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How fair is the allocation of bike-sharing infrastructure? Framework for a qualitative and quantitative spatial fairness assessment

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\section*{Abstract}

How fair is the allocation of the infrastructure of a bike-sharing system (BSS)? Design guidelines for BSS focus on optimizing the demand but not on who is served who is not. Areas where mainly young Caucasians, highly educated people live, and that have high access to community resources, presented greater access to BSS. Based on the concept of spatial fairness and its subjectivity, we developed a framework for a qualitative and quantitative assessment to help decision-makers and the general public evaluate the allocation of BSS infrastructure. First, from the general concept of justice, we developed our definition of spatial fairness assessment based on the rules of spatial equity, equality, and efficiency. Then, we developed a qualitative and quantitative spatial fairness assessment of BSS. The qualitative assessment aims to understand how underprivileged people perceived the spatial fairness of BSS taking as case study non-motorized households in Strasbourg feeling socially excluded. The quantitative assessment helps to numerically determine which distribution rule (equity, equality, efficiency) the infrastructure of a BSS follows. This assessment was applied in residential blocks inside the service area of the hybrid BSS in Munich, Germany. We developed a concept of availability as an accessibility indicator. As social indicators, we considered social milieus, access to other opportunities (e.g. health, education), and developed an equity index that is a combination of those two. As a result of the qualitative assessment, non-motorized individuals who felt socially excluded were less likely to talk about BSS at all. Furthermore, bicycles’ availability in the bike-sharing system in Munich matched the efficiency and equity rule, although lower availability of bikes correlates to residential blocks where traditional-oriented social groups live. Policy makers, stakeholders, urban and transport planners, and the general public have now available 1) the perception of a group of the underprivileged population about BSS, and 2) a quantitative methodology to identify which distribution rule(s) the infrastructure of a bike-sharing system follows and which social groups are spatially advantaged or disadvantaged by it. Further research may be oriented to apply the approach in the same city or applying them to more case studies.

\section{1. Introduction}

How should resources be allocated? The allocation problem is universal and impacts all social groups (Leventhal, 1980). If allocation follows distribution rules related to justice, this problem is solved based on an assessment of fairness (Leventhal, 1976). Fairness in resource allocation should be considered in decision-making because the attitude and behavioral responses of the people affected by the decision can affect the satisfaction and effectiveness of the allocation (Leventhal, 1980; Cropanzano, Fortin and Kirk, 2015). The allocation of public resources not only affects people’s economic and social opportunities but also influences their well-being (Fainstein, 2009). Opportunities can improve and benefit disadvantaged groups, but conversely, a low level of justice leads to resistance towards the allocation, low project consent (Wüstenhagen, Wolsink and Bürer, 2007), and low political acceptance due to low trust and perceived corruption (Ariely and Uslaner, 2017).

In terms of transportation infrastructure, we ask: how fair are investments allocated? For example, do they meet the specific needs of the most vulnerable population, such as those without access to a private car? Soja (2009) argues that

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these problems are related to spatial fairness, especially when considering the spatial distribution of urban resources. A new question arises regarding shared mobility services (e.g. car-, bike-, scooter-, ride-sharing). Specifically, if these services use public resources, how fair is the distribution of their supply? Who is afforded, and who is excluded from, access to the new shared mobility options? According to Lucas (2019), there are mainly two equally split perspectives: a) optimists, who believe that these technologies increase access and opportunities for people who cannot afford to own a vehicle; and b) pessimists, who state that these systems will mainly benefit the privileged population.

In this study, we focused on bike-sharing systems (BSS), which offer short-term rental of a bike provided in the public space where riders usually have to pay a fee and have a membership (Bütter and Petersen, 2011). BSS have emerged in the major cities around the world, most through publicly-owned companies (Shaheen, Cohen, Chan and Bansal, 2020). They have presented a significant growth of approximately 800 programs around the world with a fleet of more than 900,000 bicycles in 2015 (Fishman, 2016) to 1,600 systems and 18.7 million bicycles in 2018 (Shaheen et al., 2020).

BSS have existed in four different forms since their initial introduction in 1965 (Shaheen, Martin, Cohen and Finson, 2012). The first generation of BSS were free systems for public use. Theft and vandalism plagued these early systems and led to the implementation of dock-based systems requiring a coin deposit for use. This implementation did not completely reduce these issues mainly because of user anonymity. IT developments helped to manage this problem and the third generation of BSS tracked the location of bicycles in a dock-based system. Finally, the fourth generation of BSS is demand-responsive and self-balancing both included dock-free options and integration with the public transportation network. These BSS’s use on-board computers, the internet, and GPS for real-time tracking of the bicycles (Shaheen et al., 2012), in which big data enables real-time optimization of the bicycle fleet (Chen, Turoń, Klos, Czech, Pamula and Sierpiński, 2018).

BSS use different types of bicycles such as, among others, mechanical, electric, or cargo (Moon-Miklaucic, Bray-Sharpin, De La Lanza, Khan, Re and Maassen, 2018). Furthermore, according to the presence or absence of dock-based stations, they can be categorized into station-based (SBBSS), free-floating (FFBSS), or hybrid (HBSS), a combination of both (Schönberg, Dyskin and Ewer, 2018; Shaheen et al., 2020). FFBSS’s bikes can be locked to the bike frame anywhere in public space, without the need for fixed stations. In contrast with SBBSS, FFBSS avoid the cost of docking stations. Using GPS, bicycles can be tracked in real-time allowing smart management and reduced probabilities of bicycles’ theft. FFBSS is more convenient for users than SBBSS because the average walking distance from the bike to their destination is shorter and they do not have to worry about storing the bike at a docking station (Pal and Zhang, 2017).

BSS provides cycling-related benefits, including but not limited to improving health, reducing congestion and creating environmental awareness (Shaheen, Guzman and Zhang, 2010; Fishman, Washington and Haworth, 2014; Fishman, 2016; Ricci, 2015; Buck, 2013). In addition to these benefits, BSS avoid the maintenance, parking and security issues of privately owning a bike. Riders can take spontaneous bicycle trips, which has been shown to increase the population who cycle (Shaheen, Martin, Cohen and Pogodzinski, 2014). These systems support a first- or last-mile connection to public transportation, allowing the potential increase of inter-modal trips (Shaheen et al., 2012, 2010). Also, implementing BSS in a new city seems to enhance the city’s “sustainability image”, where tourists can experience a new city on bicycles without owning one (Ricci, 2015). Moreover, Shaheen and Chan (2015) reported 5.5% of BSS users postponing buying a car or selling their cars and Shaheen et al. (2014) showed a 50% reduction on private car usage. Due to the reduction of private car usage, BSS are actually associated with emission reduction. However, rebalancing bikes by truck can backfire in terms of emissions (Shaheen et al., 2014).

These benefits have been unevenly distributed among different social groups. Previous work on BSS showed that their typical user’s profile is male, young, and white, with high income, a high education, is already engaged in cycling, and has access to a bank account, credit card, and smart-phone (Murphy and Usher, 2015; Ogilvie and Goodman, 2012; Fishman, Washington, Haworth and Watson, 2015a; Buck, 2013; Goodman and Cheshire, 2014; Winters, Hosford and Javaheri, 2019; McNeil, Broach and Dill, 2018; Nickkar, Banerjee, Chavis, Bhuyan and Barnes, 2019, Shaheen et al., 2012). Spatially, relevant research showed that poorer/deprived areas are less likely to have access to BSS infrastructure (Ogilvie and Goodman, 2012; Goodman and Cheshire, 2014; Ursaki and Aultman-Hall, 2015; Hosford and Winters, 2018; Smith, Oh and Lei, 2015; Mooney, Hosford, Howe, Yan, Winters, Bassok and Hirsch, 2019). In contrast, areas where mainly young Caucasians, highly educated people live (Smith et al., 2015; Ursaki and Aultman-Hall, 2015; Chen, Guo, Stuart, Zhang and Li, 2019), and that have high access to community resources, presented greater access to BSS (Mooney et al., 2019).
on the demand as an indicator for where to implement new infrastructure (Gauthier, Hugues, Kost, Li, Linke, Lotshaw, Mason, Pardo, Rasore, Schroeder et al., 2014; Büttner and Petersen, 2011) and Mooney et al. (2019) found that the demand is highly correlated with the rebalancing destinations. Some systems focus their services in central (Fishman, Washington, Haworth and Watson, 2015b; Chen et al., 2019) and denser (Ursaki and Aultman-Hall, 2015) areas. Ursaki and Aultman-Hall (2015) showed that the location of stations in denser areas attracted more users (efficiency focus) but limited access to disadvantaged populations.

