Discover Cities

Research

Physical isolation is durably affecting the relationship between social bonds and economic inequality

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Abstract
The relationship between social bonds and economic inequality has long been inseparable, and the integrity of social bonds networks facilitates access to economic opportunities. In urban development, physical space provides a place for the social connection process, and diversified physical forms also determine the diversity of the structure of the social network. Physical isolation is one of the most common physical structure in cities, mainly including gated communities and natural partitions. Cutting off the physical space objectively deprives social bonds and networks. Prolonged physical isolation disrupts the connection between social interaction and economic inequality. However, this relationship has been less explored. In this paper, we take Beijing, China, a megacity that contains almost all forms of physical isolation from the community and traffic, as an example. We focus on analyzing the development and change of rules of social bonds and economic inequality when urban space is divided by major physical isolation structures based on spatial and individual portrait data.

1 Introduction

Nowadays, economic inequality in cities is increasing, slowing urban development, economic growth, and technological progresss [1]. These disparities are deeply rooted in historical contexts, where education, technology, and public services have reinforced dynamic mechanisms that perpetuate and exacerbate economic inequalities across generations. Nevertheless, there remains limited understanding of the factors shaping resource acquisition and social connectivity, as well as how these underlying influences translate into income inequality.

Social bonds and relations give individuals essential access to economic opportunities [2, 3]. For example, a primary microscopic mechanism of social bonds is homogeneity. It's a tendency for similar groups to have more opportunities for cohesion and communication [4, 5], which exacerbates the strength of social bonds [6]. Individuals are more likely to form bonds with those accessible to them and communicate with those who can benefit them. However, groups of different socioeconomic statuses are separated from each other because of physical barriers [7]. These micro-level mechanisms may consolidate and exacerbate macro-level social isolation: If resources and information are transferred only in homogenous flow and communication bonds, it may lead to significant differences in economic potential between groups [8].

Geography is the objective carrier of social bonds and relations. Unlike barrier-free social networks built on virtual Internet platforms, the existence of geographic isolation or enclosed spaces may have an impact on actual social behaviour. Studies have shown that social bonds preferences are related to physical isolation in urban development. For example,

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social connection is less frequent across physical boundaries [9], people in high-end communities are not willing to cross the walls to socialize [10, 11], and open blocks and park areas will have more varied social networks [12]. Improving the region's mixed space and land use will enhance the integration of different social groups [13]. Overall, geographic isolation or enclosed spaces limit social accessibility, making it more difficult for individuals and groups with significant differences to interact with each other and reducing the cross-group flow speed of resources and information.

The relationship between social bonds and economic inequality can be examined from multiple perspectives. These include objective dimensions, such as spatial interaction opportunities and infrastructure agglomeration, as well as subjective dimensions, such as personality traits, psychological acceptance, and other related factors. The core gap of the existing studies is that it is hard to introduce suitable instrumental variables while determining the appropriate perspective. The intermediate mechanisms are challenging to define and quantify. An outstanding result is that Toth built a cross-town social network based on Hungarian online social network (OSN) data and used it as an explanation for spatial inequality and social inequality, proving that spatial fragmentation would divide virtual social networks [14]. Other studies also showed that residential segregation trends [15, 16] and low transport accessibility networks [17] contribute to widening economic inequality gaps. Furthermore, while urban centres provide job information resources, accessibility to such information is unevenly distributed among the urban population [18], and low-income people who live far from the city center do not have the opportunity to join geographic and social clusters [19]. In these studies, the definition and measurement of social interaction behavior are still imprecise. Existing studies also fail to integrate physical isolation, real social bonds, and income inequality into a complete analytical framework.

Urban space is a complex"human-land"ecosystem with complex succession [20]. People's social psychological state in space will eventually externalise into the result of social behaviour. In social sciences and physical geography, it has been theorised that the relationship between inequalities and social bonds in cities is mediated by physical space. Spontaneous isolation areas in space (such as urban villages or slums), administrative isolation areas formed by policies (such as gated communities and regional boundaries), and significant boundaries formed naturally (such as mountains and rivers) are all silent impellers, which influence the differentiated supply of regional infrastructure, formation of formal and informal access rules, and changes in the speed of population movement [21]. Therefore, geographical isolation theoretically shapes the social-ecological performance of the whole region through people's migration, communication, and inclusion behavior [22, 23].

In this study, we try to build a relationship of"physical isolation, social bonds, and economic inequality."We try to prove that the Isolation of Physical Barriers (IPB) acts as an exogenous variable that continues to interfere with the interaction between social bonds and economic inequality. We chose a research perspective based on objective spatial contact opportunities rather than a perspective based on individual psychological contact willingness. Such a design has two advantages: On the one hand, physical isolation can be introduced into the model as an authoritative exogenous variable to deal with two-way causal problems [24]. On the other hand, it can reveal the relationship between the tangible barriers of spatial solidification and the intangible barriers of social variability [25], which is an interesting and meaningful research direction. The study focuses on how changes in objective space will affect the interaction of social bonds and economic inequality. The three main concepts involved are defined as: (1) Physical Isolation: a physical barrier is an isolated patch enclosed by walls and road boundaries that lacks interaction with the surrounding area, such as a gated community. Physical isolation has a broader geographical scope and refers to the overall assessment of the degree of isolation formed by multiple barriers in a particular area [26, 27]. (2) Social bonds: In the case of space entity as the carrier, people's objective contact opportunity is an external communication ability endowed by physical space and the basic activity conditions of the human body, which does not involve initiative and willingness [28–30]. (3) Economic inequality: economic or income inequality refers to the economic gap between groups divided by income level within a specific geographical range in a long-standing state [31, 32].

This study aims to address the following question: How does a physical barrier generate intangible social effects? We posit that the formation of social bonds is closely tied to the actual connections established between two or more individuals with inherent needs for social interaction [33, 34]. At the same time, fragmented social bonds can solidify and exacerbate economic inequality. Physical isolation is a long-term disturbing variable involved in the relationship between social bonds and economic inequality. In this study, a single unit contains multiple closed or gated barriers. Therefore, units have different physical isolation characteristics that do not change over time. Consequently, we identified 518,354 social bonds data in 5,285 grids; the data included information for social communication in the study area from 2018 to 2021, recording the starting point location, destination location, and the number of social bonds that occurred in the year. We comprehensively consider the characteristics of social bond inside and outside the physical barrier, aiming to reflect the intensity in the whole region and facilitate comparison with other research units. This analysis is based on OD

(Origin and Destination) and POI (Point of Interest) data from 2018 to 2021 within the 6-ring areas of Beijing. Social bond is represented by the WDC index (weighted degree centrality). This index reveals the relative importance of nodes in the network, with high values indicating a high frequency of population movement and bond in the nodes. We assume that the topology of enclosed or isolated spaces in the city does not change significantly during the study period of 4 years (short term) and calculate the physical isolation degree brought by micro-enclosed spaces. We adopt the 2SLS model to verify the relationship between physical isolation, social intensity, and economic inequality.

2 Study area and data

We focus on the area within the Sixth Ring Road of Beijing City (See Fig. 1), where most social communication and commuting activities occur. The urban area of Beijing is radially structured by seven concentric ring roads extending from the city center to its outskirts. The spatial functions vary significantly across different ring areas. The 1 st and 2nd rings constitute the"central government function area,"primarily dedicated to government operations, cultural activities, and financial services. The 3rd and 4 th rings form the"residential and work comprehensive functional area,"characterized by a high concentration of commercial, residential, and service facilities, as well as a significant number of high-quality employment opportunities. The 5 th and 6 th rings represent an"emerging development area,"playing a pivotal role in alleviating urban traffic congestion and driving regional growth, with numerous newly developed residential zones

