under budget constraints. Utilizing population-level disability prevalence data from the American Community Survey, inclusion weights were generated for four domains of accessibility: hearing, vision, cognitive, and independent living. A linear programming model was developed to maximize an overall communication inclusion score based on these weights. With a baseline efficiency-driven formulation, the model produced a corner solution, directing all resources to a single domain with the highest inclusion weight, exhibiting the limitations of efficiency-only decision-making for accessibility policy. To address this limitation, the model was extended with constraints related to equity, including minimum baseline allocations and proportionality conditions across domains. The revised model produced a more balanced allocation of investments while decreasing the exclusion of smaller disability groups. The findings in this study indicate how decisions for resource allocation may be formalized with mathematical optimization while revealing the limitations of efficiency-only allocation. This framework provides a transparent tool for supporting the decision in allocation in the perspective of planning accessibility under constrained resources.

Keywords: Communication accessibility; linear programming; resource allocation; equity-constrained optimization; disability policy; budget-constrained modeling

INTRODUCTION

Accessibility for people with disabilities has long been a major societal concern. Frameworks for disability rights and inclusion have expanded over recent decades. However, there are still significant barriers remaining in particular with the domain of communication accessibility. The World Health Organization (WHO) reports that minima perceivability and usability standards were not satisfied by current information and communication technologies (ICT), making it hard for people with disabilities to navigate online environments and fully participate in civic life (1). Since digital communication tends to become increasingly essential for education, healthcare, and employment, such barriers may lead to structural disadvantages and social exclusion.

These concerns also have practical relevance in real-world disability service environments, where communication barriers may impact participation and employment. This motivated the present examination in

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this study about whether a quantitative framework may support decision-making in accessibility planning for people with disabilities. Accessibility often requires an approach through law, engineering, or disability studies. However, it may also be conceptualized as a problem for resource allocation with a possibility of optimization. Understanding how to allocate limited resources of accessibility in a way that maximizes inclusion is required particularly in a situation with declining federal and state funding. Accessibility initiatives, including those supported by the Digital Equity Act, have been affected by recent budgetary reductions (2, 3). At the same time, governmental capacity to maintain or expand accessibility services was reduced. Without sufficient public investment, marginalized communities, including people with disabilities, tend to suffer delayed access to essential digital and government services. Therefore, it has become an urgent policy concern to identify an optimized and cost-effective way to deliver accessibility. However, allocating resources for the accessibility based only on intuitive notions of efficiency or population size may oversimplify the ethical and also equity-based considerations in disability policy. This motivates the need for a quantitative framework that formalizes efficiency-driven decision-making, while allowing for examination of its limitations in real-world constraints.

LITERATURE REVIEW

Global frameworks underscore communication accessibility as a fundamental human right. According to the United Nations Convention on the Rights of Persons with Disabilities (UNCRPD), accessibility and inclusive communication are explicitly identified in Article 9, requiring removal of barriers across digital, physical, and institutional environments (4). In addition, a recent integrative review mapped communication access policy, guidance, and initiatives across the Republic of Ireland, Northern Ireland, the United Kingdom, Canada, Australia, and New Zealand, indicating how implementation varies across national environments and levels of institutional support (5). In spite of legal recognition, programmatic investments, professional training, and infrastructure are specifically important matters for the accessibility.

Empirical research in the areas of healthcare and social services indicate how communication barriers influence interaction, participation, and health outcomes among people with disabilities in communication (CDs). Qualitative research in the use of interviews and focus group also showed that communication strategies preferred by patients with CDs were often adopted by physicians, leading to poor clinical interactions and unmet informational needs (6). Therefore, the subsequent development of patient-oriented communication tools enhanced clinical communication through dialogue, while facilitating mutual understanding (6).

Research on digital inclusion further expanded this perspective by underscoring individual preferences, decision-making autonomy, and intra-disability heterogeneity. These studies argued that people with disabilities should be understood as digital actors, making selective choices regarding technologies, instead of passive recipients of accessible design (7, 8). This reframing connects with digital inclusion through agency, personalization, and participation, reinforcing the need for flexible intervention strategies rather than universal solutions.