So how fair is it to plan BSS based on potential demand and not serve every area equally or not primarily serve underprivileged people who cannot afford another type of mobility? To support policy makers, transport planners and the general public in answering this subjective question, this study focuses on developing a quantitative and qualitative conceptual framework and method for assessing the spatial fairness of accessibility to the infrastructure (stations and bicycles) of bike-sharing systems (BSS). First, our goal is to develop a conceptual framework regarding spatial fairness, which synthesizes the concepts of justice, social and spatial fairness, and distribution rules. Then, we aim to quantitatively understand how underprivileged people perceive the spatial fairness of a local bike-sharing system. Due to the availability of pre-existing data, we considered the case of non-motorized households feeling socially excluded in Strasbourg, France. Finally, our third objective is to develop and apply a method to quantitatively identify which distribution rule, or a combination of rules, is or are present in the supply distribution of a bike-sharing system. Because of a lack of fairness assessment in HBSS in the literature and data availability, we applied the methodology in the city of Munich, Germany. Thus, is the distribution of the supply of the bike-sharing system in Munich according to the demand, to those that contribute the most, to those who need it the most, is it equally spread, a mixture of them or none of them?

The following section discusses the conceptual framework of spatial justice assessment, which is the theoretical core of this study, including a literature review of previous work on assessing spatial fairness on BSS’s supply. In the third and fourth sections, respectively, qualitative and quantitative assessments of the fairness of BSS, including an explanation of the methods used in and results yielded from these two methodological approaches. This paper then concludes with a discussion of the results and future applications of both assessments.

### 2. Conceptual framework on spatial fairness assessment

To introduce the terminology used in the paper, we developed a conceptual framework for defining spatial fairness assessment inspired by the justice judgment theory. Justice judgment theory explains how individuals perform a fairness assessment based on justice rules (Leventhal, 1980). Justice and fairness are two different concepts, although in some literature they are considered to be the same (Goldman and Cropanzano, 2015), and in some languages (e.g. Spanish, and French) have only one term to describe both. According to Goldman and Cropanzano (2015), justice involves morally required rules, which tend to be shared by different groups of people, with some considered to be universal (e.g. human rights) and others may vary depending on the cultural or circumstantial context (Leventhal, 1980). Fairness is a subjective assessment of whether or not justice rules are implemented in a morally worthy way (Goldman and Cropanzano, 2015). What is fair for one person, however, might not be fair for others.

Cropanzano et al. (2015) classified justice rules into four categories: a) distribution rules; b) procedural rules; c) interpersonal rules; and d) informational rules. In this research, we focus on distribution rules, which are defined as “the individual’s belief that it is fair and appropriate when rewards, punishments, or resources are distributed in accordance with certain criteria” (Leventhal, 1980). There are multiple distribution rules and this paper focuses on the three most commonly applied in literature, which are equity, equality and efficiency (Talen, 1998; Leventhal, 1980). These three rules are defined as follows:

1. **Equity or vertical equity or needs rule.** In this rule, resources are distributed according to the people’s needs, therefore, following a broad justice focus. It has also been defined as an “equal treatment for equals and unequal treatment for unequals” (Leventhal, 1980; Talen, 1998).

Two categories of needs can be assessed under the equity rule: 1) abilities and 2) social and economic opportunities (Litman, 1999). Social and economic opportunities take into account, for example, sociodemographic attributes (e.g. gender, age, race, migration background, language, income, education, values, social status, occupation, milieu, etc.), and accessibility to opportunities (e.g. jobs, education, health, social and recreational facilities, public transport, vehicle ownership, information, technology) (Geurs and Van Wee, 2004).
II) Equality or horizontal equity. This rule involves the equal distribution of resources, regardless of the different needs or abilities of people (Leventhal, 1980; Talen, 1998). “No agent is privileged over any other agent” (Varian, 1975), and “no agent prefers any other agent’s bundle to his own” (Varian, 1974). It follows an intermediate justice focus. Examples of equity include human rights and laws equally applied to all people in a given area.

III) Efficiency or contributions rule. Resources are distributed according to people’s contributions (Leventhal, 1980). In other words, the allocation is according to the usage and therefore, willingness and ability to pay (Leventhal, 1980; Talen, 1998). Then, this rule presents a narrow justice focus.

Hirsch, Stratton-Rayner, Winters, Stehlin, Hosford and Mooney (2019) classify these rules into social or spatial categories. In this study, social fairness assessment refers to who gets the resources and who does not, and spatial fairness is related to whom and where the resources are being allocated. Thus, a spatial fairness assessment determines if the spatial allocation of resources follows a rule of spatial equity, equality, efficiency, or a mix of the three (Figure 1). This concept may help to estimate the acceptance of the allocation. Additionally, distributors may have a conceptual tool to assess which rule(s) the allocation of resources follow and whether the distributors, or the people affected by the distribution, consider it to be fair, or not.

2.1. Conceptual framework on spatial fairness assessment applied on BSS’s infrastructure

Gössling (2016) classified urban transportation resources to be distributed in terms of exposure, space and time. He defines space as having three components: area used, infrastructure, and access. In this paper, we focus on assessing the fairness of spatial distribution in terms of infrastructure and accessibility.

In this section, we describe five hypothetical cases of distribution rules on BSS infrastructure in a service area related to two extreme conditions: 1) privileged area and 2) underprivileged area (see Figure 2). For allocation, we refer to which distribution rule (spatial equity, equality, efficiency, or a mix of the three) are followed in the location of infrastructure, including stations and/or availability of bicycles. Therefore, this exemplification can represent all types of BSS, regardless of whether they are SBBSS, FFBSS, and HBSS.

We distinguished five hypothetical of BSS infrastructure following the above-mentioned distribution rules (see Figure 2). In the case of spatial equity (I), most of the infrastructure would be allocated in underprivileged areas, while for spatial efficiency (III) most of the infrastructure would be allocated in privileged areas. Spatial equality (II) would allocate the infrastructure equally throughout the service area. Now the question arises of whether more than one rule can occur at the same time. The hypothetical case would be in a service area without a clear distinction between privileged and underprivileged areas. For example, spatial efficiency and spatial equity rules (IV) would be present at the same time when the infrastructure is not equally spread in the service area and there is not a clear
distinction between privileged and underprivileged areas. This case may also occur whether those who contributed the most (efficiency) are the underprivileged (equity). Finally, the three rules would be present (V) in the hypothetical case where there is no clear distinction between privileged and underprivileged areas and the infrastructure would be equally spread throughout the service area.

In the next sections, we use the conceptual framework to qualitatively and quantitatively identify which distribution rules our case studies follow.

3. Qualitative assessment

The qualitative assessment aims to understand what is the spatial fairness perception of underprivileged people. We chose the city of Strasbourg in France as a case study based on data available from interviews with individuals from non-motorized households (NMH). We included variables linked to spatial fairness aspects in a lexicometric (content) and traditional qualitative data analysis. The focus on non-car-owning households in the case of spatial justice as it relates to mobility reflects the fact that “[…] there is a disconnect between the mobility needs of low-income, non-car owning citizens to move and act freely within compact and walkable cities and the development trend for segregated, gated, car-friendly and gentrified settings, which correspond with the lifestyle preferences of middle and higher class populations (Barter, 1999; Soja, 2010)” cited by Lucas, Mattioli, Verlinghieri and Guzman (2016).

There is also a compelling aspect related to sustainability since by not possessing a private car, these households’ lifestyle is more sustainable from a mobility perspective by relying on less carbon-intensive transport modes (including cycling). This decrease in energy use is observed in multiple aspects of life as Tabbone (2017) found that in France, NMH use on average 9% less energy than their motorized counterparts (calculated on the energy usage of households only when at home, in order to exclude any mobility-related energy savings). The qualitative assessment also integrated comparative investigation between participants feeling socially excluded as it related to mobility and those who do not.

Social exclusion is a phenomenon linked to the unequal participation of individuals in society, which we consider as the opposite of social inclusion. This part of the work focuses on the role that mobility and transport play in social exclusion, so we refer to mobility-related social exclusion. Schönfelder and Axhausen (2003) linked social exclusion and mobility by claiming that transportation systems can help to perpetuate social exclusion through exorbitant costs in time or money for vulnerable groups. According to them, adding the issue of transport to social exclusion allows a better consideration of the spatial aspect of the exclusion related to activity areas (Schönfelder and Axhausen, 2003). According to McCray and Brais (2007), social exclusion occurs when portions of the population are prevented from participating in activities that affect their quality of life. They warn that this “isolation may be created by a lack of
transportation, and/or housing policies that isolate the poor, elderly, and disabled from activities in space and time” (McCray and Brais, 2007).