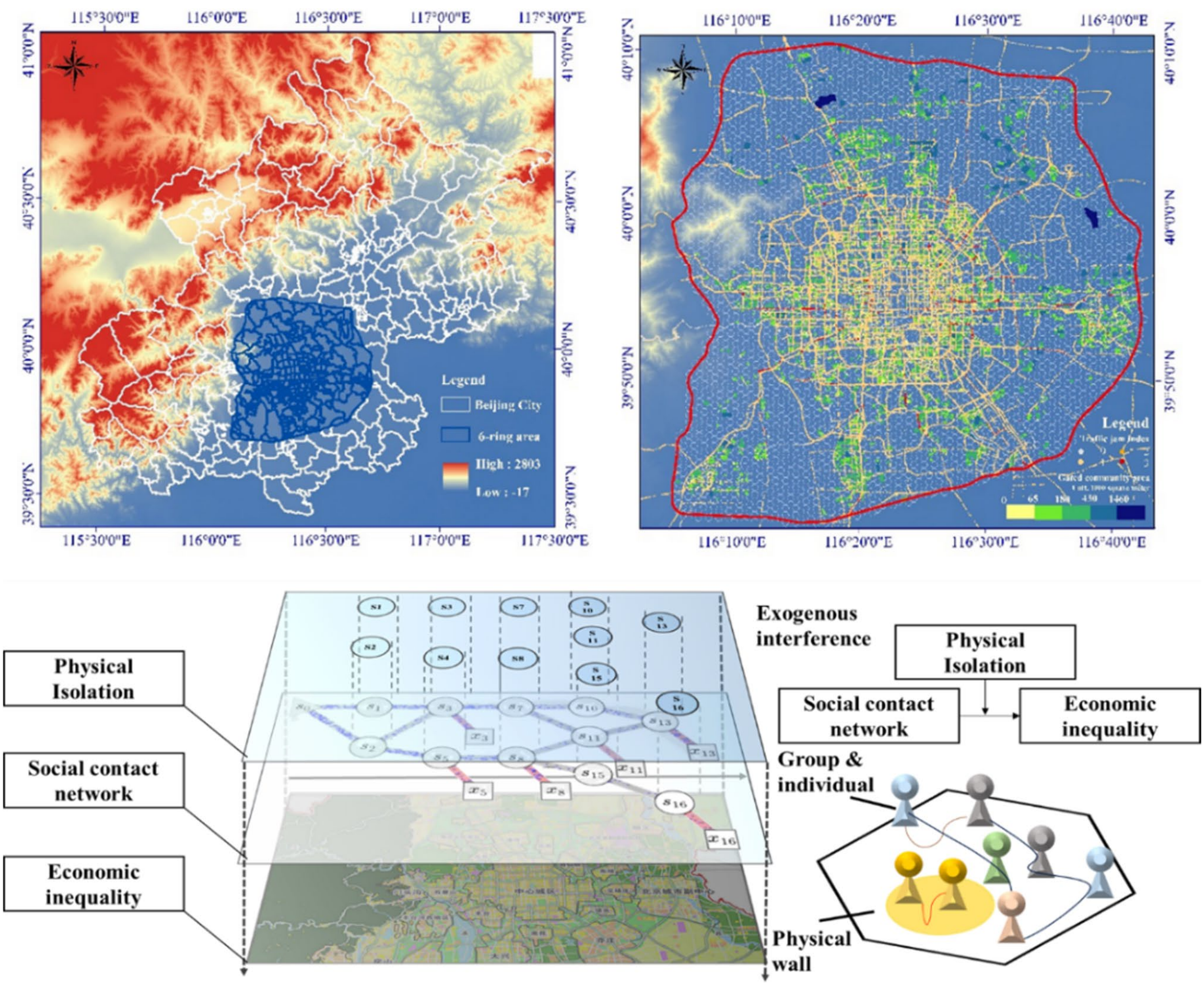

Fig. 1 Study areas within 6-ring road area and study framework

and industrial parks. The area within the 6 th ring road encompasses the majority of the city's population activities and includes 71% of the city's gated barrier units, making it highly representative for analysis. The research unit is a regular hexagonal cellular grid, each covering an area of 0.75 square kilometers. The distance from the center of one grid to the edge of an adjacent grid is uniform, with a radius of approximately 537 m. This characteristic uniformity ensures that each unit shares equivalent communication accessibility with its surrounding areas. The pedestrian distance of a standard urban block typically ranges from 500 to 1500 m [35]. Consequently, the boundary of each grid unit can be considered a significant demarcation line, influencing the choice between pedestrian travel and vehicular movement.

We quantified the isolation of the physical barrier (IPB index) from two levels, community and traffic, based on community profile and traffic congestion data. The former is the space isolated by large cluster units (such as communities, universities, closed institutions, etc.), and the latter refers to the isolation caused by the inaccessibility of actual vehicles. We calculated the weighted degree centrality (WDC) using the Origin and Destination database (OD database), which records the geographical coordinates, as well as the number of individuals within social connections. OD database is collected through mobile signaling data, and it describes the social network by recording the number of bonds between two locations and their actual movement tracks. We define economic inequality based on an individual portrait database from Baidu Location-based Service Data (LBS), individual features such as age, gender, educational level, income and consumption level, working population, and residential population in Beijing are all referenced by this database. Each feature is a percentage collected from large-scale social surveys, real-time location data, and personal information provided during app registration. Meanwhile, the LBS database also includes the total population number. Therefore, it's logically straightforward to determine the value of the population of a particular social group (such as people aged 18–35) in a specific place and time (See Fig. 1).

3 Methods

3.1 Quantification of economic inequality, social bond centrality, and physical isolation

3.1.1 Economic inequality (Gini coefficient)

Income is an essential indicator for distinguishing different groups. This study uses the Gini coefficient, a widely recognised economic tool, to assess income inequality in urban areas of Beijing from 2018 to 2021. By analyzing population portrait data derived from mobile phone signals, we focus on the Gini coefficient to gauge socioeconomic disparities within each six-ring grid, which ranges from 0 to 1 and denotes perfect equality when it is 0 and absolute inequality when it is 1. The Gini coefficient calculation is based on the portrait feature of monthly income, which reveals the average distribution of different income groups in a specific place. Therefore, it can comprehensively evaluate the level of regional income gap according to the grouping algorithm. Because the precise income data of individuals cannot be reflected in big data, income can only be divided into grouped fuzzy five segments. Specifically, monthly income levels are classified into five groups based on their median values: (1) 2,499 RMB and below, (2) 2,500–3,999 RMB, (3) 4,000–7,999 RMB, (4) 8,000–19,999 RMB, (5) 20,000 RMB and above. The median value of each group is taken to represent the income status of individuals in each group (the values are 1250, 3250, 6000, 14,000, and 25,000).

Income groups exhibit heterogeneity, with distributions that are not neatly divided into equal segments. To address this, we consider the Gini coefficient calculation formula for non-equal grouping proposed by Thomas, Wang, and Fan [36, 37]:

$$G_i = \mu^{-1} \sum_{i=2}^{N} \sum_{j=1}^{i-1} P_i \left| y_i - y_j \right| P_j \tag{1}$$

where G_i is the Gini coefficient, μ is the expected value of the total income of each group, N is the number of observations, and y_i is the income of each group i. P_i represents the proportion of the population in group i to the total population.

Since the Gini coefficient is the ratio of unequal area to completely unequal area in the Lorentz curve, the following formula for calculating the Gini coefficient can be derived:

$$G_i = 1 - \frac{1}{PW}\sum_{n=1}^{5}\left(W_{n-1} + W_n\right) \times P_n \tag{2}$$

where P is the total population in the grid area, W is the total income in the grid area, W_n is the total income accumulated to the group n (n = 1,2,3,4,5), and P_n is the total number of people in the group.

3.1.2 Social bond centrality (Weighted degree centrality, WDC)

We quantify the social network structure of each grid by the centrality index. Centrality measures are widely applied in identifying critical nodes, such as infrastructures of urban networks, and in quantitatively evaluating node importance [38]. In the social communication network (SCN), the central social nodes serve as the hubs for daily communication and activities and contribute to the overall structure of the social network [39]. The diversity of centrality measures in complex networks results from different definitions of the importance of social behavior [40]. The weighted degree centrality (WDC) combines connectivity and edge weights among many measures. For this study, WDC is the most suitable for the complete description of social bond and accessibility structures with weighted edges.

Considering the characteristics of the spatial interactive network formed by variable and directional among spatial units, we utilize the WDC approach to quantify the importance of nodes within the six-ring area [41]. In this study, each grid is considered an integrated social node, and the outflow and inflow are used as a basis to calculate the relevant edge weights between different bond nodes. The WDC of any node is defined as the sum of the weight of its associated edges. It is the multiplication of the weight of travel time and the number of people (see Eq. (3) and (4)). In addition, the travel time (t_{ji}) in the weight index (W_{ji}) is derived from the Amap API shared open platform. We obtain the road travel time (including bicycle, public transportation, and car travel) from the origin point to the destination point, and we set the boundary time as 3 h according to the maximum actual travel time within the 6-ring area.