Recent research in virtual healthcare suggests that communication accessibility is also context dependent. A qualitative descriptive study conducted with adults with intellectual and developmental disabilities (IDD) and primary care physicians reported that there was a distinct advantage from video consultation over phone interactions, including enhanced non-verbal engagement and decreased anxiety during clinical exchanges (9). Telehealth improved communication quality through participation from familiar environments for patients with barriers in traveling to clinics (9). These findings suggest how technology-oriented communication may both alleviate and exacerbate accessibility barriers depending on the context, user needs, and design. While these studies provide meaningful qualitative insights into communication accessibility across contexts, they provide limited guidance about how accessibility plans should be prioritized under constrained resources.

Literature Gap

Although prior research emphasizes the importance of communication accessibility and identifies qualitative barriers in healthcare, digital inclusion, and civic participation, the research remains mostly descriptive and policy-oriented. Most studies explain why accessibility matters and identify social and institutional challenges. However, only a few provide a quantitative framework for implementing accessibility in real-world conditions. Moreover, prior studies have not examined how purely efficiency-driven optimization under real-world constraints may lead to impractical allocation outcomes, nor how these outcomes may be mitigated through equity-based modeling considerations. Although prior studies have examined disability inclusion, accessibility barriers, and equity in service provision, relatively little work has been performed to exclusively examine optimization-based decision frameworks for allocating accessibility-related resources under budget constraints. Therefore, there is a key literature gap in developing quantitative model that translates qualitative insights into actionable decision-making tools. In order to fill this literature gap, this study particularly seeks to answer how communication accessibility resources may be optimally allocated under a fixed budget constraint to maximize communication inclusion for people with disabilities. This study hypothesized that a linear programming framework applying population-based inclusion weights and equity-related constraints will identify investment strategies on the accessibility that maximize communication inclusion while avoiding extreme concentration under a fixed budget.

METHODS AND MATERIALS

Study Design

This study employed a quantitative modeling approach through a linear programming to examine how the resources for communication accessibility may be allocated under budget constraints. Specifically, this study utilized both efficiency-driven and equity-aware allocation strategies, while recognizing that accessibility policy needs to balance the maximization of inclusion with fair considerations. Analyses were conducted by using publicly available, population-level data.

Data Source

Population-level estimates for disability categories were obtained from table S1810 in the U.S. Census Bureau's American Community Survey (ACS) that reported the prevalence of disability across various functional domains. With this dataset, nationally representative counts of individuals who reported hearing, vision, cognitive, and independent living difficulties were obtained. The ACS was specifically chosen for the data analysis in this study with its methodological rigor, large sample size, and frequent use in the areas of public health and policy research.

Construction of Inclusion Weight

In an attempt to quantify relative need of communication across disability domains, population-based inclusion weights were constructed. Designating each accessibility category as i, an inclusion weight was calculated as the proportion of the total disabled population in each category.

$$\frac{D_i}{\sum_{j=1}^{4} Dj} \qquad \text{Eq. (1)}$$

In Eq. (1), D_i denotes the ACS-based prevalence count for disability category I, and w_i is the normalized inclusion weight for that category. These weights show the relative contribution of each domain of disability to the modeled inclusion objective (Table 1). In this study, 'communication inclusion' was operationalized as a weighted accessibility score based on the disability prevalence across the four selected domains. This indicates how each unit of investment in a domain was assumed to contribute to inclusion proportionally based on the population-based weight in that domain. This was intended as a simplified policy measure without implying that the marginal inclusion benefit per individual was the same across domains. The resulting weights were normalized to make their sum reflect relative importance rather than absolute population size (Figure 1). With this normalization, comparison across categories was allowed.

Table 1. *Population-based inclusion weights by accessibility domain. Inclusion weights were derived from disability prevalence data in American Community Survey (ACS), showing the relative contribution of each accessibility domain to overall communication inclusion.*

Accessibility Domain	Inclusion Weight (ACS-based)
Hearing	0.771
Vision	0.148
Independent Living/ Navigation	0.071
Cognitive	0.010

Linear Programming Framework

A linear programming (LP) model was developed to formalize the allocation of accessibility resource as an optimization problem. The proportion of a fixed total budg*et al*located to each accessibility domain was represented by decision variables. The objective function was constructed to maximize the total communication inclusion as a weighted linear combination of decision variables by using the inclusion weights derived from ACS data.