3.1. Methods

This part of the research is based on empirical work consisting of 27 interviews with representatives from non-motorized households in Strasbourg, France (Villeneuve, 2017). The interviews focused on the daily mobility behavior, accessibility and perceptions of being socially excluded according to mobility. The participants were drawn up at random combining recruitment techniques (social networks, interest groups, banners, and snowball method) while looking for a variety of attributes: household types, income levels, and gender to gather different perspectives. Figure 3 shows attributes of the sample by gender, household types, age of participant and income level, attesting to sample diversity.

Since in this paper we focused on issues of spatial fairness, our analysis included variables linked to social and economic aspects of spatial equity. This included age, gender, income level, possession of a driver’s license, membership in a car-sharing system, possession of a monthly public transit pass, household type, ownership status of the residence, residential location and socially excluded feeling as it relates to mobility.

We combined conventional qualitative data analysis and a lexicometric analysis to understand the position of the interviewees on BSS. Only the portion of the interview related to bike-sharing was included in the analysis. The qualitative data analysis was performed using the RQDA software (Huang, 2016) with inductive coding. The conventional method of qualitative data analysis provided information directly from participants without imposing preconceived categories (Hsieh and Shannon, 2005).

The lexicometric analysis was performed by using the software IRaMuTeQ (Ratinaud, 2009). This open-source software uses the method known as ALCESTE (co-occurring lexemes analysis in simple statements of a text) developed by Reinert, 1983 (Reinert, 1983). In order to perform this analysis, we transcribed the entire contents of the 27 interviews. The content of the interviews was structured by characterizing the speech with sociodemographic variables and the specific question of the interview guide. For example, the answers to a specific question are grouped into a single body of “statements” which is then analyzed with the software and each response is associated with multiple variables, including the age, gender, income level, etc. of the individual who responded. This part of the analysis took place on the entire group of participants, allowing to compare the statements of those feeling socially excluded about...
3.2. Results

3.2.1. Lexicometric analysis

In our empirical investigation of the perception of non-motorized participants about BSS in Strasbourg, we used a lexicometric analysis to compare the statements of the participants based on various socio-demographic variables. We found significant variance with three variables: the feeling of being socially excluded as it relates to mobility, the income level and gender. We found that the participants that felt socially excluded were less likely to discuss cycling in general (-1.3 times) and bike-sharing (-2.4 times) than those who did not express that feeling. It shows that for that group, cycling and bike-sharing, in particular, don’t appear as viable mobility alternatives. When comparing the statements of the three income levels, we noticed that those with an intermediate income level were more likely to discuss bike-sharing (+2.1 times) and those with modest income were the least likely to discuss it (-0.6 times). This indicates that for the modest income group, BSS was less considered as a mobility alternative. Finally, we compared the statements of women and men and found that women were less likely to mention bike-sharing (-1.6 times) than men. This could imply that BSS is answering the needs of men more than those of women.

3.2.2. Qualitative Data Analysis

Figure 4 shows the coding structure that resulted from our analysis. The main topics discussed by the participants revealed by our inductive coding were the users of BSS, their structural aspects of BSS, the positive and negative
aspects of BSS and their usage of BSS. We also coded the material using our deductive codes of the types of fairness criteria discussed by the participants.

The Users of BSS  The participants often mention whom they think is the target of BSS, who is using it. We found that they didn’t think BSS was meant for them. Rather the participants said that BSS was for rich people, tourists or students. They said it was certainly not for the poor and not targeted at those who need it the most. For example, Sabine said:

“It’s mostly for students” Woman, 28 years old - Strasbourg area (Neudorf) - Income: affluent - Household size 2 people, car-sharing member, feels socially excluded.

Structural Aspects of BSS  Participants discussed certain structural aspects of BSS. Regarding funding BSS, the participants would rely on public authorities subsidies, potentially using gas tax for this purpose. They also mentioned some aspects regarding the usefulness of combining BSS and public transport. The analysis reveals that some NMH in Strasbourg would like to see BSS encouraged. Finally, they mentioned that BSS have an impact on the number and usage of privately-owned bicycles.

Positive and Negative Aspects of BSS  The participants who mentioned BSS also discussed some positive aspects. They said the system was successful, practical and simple to use. The analysis shows that some NMH in Strasbourg think that BSS could reduce the problem of bike theft in their city. They specifically referred to the actual bicycles which were described to be better than private bikes; requiring no maintenance and in the long run, being cheaper than owning a bicycle. For example, Samuel said:

“There is no maintenance constraint” Men, 24 years old - Strasbourg area (Contade) - Income level: Intermediate - Household type: Couple - Household size: 2 people - Car sharing: No - Doesn’t feel socially excluded.

The participants also described one negative aspect of BSS as they thought it might raise the risk of conflicts between riders and pedestrians who are sharing the same space.

Own Usage of BSS  Although many participants discussed BSS, not all of them were active users of the system, for example, Naomi said:

“So I’ve never used BSS, it is not bad, but I think it’s for tourists, for people who visit […] but I personally do not use it.” Women, 38 years old - Strasbourg area (Wihrel) - Income level: Intermediate - Household type: Single-parent family - Household size: 3 persons - Car sharing: Yes - Feels socially excluded.

Fairness Aspects  Since none of the participants commented on the type of fairness assessment associated with BSS in Strasbourg and this was not a specific topic of discussion we cannot state their perception of the distribution rules of the BSS as implemented. However, the equity distribution rule of spatial fairness was the only rule discussed. Some of the participants discussed a negative opinion on fairness and equity aspects without being prompted by the interviewer. For example, Sabine relates that:

“I don’t know if there are a lot of people in the disadvantaged neighborhoods who have a BSS subscription which is more like students and people like me so it may not be for the right audience” Women, 28 years old - Strasbourg area (Neudorf) Income level: Affluent - Household type: Couple - Household size: 2 people- Car-sharing: Yes member - Feels socially excluded.

We can summarize that even though BSS had an overall positive image, the participants felt that the system might end up being inequitable when using a broad focus of justice as they might not be targeting the most disadvantaged population.

4. Quantitative assessment

In this section, we describe the method used to identify which rule(s) (spatial equity, equality, efficiency) are reflected by the distribution of the bike-sharing system infrastructure (stations and bicycles). First, we discuss how fairness in BSS has been assessed in existing research. Then, we present a methodological framework and show how we apply this framework to assess a HBSS in Munich, Germany.
Table 1
Representative studies related to spatial equity assessment in BSS

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4.1. Previous work on quantitative spatial fairness assessment on BSS

In the literature, spatial fairness in BSS has been quantitatively assessed primarily based on spatial equality and spatial equity. Commonly, fairness in BSS is not assessed in terms of spatial efficiency, but rather efficiency as a strategy for optimizing the location of stations (García-Palomares, Gutiérrez and Latorre, 2012; Büttner and Petersen, 2011; Frade and Ribeiro, 2015) and balancing strategies (Liu, Li, Qu, Chen, Yang, Xiong, Zhong and Fu, 2015; Contardo, Morency and Rousseau, 2012).

In previous research, spatial equality and spatial equity have mainly been assessed using four accessibility indicators: a) observed demand, b) bikes availability, c) proximity to or density of the infrastructure, and d) “walking-cycling-walking” accessibility to activity locations (Chen et al., 2019). The concept of accessibility helps to assess access to certain mobility systems for different social groups in terms of users’ abilities as well as social and economic opportunities. There are multiple definitions for accessibility (Geurs and Van Wee, 2004). In this paper, we will consider accessibility as “the extent to which land-use and transport systems enable individuals to reach activities or destinations employing a combination of transport modes” (Geurs and Van Wee, 2004).

Studies addressing spatial equality and accessibility often use the Gini coefficient and Lorenz curve for their assessment (Van Wee and Geurs, 2011; Chen et al., 2019). The Lorenz curve is a cumulative line of the prevalence of the population versus the cumulative prevalence of a certain resource or attribute. The Gini coefficient is the ratio of the area between the Lorenz curve and the 45-degree line, and the total area under the 45-degree line. A Gini coefficient of 0 means perfect equality (everyone gets the same amount of resources) and a value of 1 means perfect inequality (only one agent gets all resources) (Gini, 1936).