Furthermore, the study hopes to represent the actual state of individual travel rather than the ideal state without constraints and consider the actual travel time resulting from capability and coupling constraints [42]. Therefore, the study analyzes all travels related to the OD needs of individuals within the 6-ring area during the observation period, and these activities really happened. In fact, with the open platform of Amap API, the research can comprehensively consider the travel time situation that is infinitely closer to reality: based on the objective distance, road congestion interference, traffic restriction conditions, weather conditions, etc., the open platform will calculate the actual time spent according to the average actual traffic data. Besides, considering the considerable amount of individual OD data, the research considers the grid region as the anchor point. It summarizes various OD and transit time data into grid data based on the coordinates of the starting and destination, respectively. When the research unit grid is regarded as the destination, the actual inflow quantity and different time-weighted index values of different starting points are calculated, when the research unit grid is viewed as the starting point, the actual outflow quantity and different time-weighted index values of varying ending points are calculated. Finally, the total centrality of the region is represented by the sum of the outbound degree and the inbound degree. The higher the WDC value of the grid node, the more critical position the node occupies in the actual travel of the whole city. The final WDC formula is as follows:

$$WDC_i = WID_i + WOD_i \tag{3}$$

$$WID_i = \sum_j W_{ji}A_{ij},\ WOD_i = \sum_j W_{ji}B_{ij} \tag{4}$$

$$W_{ji} = \frac{e^{-\frac{1}{2}\times\left(\frac{t_{ji}}{t_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}\left(t_0 = 3h\right) \tag{5}$$

where WID_i and WOD_i represent the weighted input degree and weighted output degree of grid i. W_{ji} represents the reachability weight between grid i and grid j. A_{ij} and B_{ij} represent the total social bond demands when grid i serves as the destination and grid j serves as the origin respectively, expressed by the total number of people who move and bond. A higher WDC indicates that grids have higher social bond intensity.

3.1.3 Physical isolation (Isolation of physical barriers, IPB)

We measured the degree of physical isolation on a grid scale. It should be emphasized that each research unit (0.75 km2 hexagonal grid) contains multiple isolation barriers (such as gated communities, universities, and closed parks), and different research units have different isolation levels. The indicators we use to measure urban physical isolation include 3 dimensions:

The average distance from the city center to the grid center (Distance from the center, DC). This index measures the objective Euclidean distance between the geometric center point of each research unit (regular hexagonal grid) and the city center (Tiananmen Square). Typically, the geographical center is considered the central social hub of most cities. The distance from the city center plays an important role in communication patterns. Individuals and groups residing at greater distances from the city centre face increased barriers to communication, as they have fewer opportunities to form social connections. Conversely, as the spatial distance between communication nodes widens, the likelihood of establishing a robust, long-term relationship between communities diminishes.

The number of amenities in the study unit (Number of amenities, NA). This indicator evaluates the amount of amenities within the research unit (grid), which can also be regarded as amenities density since each unit has the same area. Amenities and surrounding areas are significant focal points for population bond and activity. The spatial concentration of amenities indicates the areas where the affluent and the poor congregate within a city. Research has demonstrated that clustering amenities in specific locations can lead to the exclusion of low-income residents from many social interactions. Point of Interest data (POI), which includes restaurants, bars, small medical facilities, and movie theaters, can be utilized to assess these phenomena. To harmonize these contrasting dynamics, we use the number of amenities within the area to characterize this impact.

Isolation of the physical barrier/Physical Isolation, IPB. This index calculates the ratio of a single area enclosed by barriers to the area of the grid in which it is located and summarizes the squares of multiple values by grid. The impact of physical barriers is an exogenous factor that promotes the objective isolation of space. Initially, we focus on the large, gated communities within the grid unit (See Fig. 2). The closure of these communities is primarily manifested through segregating their coverage areas from the external environment, creating objectively inaccessible zones. The internal roads, facilities, and services within these communities are not accessible to the public, thereby insulating internal groups from negative externalities. We construct a comprehensive community isolation index (IPB_c, see Eq. 7) based on the enclosed areas of these communities. Subsequently, we examine transregional traffic isolation caused by railway tracks, urban roads, mountains, and rivers, using the noninteroperable areas as the basis for measuring traffic isolation (IPB_t, see Eq. 7). We hypothesise that spatial isolation caused by community closures and road barriers is unlikely to change in the short term, which allows IPB to be considered exogenous. The two-level IPB factors are used as instrumental variables

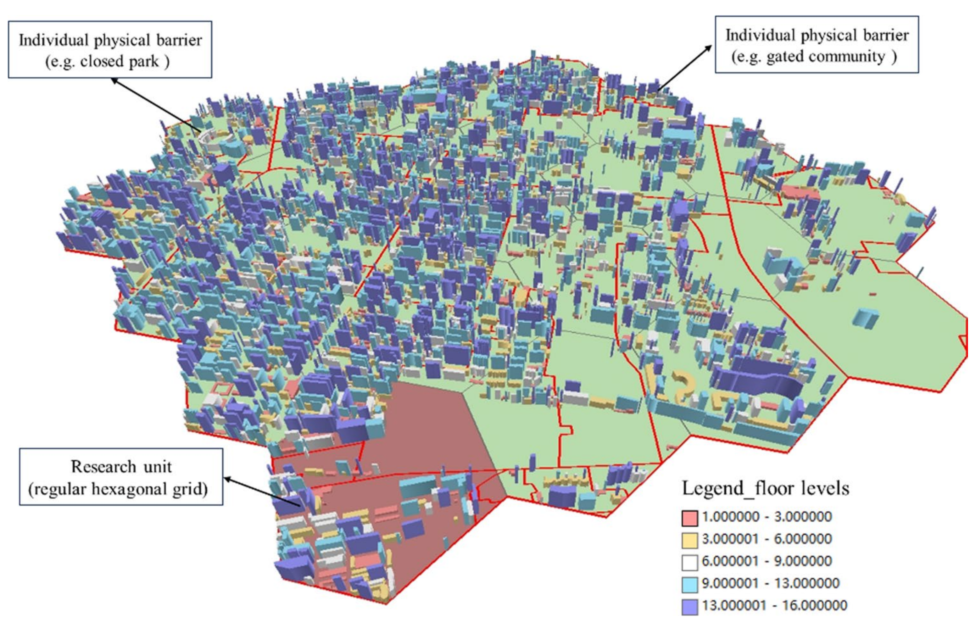

Fig. 2 The relationship between individual physical barriers and research unit (Partial study area)

to assess the impact of social bond on income inequality. We utilise the synthesis of closure degrees (C_i) to characterize the objective space isolation:

$$C_i = \alpha_i RIPB_{iC} + \beta_i RIPB_{it} \quad (6)$$

$$IPB_i = \sum_n \left(\frac{S_{ai}}{S_0}\right)^2 = \sum_n \left(\frac{Area_{iso\_i}}{Area_{all\_i}}\right)^2 \quad (7)$$

where, C_i represents the physical isolation within a single grid i, $Area_{isolation}$ represents the total area of the enclosed area within the grid, and $Area_{all}$ represents the total area of a single research unit i (S_0=0.75km^2).

The transportation network extends over a broader area, resulting in a significant disparity between spatial isolation and community isolation. This discrepancy can easily lead to inaccuracies when estimating the overall isolation degree. To address this issue, we employ a min–max normalization method [32] to calculate the relative RIPB (RI), which facilitates meaningful horizontal comparisons of relative importance between the two distinct degrees of IPB. RIPB is calculated as follows:

$$RIPB_{ij} = \frac{IPB_{ij} - \min\left(IPB_j\right)}{\max\left(IPB_j\right) - \min\left(IPB_j\right)} \quad (8)$$

where, $RIPB_{ij}$ represents the relative importance of grid node i in isolation type j. min(IPB_j) and max(IPB_j) represent the minimum and maximum values of isolation in isolation type j, respectively. The larger the RI, the higher the degree of isolation of the grid nodes. For the isolation degree brought about by community and traffic, see Eq. (8).

3.2 Model construction

3.2.1 2SLS construction

To test the hypothesis that the isolation of physical barrier (IPB) acts as an exogenous variable that continues to interfere with the interaction between social bond (WDC) and economic inequality (Gini), we employ a two-step least squares regression model. We posit that the spatial isolation induced by gated communities and traffic patterns (IPB) remains stable over a short time. Consequently, we incorporate objective measures of geographical distance (DC) and the count of large-scale amenities (NA) as instrumental variables in our study. Although we cannot definitively assert that our estimates reflect causal effects, the methodology of 2SLS significantly reduces the risk of omitted variable bias.