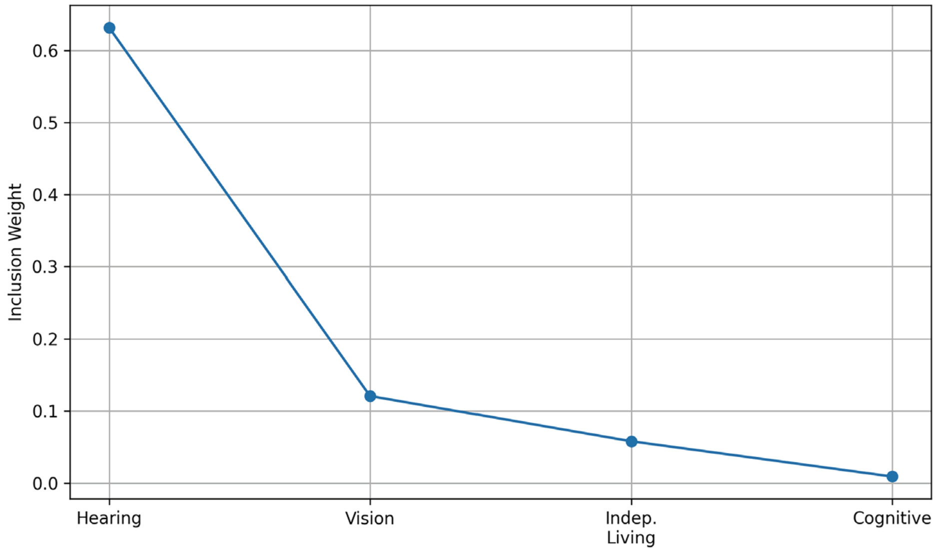

Figure 1. *Population-based inclusion weights across domains of accessibility. The relative contribution of each accessibility domain to total communication inclusion was illustrated by inclusion weights derived from American Community Survey disability prevalence data.*

$$\max Z = \sum_{i=1}^{4} w_i x_i \quad \text{Eq. (2)}$$

Subject to

$$\sum_{i=1}^{4} x_i = B \quad \text{Eq. (3)}$$

$$x_i \geq 0 \ for\ all\ i \quad \text{Eq. (4)}$$

Here, x_i denotes the proportion of the total budg*et al*located to accessibility domain *i*, w_i denotes the inclusion weight from Eq. (1), B is the total available budget, and Z is the modeled communication inclusion score.

The model was subject solely to a total budget constraint and non-negativity conditions under an initial efficiency-only formulation. With this baseline formulation, a purely efficiency-driven allocation strategy was shown how resources were directed to domains yielding the greatest marginal inclusion benefit per unit cost.

Equity-Constrained Model Extension

After recognizing that extreme or impractical allocations may be produced by efficiency-only optimization, the model was extended to apply equity-related constraints. These constraints were applied to reflect real-world policy considerations, such as minimum baseline support for all accessibility domains, limits on disproportionate investment in domains, and also consistency with population-based prioritization. Taken together, these constraints restricted the feasible solution space to allocations that balanced efficiency with equity and prevented any single domain from receiving the entire budget at the expense of others.

Solver and Implementation

Using a standard optimization solver (Simplex LP), the linear programming models were solved. For the purpose of interpretability, the total budget was normalized to one unit. This allowed results to be expressed as proportional allocations instead of monetary values. However, the structure of the optimization solution was not affected by normalization. This only enabled generalization across different funding levels.

Analytical Approach

Analyzing the model outputs by comparing optimal allocations under both the efficiency-only and equity-constrained formulations, the comparison was made, highlighting the tradeoff between maximizing inclusion efficiency and maintaining equitable distribution across accessibility domains. Results were then interpreted in the perspective of accessibility policy, highlighting how intuitive allocation tendencies were revealed, while exposing their limitations under ethical and practical constraints through mathematical optimization.

RESULTS

Baseline Efficiency-Driven Optimization

A purely efficiency-driven formulation was used to solve the initial linear programming model to establish a baseline allocation outcome. Let $x_h, x_v, x_c, x_i \geq 0$ denote the proportions of a total fixed budget that was allocated to hearing, vision, cognitive, and independent living accessibility, respectively. Using the ACS-based inclusion weights, the baseline objective function was defined as Eq. (5).

$$\text{Max}Z = 0.771x_h + 0.148x_v + 0.01x_c + 0.071x_i \quad \text{Eq. (5)}$$

Where the coefficients in the function showed the weights of population-based inclusion as derived from ACS disability prevalence data. The baseline model was subject to the total budget and non-negativity conditions as shown in Eq. (6) and (7):

$$x_h + x_v + x_c + x_i \leq B \quad \text{Eq. (6)}$$

$$x_h, x_v, x_c, x_i \geq 0 \quad \text{Eq. (7)}$$

The total budget was normalized with B=1, and under this formation, the optimal solution allocated the entire budget to hearing accessibility, yielding Eq. (8):

$$x_h = 1, x_v = x_c = x_i = 0 \quad \text{Eq. (8)}$$

This result indicated a corner solution as a well-known property of linear programming problems with a single resource constraint, along with positive objective coefficients. Since the largest inclusion weight was carried by the hearing accessibility, the objective function was maximized by allocating all resources to this domain. Even if this solution was mathematically optimal in terms of efficiency, it still represents an extreme allocation neglecting other accessibility domains entirely.