Table 1 presents an overview of existing research on spatial equity of BSS, including the assessment methods, accessibility indicators, attributes, spatial units, and study areas used in the research. Commonly, the spatial equity assessment determines which social groups living in a spatial unit of analysis are more correlated to a certain accessibility indicator to BSS’s supply (e.g. availability). Most of the literature studied SBBSS in English-speaking countries, especially in the United States. The most common spatial unit is census blocks or tracts, and most assess proximity or density of the infrastructure with sociodemographic attributes using descriptive statistics and statistical tests.
Generally, the four most commonly used methods in existing research to assess spatial equity include: a) descriptive statistics and statistical tests, e.g., Student t-test (Ursaki and Aultman-Hall, 2015) and Analysis of Variance (ANOVA) (Chen et al., 2019), b) correlation, e.g. Spearman correlation (Yan and Howe, 2019), c) regression, e.g. linear regression (Ogilvie and Goodman, 2012), poisson regression (Couch and Smalley, 2019; Fuller et al., 2011), multivariate logistic regression (Winters et al., 2019), and spatial regression (Smith et al., 2015)), and d) maps & plots (Chen et al., 2019). Finally, the social attributes mainly used in existing research are sociodemographic or spatial equity indexes, such as the subgroup inequity index (Stuart, Mudhasakul and Sriwatanapongse, 2009), Bike Equity Index (BEI) (Prelog, 2015), economic hardship index (Montiel, Nathan and Wright, 2004)), Pampalon Deprivation Index (Pampalon, Hamel, Gamache, Philipert, Raymond and Simpson, 2012), vulnerability index (Deboosere and El-Geneidy, 2018), among others.

4.2. Methods

After selecting a bike-sharing system as a case study, the first step in the quantitative assessment method (see Figure 5) is selecting and collecting the input data: a) a spatial analysis unit, b) a unit representing accessibility to supply, c) a
unit representing demand, d) the social attributes representing the privileged and underprivileged populations, and e) a unit representing the amount of underprivileged population living within a given spatial analysis unit. We call this metric equity index (EI).

The process continues by calculating the Gini coefficient of the supply accessibility unit in the spatial analysis units. When the Gini coefficient is low, we assume that the system follows the spatial equality rule. Otherwise, if the Gini coefficient is high, we assume that the distribution has an unequal allocation of infrastructure. To analyze the possibility of multiple distribution rules, we multiply the accessibility of the supply by the EI, and then we recalculate the Gini coefficient (Gini_EI_weighted). If the Gini coefficient is similar to the Gini_EI_weighted, we assume that the distribution follows an equity rule additionally to the equality rule. Because the Gini coefficient remains constant after the weighting, this means that underprivileged people live equally spread in the area of study. Similarly, we calculate Gini_D_weighted by multiplying Gini with demand and if it remains similar to the Gini coefficient, we assume that the supply also is distributed according to an efficiency rule. Finally, when Gini_EI_weighted is similar to Gini_D_weighted, it can be deduced that the distribution follows the three rules.

On the other hand, when the Gini coefficient is high, we proceed to evaluate spatial equity and efficiency instead of equality. We propose a high-level analysis as well as a deeper one. The shallow analysis aims to carry out a Spearman’s correlation test (Spearman, 1904) for EI and demand with the supply accessibility. We performed a Spearman’s rank correlation test due to the possibility of outliers, extreme values, and non-normal distribution. If the monotonic relationship is positive between EI and the supply accessibility, we assume that the distribution rule is spatial equity because the supply is aimed at the underprivileged, otherwise if the supply is aimed at the privileged the distribution follows an inequality rule. Similarly, if demand is positively correlated with supply accessibility, the system is spatially efficient, i.e. there is greater accessibility to the supply where people who can contribute monetarily to the system. Therefore, if accessibility to supply does not correlate positively with demand, the system is inefficient because it cannot sustain itself over time without external financing.

The deeper analysis focuses on exploring which social groups live in areas where there is greater supply accessibility. If privileged groups have greater access to the supply, we assume the distribution follows a spatial efficiency rule. However, if underprivileged groups live in areas with greater supply accessibility, we assume that spatial equity is the distribution rule.

Referring to Table 1, we evaluated the social groups living in areas with greater supply accessibility in three ways:

1. Visual comparison between heat maps of demand, being the accessibility to the supply and EI.
2. Spearman’s correlation test, It is used to analyze which social groups live in areas that positively correlate with accessibility to supply.
3. Feature selection and regression. They are performed to explore which social groups (independent variable) have a higher positive or negative association with supply accessibility (dependent variable I) and to the demand (dependent variable II). This helps us to understand who has access to the system and who uses it. If those who have access and use the system are the same social groups, the distribution is oriented to the efficiency rule. We consider Ordinary Least Squares (OLS) with a transformation (e.g. logarithmic or square root) of the dependent variable in case of heteroscedasticity issues as the regression method. We assume that multiple social groups might be correlated with each other. Therefore, we apply the LASSO (Least Absolute Shrinkage and Selection Operator) method (Tibshirani, 1996) for feature selection to avoid multicollinearity issues and to explore the social groups most associated to the supply accessibility and to the demand. The LASSO technique shrinks the coefficients of the regression, both increasing stability and retaining the variables with the highest association to the outcome. In other words, LASSO does variable selection and shrinkage. The selection of the shrinkage coefficient \( \lambda \) is critical in this technique because the number of variables considered for the model depends on this value. Therefore, we have to calculate the cross-validation error for each value of \( \lambda \) and select the \( \lambda \) with the smallest error (James, Witten, Hastie and Tibshirani, 2013).
4. Mann-Whitney U test for non-parametric data (Mann and Whitney, 1947). It is used to evaluate if two groups differ in a single continuous variable. The continuous variable would be the percentage of different social groups living in the spatial unit of analysis. These percentages are compared according to four different groups of spatial analysis units that are divided according to the median of the demand and accessibility to supply:
- Type I. Low accessibility to supply and low demand. The first case of these areas may have a lack of supply because there is no (potential) demand. It can, however, be a lack of demand due to a lack of supply.
- Type II. Low accessibility to supply and high demand. These areas are critical, where there is demand, but where there is not enough accessibility to supply. They may be potential places for locating stations and focusing re-balancing strategies to bring more bikes to these areas.
- Type III. High accessibility to supply and low demand. These areas present an oversupply, where potential bikes dropped-off in these areas are used or re-balanced after a long time.
- Type IV. High accessibility to supply and high demand. The system performs efficiently in these areas.

The alternative hypothesis for the test is whether the percentage of social groups living in type I, II and III areas are significantly different from living in type IV areas. Thus, the critical situation are social groups that live significantly less in type IV areas than in type I or type III, or primarily in type II areas.

Finally, spatial equity and efficiency would be present simultaneously if EI and demand are positively correlated with accessibility to supply, meaning that privileged and disadvantaged groups both live in areas with greater accessibility to supply. In these cases, there may be an unequal distribution of accessibility to the supply among social groups that are not defined by wealth (e.g. in terms of the social milieus discussed in the next section). The same procedure would apply to assess other levels of conflict.

4.3. Application of the method

We carried out a quantitative spatial fairness assessment of the HBSS introduced in the City of Munich in 2015. In 2017, the system included around 90,000 members with access to 1,200 bicycles and 118 stations (Rube, 2018). Users can pick-up and drop-off a bicycle either at stations or anywhere in the public realm. If a bicycle is returned to a station, the user gets a discount of 10 minutes to be applied to a future trip. The use of a bike cost 0.08 euros per minute or 0.05 euros per min for students. Users pay a maximum of 12 euros to use a bike for the whole day. There are also packages in which, for 48 euros per half-year, one can use a bike for up to 30 minutes every day. This half-year subscription costs only 12 euros for students (MVG Rad, 2019).

The data available for this system include the bicycles' position every five minutes and the location of the stations from mid-March until mid-April 2017 (Transit.robbi5, 2019). We used the density of bikes’ drop-offs as an indicator for demand, aggregated at the residential block level in the study period. It is assumed that the end of a trip, which we refer to as the bike drop-off, is when a bike “appears” in a new area. Bikes used longer than 150 minutes (approx. time to cross the whole service area) and traveling less than 100 meters (min. distance to be considered a trip) are excluded from the study. Bike drop-off points were used in the study, rather than bike pick-up points because the location of the drop-off is assumed to be closer to the user’s final destination than the location of the pick-up to the trip origin. Our approach was exclusively on a residential level to analyze who lives in the areas where the system is serving most accessible. The spatial unit of analysis was 2,300 residential blocks with a predominant land use categorized as residential from the ATKIS database (Vermessungsverwaltung, 2014).