In the first step of the 2SLS model, we estimate the differences in social-weighted degree centrality using the following equation:

$$AC_i = \delta + \gamma IV_i + \delta N_i + e_i \quad (9)$$

In the second step of the 2SLS model, we evaluate the potential impact of WDC on economic inequality, as predicted based on the degree of physical isolation:

$$G_i = \alpha + \beta_1 \widehat{AC}_i + \beta_2 X_i + \varphi_k + e_i \quad (10)$$

where, IV_i is the abbreviation of instrumental variables, which include IPB, DC and NA. δ and α are constant terms, N_i is a collection of control variables such as the population of the region, e_i is the error term, which is assumed to be normal distribution. The second step of the 2SLS estimation follows Eq. 10, $\widehat{AC}_i$ is WDC prediction estimated from Eq. 9, φ_k is the regional fixed effect, and e_i is the error term.

3.2.2 Control variables

This paper's basic unit of control variable data is the same as the core variables Gini coefficient, WDC, and IPB: a regular hexagonal grid. There are 5285 values per year for each type of variable. The characteristics and behaviors of individuals and groups are collected according to their location.

The number of active residents (home_pop) and the number of active workers (work_pop). The active population count is a crucial indicator of a region's vitality. Therefore, this variable is the average number of individuals engaged in living or working activities within a grid cell per hour. We assessed the average hourly active population between 12:00 and 18:00 during the middle of each month from mobile phone signaling data, and the active population is further divided into living and working categories by activity patterns. Furthermore, if the proportion of active workers exceeds that of residents, the grid area is identified as the working area, and vice versa. In contrast to residential areas, work areas tend to be more expansive and accommodating, offering enhanced opportunities for interaction among diverse groups. This flexibility is attributed to the ability of various work levels to coexist within the same space, unlike housing levels, which are typically confined to smaller grid units.

The proportion of the male population (male). The proportion of the male population in each research grid expresses this variable. The difference between genders is an essential factor affecting the characteristics of social networks and social bond. Research indicates stronger social bonds are more readily formed among individuals of the same gender. People are inclined to support their offspring or exchange social and economic resources with those of the same gender. In contrast, the formation of transgender social networks often takes a longer time. Therefore, our study incorporates the proportion of men to investigate whether there are differentiated effects on social bond and economic inequality under varying gender dominance conditions.

The proportion of car owners (car). This variable is expressed as the proportion of the population that owns one or more vehicles in the study unit. In the trajectory of urban development, automobiles embody dual-layered significance. Primarily, they function as a high-efficiency transport tool, symbolising an enhancement in the owner's commuting capabilities and their capacity for actual cross-regional interaction and social engagement. They transcend the limitations of the pedestrian

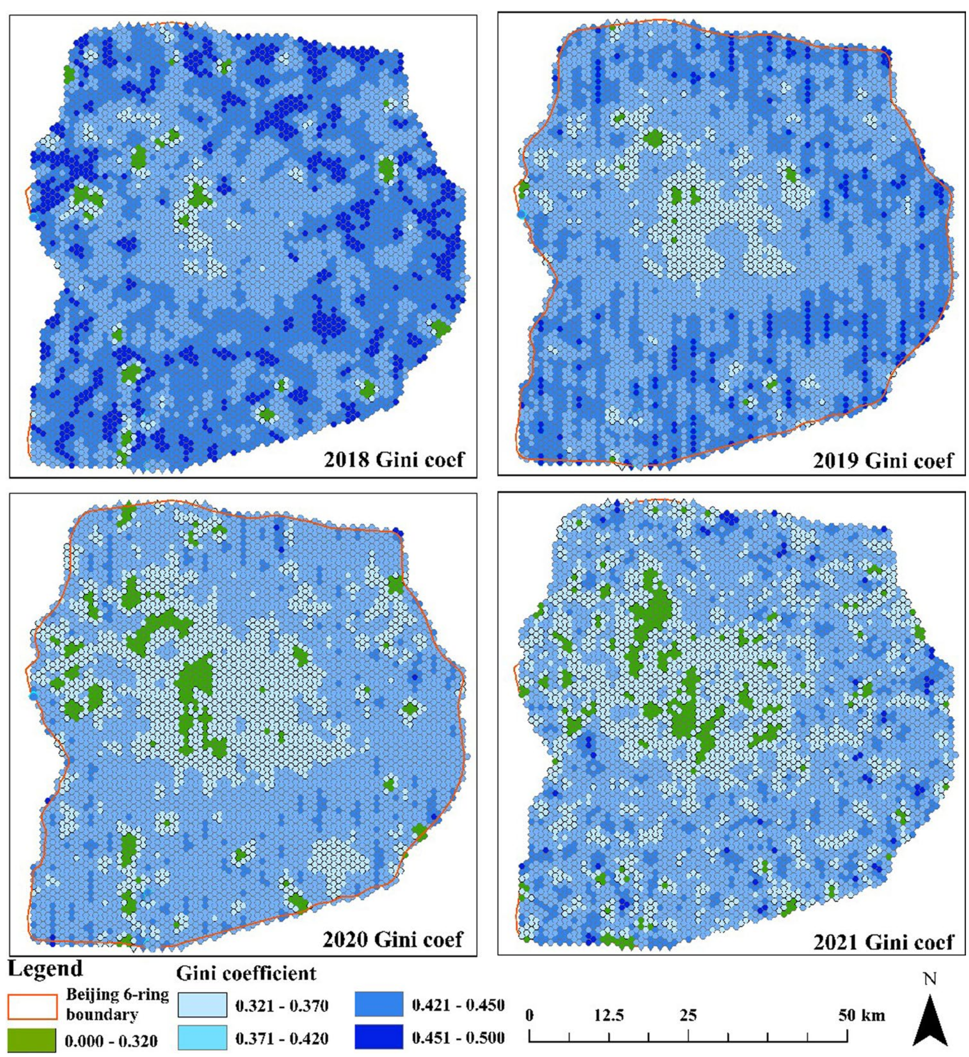

Fig. 3 Distribution of Gini coefficient in the sixth ring road of Beijing

and cyclist domains, increase the speed of resource exchange, and amplify the reach of social and communicative networks. Concurrently, automobiles also serve as emblems of personal wealth. In urban settings where public transit is more advanced, automobile possession signifies a certain level of financial accumulation and social standing because it is relatively not on the top list of low-income consumers. The prevalence of car ownership mirrors the regional social hierarchy and the disparities in income distribution.

The proportion of the prime-age population (age 25–45). This variable is expressed as the proportion of the population aged between 25 and 45 years in the study grids. As the mainstay of social production and activities, the prime-age group exhibits a strong desire for self-improvement and elevation of their socio-economic status. As a result, the prime-age exhibits a notably higher frequency in social interactions and activities of resource exchange compared to other age groups. At the same time, prime-age individuals demonstrate greater acceptance, tolerance, and empathy towards diverse groups. Therefore, a higher concentration of prime-age population may result in a higher level of WDC and a stronger concordance among regional social groups. This trend may contribute to a reduction in economic inequality.

Space lockdown of grid areas during the pandemic (COVID-19). This variable is expressed as a dummy variable, with regions that have experienced a lockdown in 2020–2021 labelled 1, otherwise labelled 0. Throughout the research period, certain zones within Beijing underwent the imposition of COVID-19 lockdowns, which engendered widespread seclusion and curtailed interpersonal interactions. Therefore, this parameter is incorporated into our analysis as a controlled critical variable. We meticulously examined all relevant data on space lockdown, ranging from news bulletins to official directives and public sentiments, regarding community and neighbourhood restrictions in Beijing from December 2019 through January 2022. We categorise grids that have lockdown histories as the experimental cohort, whereas those without such records were classified as the control cohort. In instances where a grid encountered recurrent lockdowns within the span of a year, we adjusted the weighting of the grid proportionally based on the frequency of these lockdown events.

Other control variables. We also control variables that have an impact on the long-term formation of geographical characteristics (not shown in the regression results), such as the industrial structure, the administrative division of each grid, the GDP, the year of construction of houses and roads within the region, and the main goals of regional development. We try to exclude different units'historical social, economic, and cultural inertia and more intuitively separate the physical isolation variables.

4 Results

4.1 Regional Gini coefficient results

According to Eq. (1), we use fuzzy income interval classification to first estimate the level and change in income inequality in 5,285 grids within the 6 ring districts of Beijing from 2018 to 2021. We divide the results into 5 categories by the natural classification method. The results show that the overall Gini coefficient varies from 0.32 to 0.45, and the four-year average is about 0.38. In 2018, the Gini coefficient had the highest average value of 0.43, indicating that socioeconomic inequality was most pronounced in that year. The spatial distribution of regional population Gini coefficients is highly heterogeneous, with low-Gini regions displaying pronounced spatial aggregation and polycentric patterns (see Fig. 3). Multiple spatial clusters are identified, differing in both scale and extent. Geographically, the core low-Gini areas are predominantly concentrated in the city center and northwest regions, which serve as hubs for finance, new energy, and high-tech industrial parks in Beijing, forming a large contiguous cluster. Additional subcenters are located in satellite districts, such as Daxing and Tongzhou (southwest and southeast of the city center). In contrast, high-Gini regions are primarily distributed along the periphery of the sixth ring road and are predominantly adjacent to low-Gini areas.