Equity-Constrained Optimization Results

The model was extended to apply equity-based constraints reflecting real-world accessibility policy considerations to address the impracticality of the baseline solution. For each domain, a minimum baseline allocation constraint was introduced as shown in Eq. (9):

$$x_i \geq M_i \ \textit{for all } i \in \{h, v, c, i\} \quad \text{Eq. (9)}$$

Where M_i indicates the minimum required proportion of budget to be allocated to each category of accessibility. In this study, m = 0.05, meaning that each domain was required to receive at least 5% of the total budget. With this constraint, it was ensured that all domains received a non-zero level of support as it was consistent with accessibility as a fundamental human right.

Then, a relative equity ratio constraint was introduced to limit disproportionate concentration of resources in the hearing domain compared to cognitive accessibility as shown in Eq. (10):

$$x_h \leq k \cdot x_c \quad \text{Eq. (10)}$$

Where k indicates the maximum ratio to be allocated between hearing and cognitive accessibility investments. In this study, k = 14 meaning that hearing accessibility may receive at most fourteen times the allocation assigned to cognitive accessibility. This constraint specifically shows a concern for how efficiency-driven prioritization alone may exacerbate disparities among disability groups with smaller population sizes. These parameter values were chosen as illustrative policy assumptions to demonstrate how the feasible solution space can be reshaped by equity constraints rather than as empirically established thresholds.

Then, consistency with population-based inclusion weights was maintained by including an ordering constraint as shown in Eq. (11):

$$x_h \geq x_v \geq x_i \geq x_c \quad \text{Eq. (11)}$$

With this condition, it was ensured that domains with greater affected populations received at least as much funding as those with smaller populations. At the same time, balanced allocation was still allowed across categories.

The full equity-constrained optimization problem was defined as follows in Eq. (12):

$$\text{Max}Z = 0.771x_h + 0.148x_v + 0.01x_c + 0.071x_i \quad \text{Eq. (12)}$$

Subject to Eq. (6)-(7), (9)-(11).

$$x_h + x_v + x_c + x_i \leq 1$$

$$x_i \geq M_i \ \textit{for all } i$$

$$x_h \leq k \cdot x_c$$

$$x_h \geq x_v \geq x_i \geq x_c \geq 0$$

Comparisons of Allocation Outcomes

With the equity-constrained formulation, the optimal solution shifted from the efficiency-based corner outcome to a balanced allocation across all domains of accessibility. In particular, the optimal allocation was $x_h = 0.70$, $x_v = 0.20$, $x_i = 0.05$, $x_c = 0.05$. Even if hearing accessibility still received the largest share of the budget, the presence of equity constraints required non-zero share of investments in vision, independent, and cognitive accessibility. Compared with the efficiency-based baseline model, the equity-constrained outcome decreased the total inclusion score from Z=0.771 to Z=0.5734, a reduction of 0.1976, which corresponds to a 25.6% reduction. This quantified tradeoff indicates how a moderate reduction in efficiency was needed to prevent complete exclusion of lower-weight accessibility domains.

According to the comparison between baseline and equity-constrained results, there was a key insight to show how efficiency-only optimization derived the mathematically maximal optimization but failed to apply the normative and practical requirements of policies for the accessibility. When applying equity constraints, optimization was still achieved. In addition, the feasible solution space was reshaped to identify outcomes to be both efficient and socially practical and acceptable (Figure 2).