4.3.1. Availability of bicycles as an indicator for accessibility to the supply

Availability of bicycles as an indicator of accessibility to the supply can be calculated in different ways, such as the inverse of the idle time (number of bikes per day in an area) (Mooney et al., 2019) for FFBSS, or the “ratio of [the] number of bicycles available to [the] station capacity (ranging from 0 to 1 - empty through full)” for SBSS (Reynaud, Faghih-Imani and Eluru, 2018).

In this study, we developed an innovative concept defining the availability of bicycles as the time rate in which there is at least one bike available in a buffer of distance “d” from a point where a user is willing to walk to access a bike-sharing system. The algorithm for the estimation of the availability starts with assigning every bike drop-off to a spatial unit. We intersected the time intervals between the bikes’ drop-offs and the next pick-up per spatial unit. Finally, the availability indicator per spatial unit is the rate between the intersection of the time intervals and the complete period of time evaluated in the study.

Previous research studies have used distances ranging from 250 to 500 meters to calculate a buffer of distance “d” to represent access to the systems (or service areas) or as a distance in which a user is willing to walk to access BSS (Fishman et al., 2015a; Fuller et al., 2011; Clark and Curl, 2016; Smith et al., 2015; Winters et al., 2019; Ogilvie and Goodman, 2012; Ursaki and Aultman-Hall, 2015; Hosford and Winters, 2018; Winters et al., 2019; Duran et al., 2018).
Therefore, to be on the conservative side, and taking the recommended distance of BSS design guidelines (Yanocha, Mason, Patlán, Benicchio, Alfred and Laksmana, 2018), we considered a distance $d$ of 300 meters.

4.3.2. Social milieus as social attributes

We wanted to assess spatial fairness by crossing the barriers of traditional sociodemographics by using social milieus as social attributes. Therefore, we used Sinus-Geo-Milieus information, which was provided by the marketing company Microm. This data included the dominant milieu and number of inhabitants per address in Munich for 2014.

Social milieus are groups of people with similar values and life orientations defined by everyday practices and lifestyles and have tended to have similar tastes, communication structures, and living environments (Barth, Flaig, Schäuble and Tautscher, 2017). To explain the advantages of using social milieus, rather than sociodemographic attributes, we use the example from Sinus-Milieus (Sociovision, 2018). In this example, we have two women who both are 36 years old, married with two children, and working part-time in the marketing sector, therefore, they are considered to be sociodemographic twins. These women were asked to show their “domestic altar” in an interview in their homes. One woman showed a piece of furniture against the wall, under a shelf of liquor bottles. The other woman, however, showed a wall where the skull of a bull was displayed. Although the two women shared sociodemographic attributes, the differences in their “domestic altar” exhibit that the two women have different lifestyles, values, live orientations, and that they belong to a different milieu.

The marketing company Sinus Sociovision has developed the Sinus-Milieus® approach, which is one of the leading lifestyles approaches in marketing in Europe (Sociovision, 2018). Every milieu is differentiated in terms of social-status and basic values (Figure 6). They clustered the German population into ten different milieus) by using a questionnaire based on 40 questions (Schwarz and Ernst, 2009) and around 24,000 interviews (Küppers, 2018). These were constructed from the so-called “information packages”, which included aspects from life orientations to sociodemograph-
ics, and values (Barth et al., 2017).

Sinus-Milieus® have been used in research, for example, to conduct agent-based modeling (Schwarz and Ernst, 2009; Jensen, Holtz, Baedeker and Chappin, 2016), multi-agent simulation (Soboll, Elbers, Barthel, Schmude, Ernst and Ziller, 2011), marketing research (Diaz-Bone, 2004), as well as for understanding social changes (Manderscheid and Tröndle, 2008) and mobility preferences (Von Jens, 2018; Sinus Markt und Sozialforschung GmbH, 2019). Sinus-Milieus® on a spatial scale are called Sinus-Geo-Milieus and are defined as the probability of every address in Germany to belong to a certain milieu group (Küppers, 2018). Sinus-Geo-Milieus use data from the interviews from Sinus-Milieus®, official national survey data and data collected from the marketing company Microm (https://www.microm.de/) and applied a multinomial regression model using the addresses in Germany to calculate the probability of each house in Germany to belong to one of the ten milieus (Küppers, 2018).

We extended the analysis by aggregating the different Sinus-Geo-Milieus groups by residential area according to low (traditionalists, precarious, hedonists), middle (modern mainstreamers, adaptive navigators and social ecologists) and high (established, liberal intellectuals, performers, cosmopolitan avant-gardes) social status, as well as traditional orientation (established, liberal intellectuals, modern mainstreamers, traditionalists, precarious) and progressive orientation (performers, cosmopolitan avant-gardes, adaptive navigators, social ecologist, hedonists).

### 4.3.3. Equity index

The equity index $EI$ in the spatial unit $j$ defined as the rate of the prevalence of low social-status milieus in spatial unit $j$ with the average of the accessibility defined by Geurs and Van Wee (2004) to the opportunities to basic needs, such as healthcare, social and recreational facilities, education, transport, and proximity to the city center.

$$EI_j = \frac{\text{Milieu}_{low\;status}}{\frac{1}{n} \sum_{i=1}^{n} a_1 e^{-a_2 D_i}}$$

(1)

where $D_i$ is the distance from the spatial unit to the built environment opportunity $i$, $n$ is the total number of opportunities in the study and $a_1$ and $a_2$ are parameters of the decay function of willingness to walk. As Chen et al. (2019) did, we used $a_1 = 1.0126$ and $a_2 = 0.0013$, from Zhao, Chow, Li, Ubaka and Gan (2003), who measured the decay function for walking to public transport in feet, therefore, we converted distances to feet. It is worth mentioning that accessibility to opportunities can vary depending on the units of the chosen model parameters. For a comparison between different EI, they should have the same metric units.

The indicator for the accessibility to basic needs was calculated as the distance of the spatial unit to the following opportunities: town hall, main train stations, universities, supermarkets, playgrounds, schools, pharmacies, kindergartens, hospitals, sports centers, cycle-ways, and public transport stations. Built environment data was downloaded from OpenStreeMaps (OpenStreetMap-contributors, 2019).

### 4.3.4. Feature selection and regression

We carried out two regressions, one with the availability of bicycles as the outcome and other using density of the drop-offs as the outcome. As independent variables, we included the percentage of each social group in every residential area. Also, after a recommendation of Bhuyan et al. (2019) in considering "residential population density, land use, facilities, attractions, origin-destination trips, etc" in similar research, we add population density and the walking accessibility to basic opportunities, which help to analyze whether a residential block does not have access to BSS, to which other opportunities would not have access too. We calculated walking accessibility similarly to the calculation of the denominator of EI (see Equation 1). Accessibility to the city center was the exception because walking accessibility would not make sense because of the commonly great distance. Therefore, we considered the straight-line distance from the centroid of the residential block to the town hall. To overcome heteroscedasticity issues, the square root was calculated for the availability and the logarithm for the bikes drop-offs. The independent variables were the groups of milieus, access to opportunities, and population density. The logarithm of the independent variables was taken, in case the variables were not normally distributed, as was the case of all the variables but for the distance to the town hall. Lastly, the independent variable was log-scale because of the prominent skewness, and the independent variables were normalized and due to the different units.

The entire analysis has been carried out using the R programming language (R Core Team, 2013).
Table 2
Descriptive statistics

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<th>Pctl(75)</th>
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<td>0.00</td>
<td>0.01</td>
<td>0.87</td>
</tr>
<tr>
<td>Sports Centre [acc.]</td>
<td>0.08</td>
<td>0.15</td>
<td>0.00</td>
<td>0.0001</td>
<td>0.09</td>
<td>0.94</td>
</tr>
<tr>
<td>Community Centre [acc.]</td>
<td>0.04</td>
<td>0.11</td>
<td>0.00</td>
<td>0.0001</td>
<td>0.02</td>
<td>0.86</td>
</tr>
<tr>
<td>Low social status [%]</td>
<td>0.20</td>
<td>0.26</td>
<td>0.00</td>
<td>0.00</td>
<td>0.33</td>
<td>1.00</td>
</tr>
<tr>
<td>High Social status [%]</td>
<td>0.57</td>
<td>0.34</td>
<td>0.00</td>
<td>0.25</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td>Middle social status [%]</td>
<td>0.21</td>
<td>0.19</td>
<td>0.00</td>
<td>0.05</td>
<td>0.33</td>
<td>1.00</td>
</tr>
<tr>
<td>Traditional orientation [%]</td>
<td>0.51</td>
<td>0.28</td>
<td>0.00</td>
<td>0.28</td>
<td>0.75</td>
<td>1.00</td>
</tr>
<tr>
<td>Progressive orientation [%]</td>
<td>0.47</td>
<td>0.28</td>
<td>0.00</td>
<td>0.23</td>
<td>0.70</td>
<td>1.00</td>
</tr>
<tr>
<td>EI</td>
<td>0.78</td>
<td>1.04</td>
<td>0.00</td>
<td>0.00</td>
<td>1.28</td>
<td>8.66</td>
</tr>
</tbody>
</table>