According to temporal progression, the area characterized by a high Gini coefficient (0.450–0.500) showed a consistent annual decline from 2018 to 2020. Specifically, it contracted by 491 grid units from 2018 to 2019, marking a 71.68% reduction, and further decreased by 179 grid units from 2019 to 2020, representing a 92.26% decline. In contrast, the area with a low Gini coefficient (0.000–0.320) expanded steadily from 2018 to 2021. This expansion included a 62.88% decrease from 2018 to 2019, followed by a dramatic 644% surge from 2019 to 2020 and a moderate 10.07% rise from 2020 to 2021. Post-2020 pandemic control measures significantly widened the spatial extent of low Gini coefficients, reflecting a notable reduction in income inequality, potentially linked to migration trends and reduced cross-regional interactions among diverse populations. Meanwhile, the area with a medium Gini coefficient (0.320–0.420) experienced steady growth from 2018 to 2020, increasing by 47.10% from 2018 to 2019 and by 38.68% from 2019 to 2020, before a slight contraction of 45.88% from 2020 to 2021. Throughout this period, the overall spatial distribution patterns of the Gini coefficient remained relatively stable, with the coverage areas of medium and low Gini coefficients gradually expanding around multiple low-value centers (see Fig. 3).

4.2 Weighted degree centrality (WDC) results

To capture the actual social structure within the study areas, we use the actual communication and offline bond data between different regions to build a network and represent it by the weighted degree centrality (WDC) index reflecting social bond (See Fig. 4).

(1) Between 2018 and 2021,weighted degree centrality demonstrated a clear spatial agglomeration pattern, radiating outward from the urban core to the periphery, with weighted degree centrality (WDC) levels progressively declining toward the edges. Outside the main urban hubs, urban social networks also exhibited multi-centric development, predominantly concentrated in Daxing and the newly established northern satellite cities, reflecting a distribution pattern similar to that of the Gini coefficient.

(2) From 2018 to 2021, the weighted degree centrality (WDC) indicators showed a gradual annual decline. The average social centrality index was 50,727.97 in 2018, surged to 500,042.28 in 2019, dropped to 45,549.82 in 2020, and further decreased to 45,229.11 in 2021. Overall, the changes were relatively modest, with percentage changes of 1.35%, 8.98%, and 0.71%, respectively. Notably, external control policies, particularly those related to the pandemic, contributed to the most pronounced decline in social centrality WDC between 2019 and 2020.Compared with the results of WDC in 4.1, it can be inferred that there are some common rules between the Gini coefficient and social bond. For example, the average Gini coefficient decreased yearly in 2018–2019. Regions with high Gini coefficient

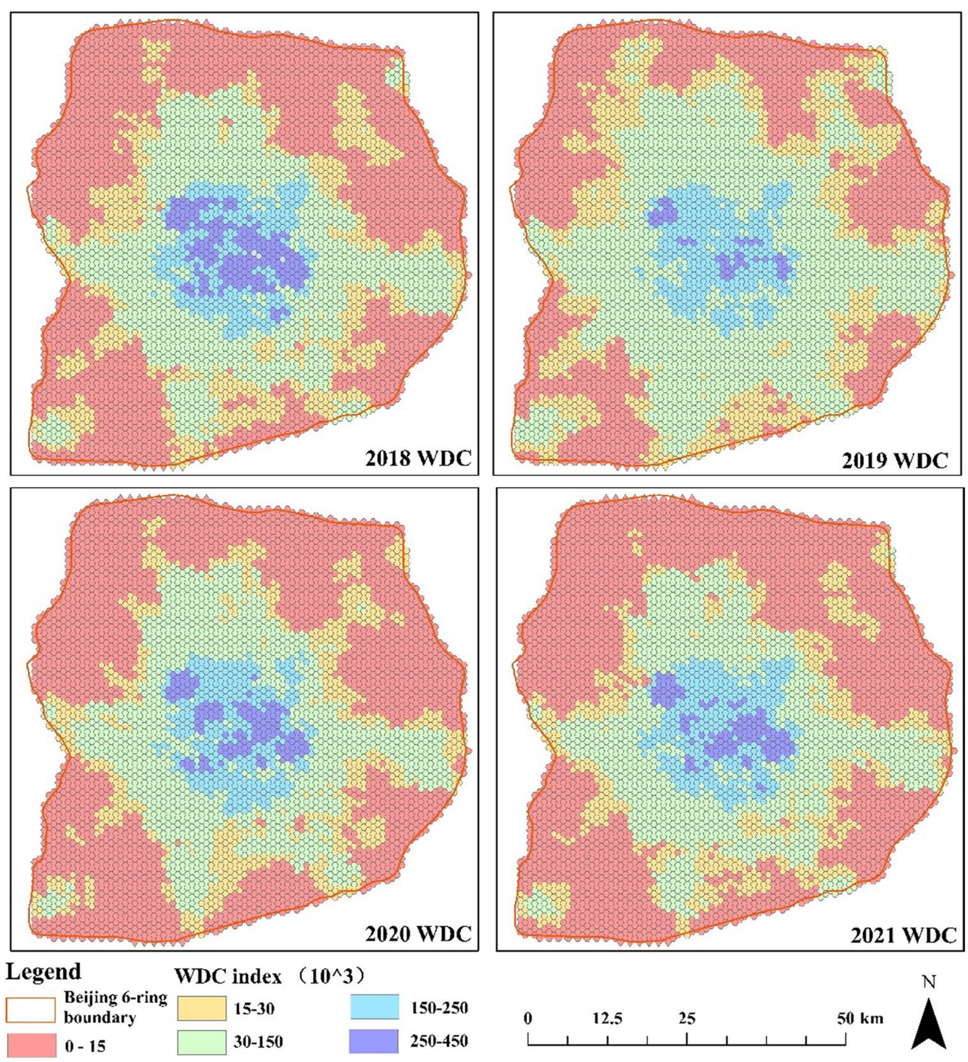

Fig. 4 Distribution of WDC in the sixth ring road of Beijing from 2018 to 2021

values gradually disappeared, while regions with low and medium social interaction intensity gradually expanded their coverage. However, correlation cannot be obtained only through regular observation. Further measurement with the causal analysis model is necessary.

(3) Since 2020, the spatial distribution of social networks has exhibited a clear tendency towards contraction. Specifically, between 2019 and 2020, the geographical span of WDC indicators at or above the 15,000 level has, on average, reduced by 23.4%. Since 2018, the coverage area of 30,000–150,000 weighted degree centrality has been decreasing, with annual decreases of 34.7%, 4.3%, and 4.56%, respectively. These regions were replaced by regions with 15,000–30,000 levels, indicating that the trend of social bond degradation was more likely to exist in areas with low and medium social intensity. In contrast, the area of regions with WDC above 150,000 showed little change, and these grids were steadily distributed in the single center of the city, which was consistent with our hypothesis. This observation implies that social circles or networks of moderate to high bond intensity may possess a more resilient and stable framework.

4.3 Physical isolation results

According to Eq. (6) and Eq. (7), we calculate the objective physical isolation degree of space on the sixth ring road caused by two main factors:IPB_c and IPB_t. The average isolation degree of the gated community is 0.20 (standardized average value is 0.27), the average traffic isolation degree is 2.73 (standardized average value is 0.43), the total isolation result is 0.32, and the weight of α and β of Eq. (6) are 2.5 and 0.5. The distribution of these results is depicted in the accompanying Fig. 5, where IPB_c and IPB_t are standardized results, and the overall isolation is calculated based on two standardised indicators. In the community isolation index, areas with high isolation are concentrated at the edge of the sixth ring, which means that large enclosed communities are concentrated in these grid units. Due to the large partition area of the physical barrier of the building group, it is difficult to communicate inside and outside, and the opportunities for fair sharing and bonds between the space outside and inside the wall are reduced. At the same time, the areas with high traffic closure are also concentrated in the outer ring (4–6 ring areas), while the area within the fourth ring has a low closure, which means that in actual traffic exercise, people have fewer opportunities to reach the areas outside the fourth ring with insufficient road network density in the fourth ring (See Fig. 5).