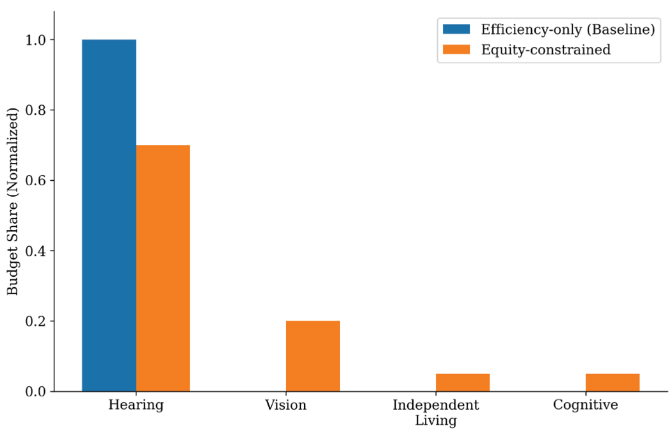

Figure 2. *Comparison of baseline and equity-constrained accessibility allocations. A corner solution is produced by the efficiency-only model, allocating all resources to hearing accessibility, while a balanced allocation is yielded across accessibility domains by equity constraints.*

DISCUSSION

This study provides an important insight into a quantitative framework for allocating resources to communication accessibility under budget constraints through linear programming. As shown in the baseline formulation, the inclusion was maximized only on population-weighted demand so that the model produced a corner solution with all the resources allocated only to hearing accessibility. However, even if this was mathematically optimal, this was incompatible with real-world accessibility goals.

Corner solution derived from efficiency-driven model was not a flaw of the model but rather an inherent property of linear programming under objective coefficients being strictly positive and limited to a single budget restriction. More importantly, this study provides a main policy concern as to how smaller disability groups may be exposed to a risk of systematic exclusion if investments are made on accessibility only by aggregate population size. Therefore, the efficiency-driven model proposed in this study as a baseline allocation served as a diagnostic tool to clarify why purely efficiency-based approaches are insufficient for planning accessibility with budg*et al*locations.

Seen in this perspective, equity-related constraints fundamentally altered the structure of optimization process, while producing a more balanced allocation across domains in accessibility. With minimum baseline constraints, all the disability groups were ensured to have received some level of support. Relative equity ratio constraints ended up limiting disproportionate concentration of resources. At the same time, consistency was maintained with population-based demand with ordering constraints. Putting all of them together, these constraints eliminated a possibility of extreme allocation as a corner solution but produced an outcome that better suited with social and policy expectations.

However, there are several limitations in this study that should be acknowledged. The model proposed in this study relied on population-level prevalence data, while assuming linear relationships between allocation investments and inclusion outcomes. This may have oversimplified real-world dynamics, including diminishing returns or interaction effects among domains of accessibility. Furthermore, the equity constraints introduced in this study may show only one specific formulation of fairness and should not be interpreted as definitive but illustrative. Since public disability-related spending is normally not reported by the functional disability domains but by program or agency, this study focuses on a normative optimization framework instead of direct comparison with government budg*et al*locations specific to domains.

Additional limitations should also be noted. First, the model used in this study did not apply cost heterogeneity across domains of accessibility, although real-world interventions such as visual supports, assistive technologies, and navigation-related accommodations may substantially vary in implementation cost. Second, the inclusion weights generated in this analysis were based on disability prevalence rather than empirically validated marginal inclusion benefits. Therefore, the model was built with assumptions that higher prevalence corresponded to greater potential inclusion gain. Third, there may be an overlap between disability categories in ACS reporting. This means that some individuals may be represented across more than one functional domain. As a result, the weights need to be interpreted as simplified policy-related estimates rather than precise measures of unique service demand.

With these limitations, the results in this study emphasize the value of quantitative optimization as a tool for decision-making process in planning accessibility. With formalization of both efficiency and equity considerations, the model proposed in this study provided a structured framework for exploring complex policy tradeoffs under limited resources. It is recommended for future study to extend findings in this study by applying nonlinear benefit functions, multi-objective optimization, or context-oriented cost data to examine investment strategies on accessibility in a more refined way.

CONCLUSION

This study provides an important insight about a quantitative framework for allocating resources to communication accessibility under budget constraints through a linear programming. The analysis in this study exhibits how efficiency-driven allocation only based on population demand leads to a corner solution as an extreme and impractical outcome as shown in the modeling of accessibility investment as an optimization process. This highlights the limitations of intuitive decision-making in accessibility policy. When equity-based constraints were introduced, the model produced more balanced allocations that better respected both efficiency and equity across disability groups. The proposed quantitative framework in this study demonstrates how mathematical optimization may serve as an adaptable decision-making support tool for planning accessibility, especially under limited public budget.

CONFLICT OF INTEREST

The author declares no conflicts of interest related to this work.

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