4.4. Results

The quantitative assessment was carried out in residential blocks inside the service area of a HBSS in Munich. Table 2 shows the descriptive statistics of the variables used in the assessment. **Heat maps** Figure 7a, 7b, and 7c show the spatial distribution of the availability, bikes drop-offs and the equity index in the residential blocks inside the service area. Availability is higher in residential blocks closer to the city center, especially in the north and northwest, where the main universities are located, and in the southeast areas close to the main river. On the other hand, availability is lower in the west, and northeast, which are areas with better rapid transit connections. Drop-offs were also greater in areas close to the center and north of the city, but there is a lower demand closer to the border of the service area. Because there is greater availability of bikes and more drop-offs in the center and north, we can assume the supply of the system follows an efficient rule in these areas. The EI is higher in the north and south. Therefore, the system is partially available for the underprivileged in the southern part, and reflects that this distribution is based on the equity rule. However, overall the system does not reflect a clearly defined distribution principle but rather a mix of rules (equity+efficiency) with a predominance of efficiency.
Figure 7: The average and standard deviation of critical parameters: Region R4
**GINI coefficients.** Figure 8 shows the Lorenz curves and Gini coefficients. The Gini coefficient for the distribution of availability is 0.525. When weighted with the EI, GINI_EI_weighted is 0.470, and finally, when weighted with the observed demand GINI_D_weighted is 0.311. Since the Gini coefficient is in the middle range, we cannot assume that the system is spatial equal or unequal. In this case, the other coefficients do not give us relevant information, but a possible tendency to equity and efficiency since the Gini coefficient decreases after weighting it with the EI and demand.

**Spearman’s correlation.** Figure 9 shows the Spearman’s correlation matrix between the variables in the study. We can see a positive correlation between availability and the bikes drop-offs (0.54) but also a weaker correlation between
Table 3
Feature selection and OLS regression Results

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Availability [sqrt(%)]</th>
<th>Drop-offs [log(count/ha)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Population density [log(inh./ha)]</td>
<td>0.626*** (0.531, 0.720)</td>
<td>0.434*** (0.392, 0.475)</td>
</tr>
<tr>
<td>BSS station [log(acc.)]</td>
<td>0.704*** (0.614, 0.794)</td>
<td>0.128*** (0.088, 0.167)</td>
</tr>
<tr>
<td>Town hall [km]</td>
<td>−0.309*** (−0.437, −0.181)</td>
<td>−0.236*** (−0.286, −0.187)</td>
</tr>
<tr>
<td>Hospital [log(acc.)]</td>
<td>0.189*** (0.076, 0.301)</td>
<td>0.072*** (0.038, 0.107)</td>
</tr>
<tr>
<td>Public transport station [log(acc.)]</td>
<td></td>
<td>0.061** (0.017, 0.106)</td>
</tr>
<tr>
<td>Bakery [log(acc.)]</td>
<td>0.093*** (0.046, 0.140)</td>
<td>0.097*** (0.036, 0.118)</td>
</tr>
<tr>
<td>School [log(acc.)]</td>
<td>0.075*** (0.030, 0.120)</td>
<td></td>
</tr>
<tr>
<td>Kindergarten [log(acc.)]</td>
<td></td>
<td>1.757*** (1.724, 1.790)</td>
</tr>
<tr>
<td>Traditional orientation [sqrt(%)]</td>
<td>−0.503*** (−0.599, −0.407)</td>
<td>−0.370*** (−0.410, −0.330)</td>
</tr>
<tr>
<td>Constant</td>
<td>4.369*** (4.289, 4.450)</td>
<td>1.757*** (1.724, 1.790)</td>
</tr>
<tr>
<td>Observations</td>
<td>2,300</td>
<td>2,300</td>
</tr>
<tr>
<td>R²</td>
<td>0.335</td>
<td>0.551</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.333</td>
<td>0.549</td>
</tr>
</tbody>
</table>

Note: ∗p<0.1; **p<0.05; ***p<0.01

availability and EI (0.19). From the shallow analysis, we assume that the distribution follows the rules of “equity + efficiency”. However, the tendency is towards efficiency because the correlation is much higher. In the deep analysis, we observe that the milieus of the established (-0.35) and liberal intellectuals (-0.25) have a negative correlation with availability, while the other milieus a positive correlation. The highest positive correlation is with the cosmopolitan avant-gardes (0.37), followed by hedonists (0.25). If we do the same assessment aggregating the social milieus in terms of social status low (0.22), middle (0.207), high (-0.22), we assume the distribution is inefficient because of the negative correlation to the high social status. However, all the social groups have similar “sign” in the correlation with the drop-offs and availability, which means that where there is higher demand there is also higher availability, therefore, we assume that the distribution follows an efficiency rule. Furthermore, we found that the highest correlation with availability was based on basic values, traditional orientation (-0.44) vs progressive orientation (0.44), and not with social status.

In conclusion, the system seems to be distributed under the “equity+efficiency” rules in the shallow analysis because the system is serving both privileged and underprivileged groups (shown in the deeper analysis). In addition, the system is socially inefficient by not serving the majority of the high-status population but spatially efficient because the supply is more accessible where there is more (observed) demand.

According to the other variables, areas with higher availability have a higher population density (0.48) and are closer to the town hall (-0.41). With regard to the accessibility to walking opportunities, the highest correlations are the accessibility to bakeries (0.35), supermarkets (0.31), hospitals (0.31) and schools (0.28). It is worth noting that the EI correlates negatively with the walking accessibility to schools (-0.04), hospitals (-0.02) and sports centers (-0.03).

Feature selection and regression results. Table 3 shows the results of the two linear regressions. The model, including the drop-offs, fits the data set better with a R² of 0.55, including 9 variables. On the other hand, the model, including availability, fits worse with a R² of 0.33 and 6 variables. The population density, walking accessibility to the bike-sharing stations, and distance to the town hall were parameters that are most associated with the dependent variables in both models. According to social milieus, the traditional orientation group was the only social group that was significantly selected by the LASSO selection technique and presented a negative association. Since both models are negatively associated with the same population, we assume that the system presents an efficient distribution because the availability is oriented to the demand. Since variables related to the social status were not selected by the LASSO selection technique, the assessment could not be evaluated in terms of serving the underprivileged and privileged population. Finally, the model including the drop-offs presented as well a high correlation with walking accessibility.
Table 4  
Comparison of the prevalence of milieus in blocks Type IV with blocks Type I, II and III

<table>
<thead>
<tr>
<th>Availability</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop-offs</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Milieu group</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Established</td>
<td>29.11%*</td>
<td>12.23%*</td>
<td>18.53%*</td>
<td>5.44%</td>
</tr>
<tr>
<td>Liberal Intellectual</td>
<td>24.65%*</td>
<td>12.95%</td>
<td>17.99%*</td>
<td>10.06%</td>
</tr>
<tr>
<td>Performers</td>
<td>9.95%</td>
<td>10.16%</td>
<td>10.52%</td>
<td>13.68%</td>
</tr>
<tr>
<td>Cosmopolitan</td>
<td>5.35%</td>
<td>12.42%</td>
<td>7.85%</td>
<td>20.62%</td>
</tr>
<tr>
<td>Main Streamers</td>
<td>6.29%</td>
<td>8.11%*</td>
<td>7.64%</td>
<td>5.54%</td>
</tr>
<tr>
<td>Adaptive Navigators</td>
<td>7.18%</td>
<td>8.97%</td>
<td>9.86%</td>
<td>11.14%</td>
</tr>
<tr>
<td>Social ecologists</td>
<td>2.89%</td>
<td>5.48%</td>
<td>3.67%</td>
<td>7.57%</td>
</tr>
<tr>
<td>Traditionalists</td>
<td>5.31%</td>
<td>9.73%</td>
<td>9.32%</td>
<td>8.49%</td>
</tr>
<tr>
<td>Precarious</td>
<td>2.68%</td>
<td>4.24%*</td>
<td>3.48%</td>
<td>2.93%</td>
</tr>
<tr>
<td>Hedonists</td>
<td>4.89%</td>
<td>13.05%</td>
<td>8.99%</td>
<td>12.15%</td>
</tr>
</tbody>
</table>

* Bold: significantly different than Type IV (p < 0.05)  
* Significantly less addresses than in Type IV (p < 0.05)

to public transport stations, and points of interest such as supermarkets, bakeries, schools, kindergartens.