4.4 OLS and 2SLS model results

4.4.1 OLS Model

We use cross-sectional data to investigate the yearly impact of physical isolation on weighted degree centrality (WDC). The results of the basic regression of OLS show that at the 0.1 level, the three isolation models generally exhibit significant effects on WDC. Specifically, in the 2018–2019 models, increases in community, traffic, and total isolation correlate

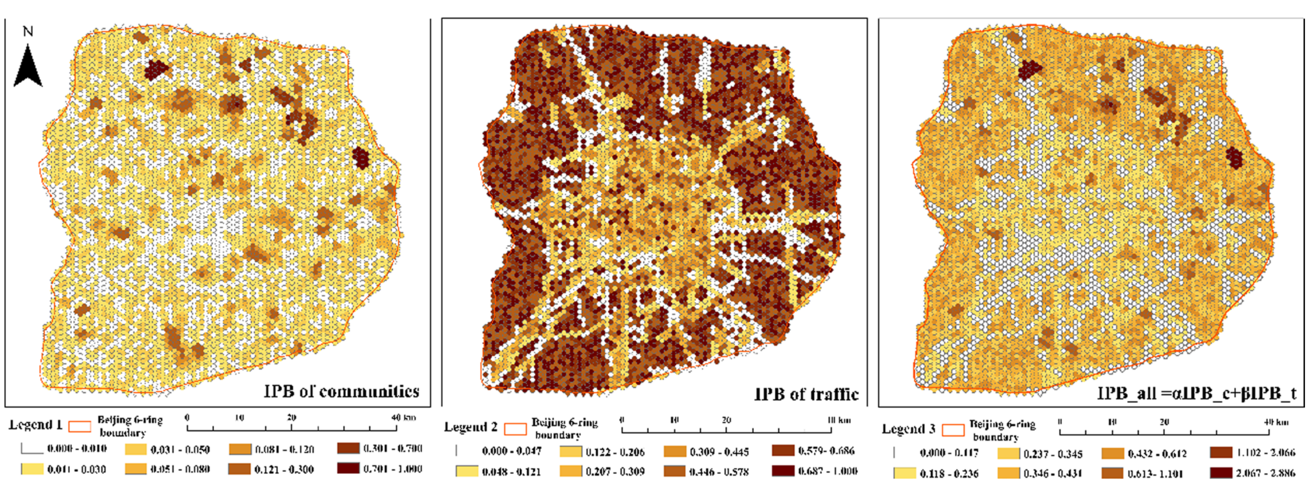

Fig. 5 Geospatial structure of the IPB

with a decrease in WDC. Notably, for the 2020 and 2021 models, time-invariant traffic isolation does not significantly influence the WDC of the current year. Regions closer to the city centre and equipped with more amenities exhibit higher levels of WDC. These areas offer more densely interconnected spaces that cater to diverse groups. We further explore the impact of WDC on economic inequality (See Table 1, 2). In 2018–2020, increasing WDC has a significant effect on reducing income inequality within the same year, with the most pronounced coefficient in 2018. However, by 2021, this effect had diminished. The overall results of the normal least squares (OLS) regression indicate that a 10,000-unit increase in the average WDC corresponds to a 0.57×10^{-3} unit decrease in the Gini coefficient. Regarding demographic traits, a 10,000 unit drop in the resident population and a 10,000 unit increase in the working population are associated with a Gini coefficient reduction of 9.45×10^{-3} and 0.023 units. Additionally, a 1% reduction in the automobile ownership rate and the prime-age proportion correlates with a Gini coefficient decrease of 0.09 and 0.04 units. A 1% decrease in the proportion of male population leads to a reduction in the Gini coefficient of 0.08 units. Furthermore, during the COVID-19 pandemic, the Gini coefficient in areas under lockdown was, on average, 0.02 units higher than in regular areas. This discrepancy arises from the lockdown policy's additional impact, which includes the displacement of nonresident populations, diminished objective communication and income opportunities in these isolated zones, and heightened income disparities. To test the stability and efficiency of our results, we incorporate the two-step least squares (2SLS) model and conduct a comparative analysis of the estimation effects between OLS and 2SLS.

Table 1 Influence of physical isolation on weighted degree centrality (OLS)

			Dependent variable: WDC	
Year	Variables	(1)	(2)	(3)
2018	IPB_c	−516.91***		
2018	IPB_t		−778.53*	
2018	IPB_all			−11,493.54***
2018	DC	−4.28***	−4.25***	−4.23***
2018	NA	206.34***	206.37***	205.09***
2018	Adjusted R^2	0.6311	0.6312	0.6325
2018	F Statistic	508.66	524.15	519.23
2019	IPB_c	−458.93***		
2019	IPB_t		−1455.02***	
2019	IPB_all			−11,293.11***
2019	DC	−3.37***	−3.32***	−3.32***
2019	NA	128.25***	128.29***	127.14***
2019	Adjusted R^2	0.6849	0.6863	0.6873
2019	F Statistic	731.91	758.37	748.08
2020	IPB_c	−348.32**		
2020	IPB_t		−521.07	
2020	IPB_all			−9090.89***
2020	DC	−3.37***	−3.35***	−3.33***
2020	NA	185.97***	186.01***	185.05***
2020	Adjusted R^2	0.6846	0.6847	0.6857
2020	F Statistic	641.52	654.23	651.46
2021	IPB_c	−240.52*		
2021	IPB_t		680.91	
2021	IPB_all			−4555.784***
2021	DC	−2.42***	−2.44***	−2.41***
2021	NA	160.01***	160.20***	150.55***
2021	Adjusted R^2	0.7041	0.7042	0.7043
2021	F Statistic	789.11	799.11	7979.61

$P < 0.05$*, $P < 0.01$ **, $P < 0.001$ ***

Table 2 Influence of weighted degree centrality on economic inequality (OLS)

	Dependent variable: Gini index				
	2018	2019	2020	2021	4 years
WDC	−1.22***	−0.62***	−0.58***	−0.36	−0.57***
home_pop	9.45***	11.61***	9.05***	9.67	8.56**
work_pop	−2.33***	−2.08***	−1.61***	−1.26*	−1.94**
male	−0.08***	0.10***	0.08***	−0.06	0.08***
car	0.06	−0.09***	−0.08**	0.03	−0.09**
age25-45	−0.14***	0.05*	0.01	0.03*	−0.04**
COVID-19	/	/	/	0.0008	0.0229**
Adjusted R^2	0.1542	0.2346	0.1308	0.1277	0.1148
F Statistic	121.62	189.18	121.61	122.39	268.54

P < 0.05*, *P* < 0.01 **, *P* < 0.001 ***

4.4.2 2SLS Model

According to previous studies, there is a two-way causal link between social bond and economic inequality. In this study, we prefer to focus on the one-way impact of social communication on economic inequality. Therefore, we introduce exogenous variables into the model as instrumental variables to control the reverse causality, which include Isolation of Physical Barriers (IPB), Distance from the Center (DC) and Number of Amenities (NA). These variables are validated to affect WDC but not on economic inequality (see Model tests). Therefore, the results of 2SLS are composed of two parts: the first part is the effect of the instrumental variable set on the social communication proxy variable WDC, and the second part is the effect of predicted (WDC)ˆon social and economic inequality under the interference of instrumental variables (See Table 3).

We observe a trend: if urban structures contain fewer physical isolation barriers, closer distances, or more spatially concentrated amenities, the weighted degree of centrality tends to become less dispersed. The model estimation results, detailed in Table 3 Model (3), corroborate this observation. Three distinct models affirm a significant correlation between social centrality (measured by weighted degree centrality, WDC) and the dimensions of urban isolation, including the degree of centrality (DC), number of amenities (NA), and isolation of physical barriers (IPB). The three instrumental variables, DC, NA, and IPB, reflect different levels of potential geographical sources of social isolation. Specifically, the higher

Table 3 Influence of physical isolation on social bond(2SLS)

Dependent variable: WDC			
	(1)	(2)	(3)
IPB_c	−368.91***		
IPB_t		−1115.73***	
IPB_all			−7196.88***
DC	−3.98***	−3.94***	−3.95***
NA	171.95***	171.96***	171.91***
home_pop	0.48***	0.52***	0.51***
work_pop	2.81***	2.75***	2.76***
male	−21,562.05***	−20,648.81***	−20,042.05***
car	4769.21*	2558.02*	2508.86*
age25-45	20,280.51***	20,467.45***	20,572.42***
COVID-19	353.26	334.63	334.29
Observations	5285	5285	5285
Constant	0.000	0.000	0.000
R^2	0.6407	0.6532	0.6533
Adjusted R^2	0.6405	0.6530	0.6532
F Statistic	751.68***	777.45***	780.08***

P < 0.05*, *P* < 0.01 **, *P* < 0.001 *** the degree of isolation, the lower the centrality within the urban social network, indicating a reduced intensity of social interactions within the network. In addition, a closer distance to the urban center and a higher density of amenities (the more the number of amenities in a grid) correlate with a heightened centrality of the social network and elevated social accessibility, which indicates that the hot spots of social activities are concentrated in the main urban center and the area with relatively perfect relatively comprehensive infrastructure, thereby providing ample venues for social interaction.