Mann-Whitney U test results. We have classified the residential blocks into four types based on the availability and bikes drop-offs (see Figure 7d). Table 4 shows that established, mainstreamers and precarious live significantly more in Type II areas than in Type IV areas, and established and liberal intellectuals live more in Type I areas and Type III areas than in Type IV areas. Established and liberal intellectuals do not seem to use the system because even if they have a high level of availability in their residential areas, there are still low bicycle drop-offs (Type III areas). We found that mainstreamers and precarious milieus live significantly more in Type II areas than in Type IV areas. We, therefore, assume that they are potential users of the system, but have little access. We have found once more that social status is not a factor highly associated with the usage of BSS, but the basic values are. In view of the underprivileged population, for example, accessibility is higher where hedonists live (progress orientation), but there is no offer in areas where precarious people (traditional orientation) live. We observed that social groups with basic values oriented to the progress live more in Type IV areas. In summary, we cannot adopt a distribution rule of the system based on social status, but the distribution falls in the case of efficiency in that those who do not use the system have less access to the supply.

5. Discussion

Distribution rules are harder to choose when resources are limited. However, this is often the case and can start arguments over social versus economic sustainability. By economically sustainable, we mean that monetary resources to maintain the system would be readily available. By socially sustainable, we mean that the people most in need can access the system easily. When the spatial equity rule is applied, more resources are needed to make BSS economically and physically accessible as possible in underprivileged areas. Also, the neediest people (with lower economic resources) have better access to the system, which makes it socially sustainable but probably less profitable. Spatial equality rule can be more profitable than spatial equity but higher resources are required to build and balance a system in such a way that every area has equal availability. Spatial efficiency is the most profitable distribution rule and the system can be economically sustainable. However, those who might benefit the most from access to the system might not have access. Cases reflecting multiple rules, such as case IV and V (Figure 2), depending on the socio-spatial distribution of the city. Case IV would need fewer resources than case V, and would not have the clashes between social and economical sustainability. However, the distribution of the infrastructure can create other social clashes depending on which social groups are served more and which less. Finally, Case V would have similar opportunities, implications, and costs as the case of equality, because of the high infrastructure required.
Since fairness is a subjective assessment, one hypothetical case can be “fairer” to one person than other, depending on moral intuitions (Varian, 1975), culture, (Rochat, Dias, Liping, Broech, Passos-Ferreira, Winning and Berg, 2009; Stobart, 2005), individual preferences (Ambec, Garapin, Muller and Rahali, 2019) or situation (Schmitt, Barbacny, Binz, Buttgereit, Heinz, Hesse, Kraft, Kuhlmann, Lischetzke, Nisslmüller et al., 1994). A possible “general fair” assessed allocation would exist “when all agents have the same tastes, even though they may have different abilities” or needs (Varian, 1975). Otherwise, conflicts can occur after deciding what is fair or not. However, by interviewing a segment of the population that is at a transport disadvantage, we have shown that equity-based distribution rules are the ones desired by this population.

If spatial equity rule is reflected, underprivileged people can have greater access to opportunities and improve their mobility for a more balanced society. This rule was the only one referred to by the unprompted participants in Strasbourg. This shows that the equity-based or any combination of rules including equity distribution are the desired form of distribution from the perspective of the mobility vulnerable group that are NMH. Spatial efficiency might be profitable, but can be perceived as being for elites, in which the neediest are not served and the system can be subject to vandalism. On the other hand, “national elites set the standard” and “people hope to move on in life by imitating prestigious styles and behavior” (Kuipers, 2013), consequently if the elites use the system, disadvantaged social classes might want to use the system as well. Spatial equality might be very expensive to fulfill the needs of the whole service area but everyone can have access to it. According to (Varian, 1975), equity + efficiency would be called “fair”, in which the allocation would have the properties of efficiency and equity. Finally, equity+efficiency+equality would be costly but it would fulfill the three rules which would minimize conflicts or interests. In the end, even if BSS are considered “fair”, resources could be allocated somewhere else e.g. to build a school in a needed neighborhood. Would this case be fair? Therefore, an absolute fair system might not be possible.

The qualitative assessment helps us to understand how people perceive the spatial fairness of the BSS and if it is a concern. For the qualitative assessment, we chose the city of Strasbourg, France as a case study because of the data available from interviews with non-motorized households. The quantitative analysis helps to numerically assess which distribution rule(s) the allocation of infrastructure follows. We studied Munich since the city has a hybrid bike-sharing system with available data. The qualitative assessment helped us to prepare, validate and interpret the numerical outcome from the quantitative assessment. One approached informed the other. Even though we used two different cities, they are somewhat comparable. Both cities used as case studies are located in central Europe, are not capitals but are representative cities of their countries, have a “relatively well-developed bicycle infrastructure” (Martens, 2007), and are both located next to a river that greatly impacts the urban structure.

Furthermore, in the qualitative assessment, participants were not asked directly about their opinion on BSS but we extracted the content where BSS are referred to. The disadvantage is that we do not have extensive information because BSS perception was not asked directly, but the advantage is that we have their honest thoughts, feelings, and opinions because participants talked about these systems without being asked. Those who felt socially excluded were 2.4 times less likely to discuss BSS compared to those not feeling socially excluded. To the best of the authors’ knowledge, this is the first time that feeling socially excluded is associated negatively with BSS. This demonstrates that some of the most vulnerable populations in terms of mobility is not inclined to think about BSS as a solution and could be interpreted to reflect a lack of equity in BSS.

Theoretical knowledge for cycling planning is poorly developed, in comparison with motorized traffic planning (Koglin and Rye, 2014; Aldred, 2015), especially because of the difficulty for data collection. However, for BSS the GPS-based data helped as to collect trip information to implement our theoretical spatial justice framework. Then, we apply it the distribution of the availability in the service area of the HBSS in Munich from the quantitative assessment, which mainly showed three classifications:

1. Efficiency + Equity (Case IV, see Figure 2). Underprivileged and privileged people live in areas with higher availability. Therefore, we assume that the allocation follows these two rules together.

2. Efficiency. Efficiency is present where the usage of the system is directly proportional to the availability, i.e. where usage is higher, there is a higher availability, and vice versa.

3. Distribution oriented to progressive values. Social status was not an indicator of the distribution of availability. However, the distribution was oriented to the basic values. Social groups with an orientation to progressive values (especially cosmopolitan avant-gardes) instead of traditional-oriented values (especially established) live in areas with higher availability.
By revealing the distribution rules that the BSS infrastructure follows, policy makers and stakeholders can assess if the accessibility to a bike-sharing system follows their ideologies. Urban and transport planners can assess the design or modification of a bike-sharing system based on distribution rules and stakeholders’ preferences, or influence on policy makers (Koglin and Rye, 2014) to mitigate injustices. Finally, the general public can have information about the system in their cities to judge if it is spatially fair or not based on their ideologies, world views, and needs. They can protest if urban politics excludes certain groups (Koglin and Rye, 2014; Swyngedouw, 2008).

In terms of the efficiency rule, the system is partly economically viable because the demand is higher where the supply is more accessible. Also, under- and privileged people both have physical access to the system. If we would have stopped the analysis there, we would have assumed that the system is socially sustainable, since most disadvantaged people have high access to the system. However, the distribution of the availability of bikes seemed to be following basic values rather than social status. A social clash is present: traditionalists vs progressives. In this sense, traditionalists might perceive that the system is not oriented to them. Their main orientation is tradition, they might think that traditional transport modes as public transport or driving are more convenient, or because owning is also one of their main values, they prefer their own bike (Fishman, 2016). Similarly, in the qualitative assessment, BSS in Strasbourg were perceived to be for students, and we, therefore, assume that it is not perceived for elderly or traditionalist people.

As being the system tending to efficiency, we confirmed the argument of Aldred (2015): “current policy prioritises ‘commuter’ and ‘utility’ cycling ”, marginalizing those with traditionalist orientation, which tend to be older people with lower IT and technology affinity (Sociovision, 2018) and cycling for leisure. It might be that the stratifying force on new mobility systems relays on adaptation to the new technologies, which the traditionalists might not follow.