Furthermore, the simultaneous increase of the living and working population in the region will increase the value of WDC. Regions with a lower proportion of men and a higher proportion of young people have a higher degree of social centrality, which indicates that female and prime-age people are more likely to form social networks characterized by offline communication in inaccessible areas. The traffic isolation degree model (Model (2)) shows that with the expansion of the traffic isolation area, the WDC decreases, indicating that specific communication of the crowds is also significantly related to the accessibility of vehicles, and this effect is more significant than the effect of isolation of communities.

Analogously, the community isolation model (Model (1)) also shows that with the expansion of the gated communities, the WDC in these areas also decreases. However, different from models (2) and (3), when only community isolation is considered, the higher the proportion of people with cars in the area, the higher the WDC of the area will be promoted. The proportion of vehicles represents the ability of people in the area to communicate with the outside world; this result suggests that the closure of the community can restrict the interaction between pedestrian and vehicular traffic on a more granular scale. In areas with a similar degree of community isolation degree, the ability of people's agency to reverse external communication is more important.

The results of models (1)-(3) in Table 4 confirm that the degree of WDC predicted by physical isolation is closely related to the degree of income inequality. The weaker intensity of social communication (WDC) leads to a higher degree of economic inequality. This result robustly corroborates the relationship we proposed between social bond barriers and income inequality. It further demonstrates that the closed structure of urban areas serves as a critical indicator of the bonds and accessibility network intertwined with economic inequality. In particular, in regions with a higher male population and a predominance of service-orientated amenities demographics, a higher income inequality is observed, whereas areas with a population of prime age and a workforce-centric demographic experience lower economic inequality. This reveals a significant challenge for low-income groups in sharing economic resources with local groups and communities dominated by poorly inclusive groups (See Table 4).

Additionally, regional lockdowns initiated in January 2020 have pronounced affected income inequality. In areas under lockdown, low-income individuals faced reduced economic opportunities, which exacerbated the wealth gap between other groups. Moreover, in Model (1) Table 4, car ownership is no longer the key factor affecting regional income inequality. Combined with the results of step 1 (See Table 3), it can be shown that cars have dual characteristics of assets and transportation tools. However, the transportation function is more prominent than the asset function in actual urban

Table 4 Influence of regional social intensity on economic inequality(2SLS)

	Dependent variable: Gini index		
	Instrumental variable		
	(1)	(2)	(3)
	IPB_c	IPB_t	IPB_all
WDC	−1.84***	−1.02***	−1.03***
home_pop	8.63***	8.59***	8.59***
work_pop	−1.93***	−1.96***	−1.96***
male	0.03***	0.03***	0.03***
car	0.01	0.01	0.01
age25-45	−0.05***	−0.05***	−0.05***
COVID-19	0.002**	0.004**	0.002**
Observasions	5285	5285	5285
Constant	−0.000	−0.000	−0.000
Adusted R^2	0.2459	0.2461	0.2463
Year	Yes	Yes	Yes

$P < 0.05$*, $P < 0.01$ **, $P < 0.001$ ***

communication (car ownership can significantly influence WDC in step 1). In this study scenario, the prevalence of car ownership in a region does not necessarily correlate with a decrease or increase in wealth disparity within that region.

4.4.3 Model tests

Sargan test. We use the Sargan method to test whether the instrumental variables are exogenous, and the results of the sargan test of the three models show that the null hypothesis cannot be rejected (H0:all instrumental variables were exogenous), indicating that there are no endogenous instrumental variables among IPB, DC and NA. And it can be considered that the random jamming items in the three models are unbiased, and the statistics naturally follow the chi-square distribution (see Tables 5, A1 and A2).

Weak instrument test. Weak instrumental variables are tested by reference to the K-P rkF statistic, because the model has a partially heteroscedastic characteristic. In the first step, the regression F statistics are all greater than 10, rejecting the null hypothesis (H0, there are weak instrumental variables). The minimum eigenvalue statistic is 4653.91 > 13.96 (15% level), rejecting the null hypothesis (H0: there are weak instrumental variables), there are no weak instrumental variables in the model, which means IPB, DC, and NA instrumental variables all have strong explanatory effects and can be retained. (See Table 5, B1, B2, and B3).

Hausmann test. The Hausmann test confirm that there is no significant correlation between degree of IPB and second-stage dependent variable, regional income inequality (Gini coefficient) in the three models. The 2SLS instrumental variable model provided better fitting results than the OLS regression (see Table 5 C and D). Robustness checks of the replacement region variables confirm that the results are basically stable and do not limit observations to the typical near-centre grid regions. To examine whether the effect of insularity on income inequality is best mediated by social bond centrality, we regressed all explanatory variables in the equation and found that IPB remained the most robust IV among these comprehensive models and WDC remained a statistically significant predictor of income inequality.

Endogeneity test of weighted degree centrality (WDC). The results of Hausmann test have already shown that there are indeed endogenous explanatory variables in the model, and we want to examine precisely that WDC is the endogenous one. Our results reject the null hypothesis (H0: variables are exogenous), indicating that the WDC variable is indeed the endogenous explanatory variable in the Hausmann test. Therefore, in the final model, Gini coefficient is the explained variable, WDC is the endogenous explanatory variable, and IPB, DC, and NA are the instrumental variables. This setting can be considered reasonable and explanatory (see Table 5 E).

Managing bias and variability. In order to explore the impact of systematic measurement bias and variability, the research first changed the measurement scale and used 1000 m, 2000 m and 3000 m square grids as research units to analyze the research problems for many times, and the basic results obtained were similar to the original model. In addition, this study re-validates this model by using the data of a small-scale community sampling survey in Shenzhen in 2022. It can be observed that the influence directions of the three variables in the new 2SLS model are basically the same. In the first step, the influence coefficient of IPB on WDC is −457.1, and that of $\widehat{WDC}$ on Gini coefficient is −1.33. It can be considered that the research results of this paper are stable and credible after changing the collection method and research area.

Table 5 Four kinds of model test results

	Instrumental variable: IPB, DC and NA		
	IPB_c	IPB_t	IPB_all
A1. Sargan test(score)	1.9286	1.3601	1.9365
A2. Sargan test(P value)	0.38	0.51	0.37
B1. Kleibergen-Paap Wald F	2306.79	2356	2359.48
B2. Minimum eigenvalue statistic	4653.91	4673.36	4705.88
B3. 2SLS Size of nominal 5% Wald test	12.83(15%)	12.83(15%)	12.83(15%)
C. IPB & Gini coef	0.113	0.156	0.131
D. Hausman test (Prob > chi2)	0	0	0
E. Endogeneity test(P-value)	0.014	0.015	0.014

5 Discussion

This study demonstrates the relationship between physical isolation, social bond, and economic inequality. Specifically, the structure of the closed or gated space in planning is an important index that affects the interaction between social bond and economic inequality. Broadly, our findings reveal a discernible pattern in which urban isolation characterized by substantial distances, numerous physical barriers, and limited amenities tends to foster reduced levels of social bonds, and this relevance indirectly reduces economic equity. In addition, soft inclusion features of nonphysical variables also impact social bond and economic inequality [43]. Regions characterized by a substantial workforce, a prime-age population, and a relatively high proportion of females demonstrate stronger social connectivity. Instrumental variables control this one-way causality of social bonds affecting the degree of economic inequality, which also reduces the risk of short-term biased estimation caused by reverse causality.

This study also demonstrate that fine-grained spatial planning and adjustment are essential. Beijing's rapid urban expansion has led to severe segregation between different economic classes, and most of the city's isolated physical structures are characteristics left over from short-term planning in the past. For example, the phenomenon of walled slums in Chinese cities [44]. The long-standing inequalities of ethnicity, economic class, and social status in gated communities in metropolitan areas of the western United States [45] are a microcosm of this phenomenon. In the early development, cities emphasized protections such as micro-privacy and security, and the planning of large communities was almost designed to be isolated, with few communication opportunities for people inside and outside the boundaries, fostering a palpable sense of social isolation. At the same time, the design of the main roads also did not consider the problem of traffic relief in clogged areas. It adopted the multi-vein topology of road distribution, contributing to the serious problem of chronic local traffic congestion in Beijing. No policy can solve the congestion problem by opening local roads or increasing selectivity. Our study unveils a fresh paradigm for urban micro-governance: by unlocking the barriers of enclosed entities in strategic areas and introducing critical byways, we can reshape the regional communication network. This physical and spatially based approach aims to achieve higher social equity.