The uneven distribution can lead to complaints about public resources being oriented to transportation systems that traditionalists do not use. Reciprocally, in Strasbourg, non-motorized interviewees feeling socially excluded perceived BSS being oriented to the rich and not for the poor, and not targeted at those in need. Potential political impacts could include a decrease in the political acceptance and trust in the government (Ariely and Uslaner, 2017) and the tendency for low acceptance of the system and resistance to approve it or to use it (Wüstenhagen et al., 2007), as well as a possibility of vandalism of the infrastructure. As an extreme analogy, in Chile, people caused damages to the metro in Santiago valued in 300 million dollars. Even though Chile has relatively good macroeconomic figures (efficiency), “if the image of Chile is scratched, an enormous social, cultural, economic and political injustice becomes evident” (inequity) (Zúñiga, 2019).

Moreover, high social status traditionalists in Type III areas (see Table 4) have good access to the system but they do not use it, leading to an oversupply. Oversupply can lead to the same rejection as a feeling of “unfair” use of the public space. A privately owned free-floating service in Munich closed in 2018 due to vandalism to their bicycles because of the uneven use of the public space: “Within a short time, the provider showered the city with bicycles in the summer of 2017, often placing up to 30 of them in one location” (Rau, 2018). Furthermore, as shown in the qualitative assessment, BSS were perceived to be increasing the number of bikes in Strasbourg which presented conflicts with pedestrians in the public space.

The critical situations are Type II areas (see Table 4), in which mainstreamers and precarious are significantly more prevalent than in Type IV areas. This population might be potential users of the system, and decision-makers might focus their attention on them due to the low availability. These areas can serve as potential places to implement new stations, and also to improve re-balancing strategies, such as operator-based relocation strategies, where trucks take bicycles from oversupplied areas e.g. Type III and take them to Type II areas, or user-based strategies by offering incentives to the users as discounts when driving from Type III to Type II areas or a mix of both (Reiss and Bogenberger, 2017).

Implementation of new stations and changing the re-balancing strategies can be performed where the allocation does not satisfy the fairness perception of the disadvantaged population in the distribution or does not fit the ideologies of transport planners and policy makers. If the distribution is to be tailored specifically to underprivileged populations, more stations have to be implemented where these people live and also where they commute, and the re-balancing strategies user- or operator-based should be planned so that the residential blocks of the underprivileged population have at least one bicycle close to them the most of the time. Moreover, in terms of access to opportunities, we found that in Munich the equity index is negatively correlated to the distance from the city hall, which shows distance constrains underprivileged people’s use of the bike-sharing system. Therefore, if the goal is to increase the usage and thus, the availability among this population, electric bicycles might be a suitable option. Another approach can be serving all social groups equally. In this approach, stations and re-balancing strategies have to focus on Type I and Type II areas, inserting more bicycles or taking them from Type III and Type IV areas until there is not a group living significantly
more in Type I and II areas than in Type IV, and Spearman’s coefficients are positive between in all the groups and availability.

A remaining question is whether cities should bother providing access to BSS when the motivation to use it is virtually nonexistent (e.g. Type III areas). This might happen according to the preferred distribution rule(s). For example, if we want to follow primarily an equity rule in the system, we might implement stations and focus on re-balancing strategies where underprivileged people live. If the infrastructure is not being used, user-based discounts can be applied not only in the drop-off but in the pick-up. If the main value of the targeted population is tradition, educational workshops can be useful to teach them how to access technology. Electric bicycles might also be a good option, so traditionalists see the system as convenient as driving. The qualitative investigation revealed that the population of NMH in Strasbourg had an abundantly positive impression of BSS mentioning several positive aspects and only a single negative aspect to BSS. Furthermore, several participants who had not used BSS mentioned their willingness to become users.

Regarding the access of opportunities, we found that in Munich the equity index is negatively correlated to the distance to the town hall, which shows distance constrains for underprivileged people using the bike-sharing system. Therefore, if the goal is to increase the usage and thus, the availability among this population, electric bicycles might be a suitable option.

Knowing that the demand is greater where progressive people live means that market orientation for the implementation or expansion of new systems can focus on this population. However, targeting milieus to make BSS more attractive could be argued as meeting a psycho-social need. This approach can be assessed as fair when efficiency is the targeted distribution rule. Media, political parties, ministries, unions, churches, and associations use similar approaches to identify potential followers, as well as for product development, and market positioning (Sociovision, 2018). For instance, two luxury automobile makers have used milieus to position and to segment their markets (Barth et al., 2017). Public transport and shared mobility could compete with private autos by doing the same, and carry out further research “beyond sociodemographics”.

Moreover, this research presents similar results as a study carried out by Sinus-Milieus® from an online survey funded by the Federal Ministry of Transport and Digital infrastructure in Germany (Sinus Markt und Sozialforschung GmbH, 2019). They found that cosmopolitan avant-gardes and performers are associated with above-average usage of BSS, whereas, traditionalists and precarious people use BSS at a rate below average.

Another particular strength of this study is the selection of HBSS as a case study. Regarding the type of BSS, few studies have dealt with HBSS (Albiński, Fontaine and Minner, 2018). Chen et al. (2019) is one of the only studies which assessed the accessibility to the hybrid system in Tampa, United States. Moreover, Hirsch et al. (2019) suggested the neighborhood level as a spatial unit for further research on FFBSS, and we considered an even lower spatial level: residential blocks. Finally, Reynaud et al. (2018) stated that only a few studies focused on the availability of bicycles. We developed a new concept of bikes availability that includes different types of BSS, considers a typical desirable walking distance to access the system, and also focuses on real access to the system by having at least one bicycle available. We could not include the temporal component due to the lack of long-period data availability of the observed demand.

According to the concept of accessibility (Geurs and Van Wee, 2004), four main components shape accessibility: 1) land-use, 2) transport, 3) temporal and 4) individual. Our paper is one of the few considering a spatial fairness assessment that includes the transport, land-use, and individual components. For the land-use component, we considered opportunities at the destination of a trip, such as residential locations and opportunities at the destination such as jobs, shops, healthcare, social and recreational facilities. The individual component is the needs and opportunities of travelers, which we included as social status and basic values. We did not include the temporal component due to the long-term data availability of the observed demand.

6. Conclusions

How fair is the allocation of the infrastructure of a bike-sharing system? Policy makers, stakeholders, transport planners, and the general public have now available 1) the perception of a group of the underprivileged population about BSS, and 2) a quantitative methodology to identify which distribution rule(s) the infrastructure of a bike-sharing system follows and which social groups are spatially advantaged or disadvantaged by it. If they consider the system unfair, the implementation of new stations, and user- and operator-based strategies can be used to refocus on the target population.
Non-motorized households feeling socially excluded rarely talked about cycling at all. They perceived that BSS present a spatial conflict with pedestrians and are oriented to students and the rich rather than those who need it the most.

The quantitative assessment was carried out in a HBSS in Munich. Results show that the system follows the spatial efficiency and equity rules because the higher availability is in areas where privileged and underprivileged people live. Moreover, it is also efficient in terms of the supply being more accessible where the observed demand is higher. Surprisingly, availability was not oriented to the social status but rather to basic values of progressive vs traditional. This result is complemented by a statement in the interviews that BSS serve mainly students.

Is this system fair? This depends on the subjective perspective. For some, it might be fair because where there is high demand, the system presents high availability. But for others, it might be unfair, because BSS do not fulfill the needs of the traditional population or it should be exclusively oriented to the underprivileged who do not have access to their own vehicle. It also might be unfair to some who believe the whole service area should cover all blocks equally. And maybe for others, the money invested in BSS should be used to improve conventional cycling infrastructure.

The two split perspectives proposed by Lucas (2019) appear to be mutually exclusive but after including marketing, education, proper infrastructure planning, design, and re-balancing strategies, BSS can be efficient and at the same time practical, simple to use, convenient (as stated in the qualitative approach), and accessible for those who might need them the most.

Further research can be oriented to carrying out a qualitative and quantitative approach in the same city or applying them to more case studies. Interviews can be carried out asking specifically about the perception of spatial fairness on BSS to privileged and underprivileged populations. The approach in Munich can be extended to compare the population inside and outside the service area and to more types of BSS in the city.

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Author Contribution Statement

The authors confirm the contribution to the paper as follows: David Duran-Rodas: conceptualization, methodology, software, verification, writing, visualization; Dominic Villeneuve: conceptualization, methodology, software, writing, visualization; Francisco Camara Pereira: supervision, conceptualization, methodology, writing - review; Gebhard Wulfhorst: supervision, writing - review & editing, visualization.

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