Our analysis suggests why and how enclosed and gated spaces in cities can effectively influence the relationship between social bond and economic inequality. In many areas, eliminating isolation is often an implicit goal of urban planning, for example, the"unclog road capillaries"plan in Chinese cities [46], the Concord Pacific Place community of Canada with open and diverse [47], the Singapore mixed residential community [48]. All policies and activities aim to balance social isolation and spatial equity. The ultimate goal of our research is to quantitatively and accurately ascertain the equilibrium between the two objectives. We focus on the degree to which the liberation of enclosed areas, enhanced road accessibility, and the cultivation of an inclusive community ecosystem can effectively contribute to reducing economic inequality.

Why does physical isolation in cities matter? Persistent physical isolation restricts spatial accessibility, fostering low-intensity social bonds within the region, which ultimately hinders efforts to reduce economic inequality. Compared to the short-term direct impact of soft inclusion, such as temporary population characteristics or external stimulus, physical isolation is a long-term important indirect interference factor of social interaction, which is more difficult to change [26]. This perspective is supported by previous research. For example, studies have revealed that providing communities with access to interaction spaces can enhance emotional well-being and reduce neighborhood crime rates [49]. The rapid expansion of cities has led to apparent spatial isolation between locals and the external population. Due to asymmetric work information, the lack of social resources, and the excessive distance from the core development area, the income gap between low-income groups and other groups has gradually widened [50]. At the same time, social bond and economic inequality have formed a reinforcement model in places where gated spaces have existed for a long time. Changing the conceptual isolation of some groups needs to start with the basic spatial form. For example, although governments mandate the joint construction of commercial and public rental housing (or low-priced housing areas such as return housing), high-income residents will still spontaneously build temporary walls to avoid engaging with other groups [43]. Thus, exploring and pioneering innovative approaches in urban micro-space planning is necessary. We posit that by creating more open communities and public social spaces, positive social bond networks can be gradually formed in the long period, ultimately improving overall equity performance.

How does a physical barrier generate intangible social effects? We describe three levels of urban topological indicators that capture different dimensions of urban spatial isolation. The effects of the average distance from the centre (DC), the number of amenities in the study unit (NA), and the isolation of physical barriers (IPB) are all worthy of policy reference. It is noted that physical barriers are the most difficult factors to change in spatial planning, because they involve multidimensional benefits such as environmental and human settlement satisfaction [40, 41]. In terms of optimising economic inequality, the research results may provide detailed and long-term spatial optimisation guidance for areas with high inequality in the city, such as removing walls and erection of road nodes. On the contrary, the distribution of amenities changes relatively quickly and is a less reliable tool for social network fragmentation. However, it is more relevant to ever-changing urban planning. Because public planners often change regional infrastructure goals, adjusting the amount of amenities can be an efficient tool for adjusting short-term social interactions, thus affecting short-term social inequalities.

In addition to physical isolation, our findings suggest that soft inclusion indicators in grids can also have a moderating effect on WDC and economic inequality: (1) *The acceptance effect of different groups.* The likelihood of seeking equality is also influenced by the composition of the regional population. Populations with a higher proportion of women and of prime age tend to foster social networks that are characterised by face-to-face interactions, such as visits and exchanges. Regions dominated by male [42] and residential populations often exhibit higher levels of income disparity. Housing, as a direct reflection of the capability of personal assets, signifies that a higher concentration of residents in a region can signify stronger economic divides. This finding not only validates our hypothesis but also underscores that group characteristics determine regional inclusion ability. (2) *Interregional commuting ability and social connections.* The proportion of cars represents the ability of people in the area to communicate with the outside world, as well as the asset status of the regional population. Our findings also suggest that in regions with similar isolated topologies, the individual's accessibility ability to communicate in reverse with outside areas is more important. In the metropolis, automobile ownership serves predominantly as a mode of transportation rather than a marker of wealth, enhancing social interaction without exacerbating disparities. This offers a new perspective on enhancing the intensity of cross-regional social bond, beyond simply opening up urban isolation areas, it can also be realised by elevating the objective commuting and communication capabilities from traffic behaviour optimization [43]. (3) *Phenomenal isolation due to COVID-19.* The implementation of uniform lockdown policies on a broader scale directly impacts income inequality, rather than indirectly affecting it via social bond networks. Spatial control policies during COVID-19 can be seen as an exogenous quasinatural experiment, and our results can be interpreted as that, in the context of general emergency control, people may maintain communication through electronic devices and virtual methods, thus space closure has less impact on social bond network [44]. The release of spatial control policy signals, as well as a large area of partition, reduces people's opportunities to obtain higher incomes, on the one hand through the reduction of interpersonal communication and resource exchange channels, on the other hand, the overall socioeconomic situation reduces the income dividend.

6 Conclusion

Our research aims to bridge the gap between spatial inequality and economic inequality, exploring specific approaches to altering social income inequality through fine-grained spatial openness strategies. The main findings of our study are as follows. First, the reduction of physical isolation within urban spaces (such as the opening of the walls of closed communities and the increase of road branches) can enhance social interaction, thus decreasing economic inequality within regions, although it does not directly impact economic inequality itself. Second, the closer the distance to a city's single centre and the higher the density of facilities, results in the higher social bond intensity and the lower the degree of inequality. Third, compared to the influence of tangible physical barriers, enhancing the inclusiveness of communities within a region is also a significant pathway to directly strengthen social connections and reduce economic inequality.

The uniqueness of this study lies in two aspects. On the one hand, we introduce a bridging variable that connects spatial inequality with economic inequality, the actual centrality of social bond. We use large-scale commuting data from the population to enable a more granular quantification of the actual social communication network. It is distinct from previous studies that relied on internet social data or survey data [14, 15], in which social networks in a real space cannot be described very accurately. We focus on the real spatial interaction process between individuals and define centrality (WDC) based on the number and direction of cross-regional social demand. On the other hand, we incorporate relatively invariant indicators of the degree of closure as instrumental variables into the models. This approach addresses the bidirectional causal effects between social networks and economic inequality, producing relatively credible research results. Furthermore, our specific findings provide valuable information for the opening of closed spaces with significant social inequality in cities [45, 46]. The opening of large communities near urban edges and polycentric areas, as well as regions with sparse road networks and more inclusive populations, has shown to be significantly valued in reducing inequality. The theoretical significance of this paper is that it constructs the influence relationship between social interaction and economic inequality from the perspective of spatial isolation, and reveals the dual strengthening effect of"physical wall"and"social wall"on economic inequality. The practical significance is to guide the reasonable blank space planning of small and micro closed Spaces in the future, so that social interaction and economic inequality are in a reasonable category.

However, we cannot claim to find a complete causal link between spatial inequality and economic inequality because there may be confounding variables that explain our results. Indeed, the long-term evolution of neighborhoods is a complex phenomenon that includes mechanisms and feedback loops that we cannot evaluate in this paper. The long-term evolution of neighborhoods is a complex phenomenon that includes mechanisms and feedback loops that we cannot assess in this paper. However, our observations give us confidence to suggest that thoughtful urban planning may effectively slow the rise in urban inequality. We hypothesize that improving access between isolation spaces, promoting mixing levels, and supporting a more equal distribution of services could repair isolation social networks and improve economic outcomes. Besides, the database used in this article cannot accurately provide the personal characteristics of each pair of social bonds. Therefore, we cannot judge whether an interaction is a social bond under equal conditions or cross-class social bond. Future research can conduct a large-scale survey covering the whole area, with an individual or a group as a more precise object.

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Author contributions As the lead author, Pingzhen Lu has taken primary responsibility for conceptualizing the article, developing the structure, and writing the majority of the content. Prof. Fangzhou Xia, has made significant contributions to the literature review and analysis providing a thorough examination of relevant research and theories. Prof. Jinming Yan, has provided invaluable guidance and supervision throughout the writing process. Prof. Jianfu Shen, providing a thorough examination of relevant research and theories. Prof. Eddie Chi Man Hui have contributed to the revision and refinement of the article, ensuring its clarity, coherence, and accuracy.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Ethical approval was obtained from the Institutional Review Board. Participants agree to participate in and understand the purpose, risks and benefits of the study, and agree to abide by the rules and conditions of the study.

Consent for publication This manuscript has not been published or presented elsewhere in part or in entirety, and is not under consideration by another journal. All the authors have approved the manuscript and agree with submission to your esteemed journal.

Competing Interests The authors declare no competing interests.

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