ABSTRACT
Spatial relations among urban elements (buildings, streets, etc.) constantly affect the quality of urban spaces, creating more or less livable cities. The study of urban form has been a way of objectively quantifying such relations to understand their dynamics. Urban livability is the ability of urban spaces to fulfill the expectations of its inhabitants for wellbeing and quality of life. Measurable spatial patterns underlie the emergence of livable cities. Still, few researchers have considered if and how these patterns affect socioeconomic conditions across spatial scales. This paper explores the relationships between indicators of socioeconomic livability and cross-scale patterns of demographic and morphological densities within the Metro Vancouver (MV) region (Canada). Indicators of accessibility, social diversity, affordability, and economic vitality were quantified and compared among five population density clusters composed of 3450 census dissemination areas (DAs) in MV. Morphological indicators of intensity, centrality and diversity were aggregated at the DAs using spatial network analysis with five radii from 400 to 4800 m. Socioeconomic indices were regressed on urban form variables to assess the importance of the built environment on predicting livability-related qualities. Overall, indicators of the intensity of urban form were the most significant to predict the socioeconomic metrics.

POLICY RELEVANCE
Policies that aim to solve urban issues should consider nonlinear relations among variables. In the case of MV, indicators of accessibility, social diversity and economic vitality are directly correlated with each other and inversely correlated with affordability. Medium to high-density zones presented a fair equilibrium among the different livability qualities analyzed. Attributes aggregated with the 4800 m radius were highly important to predict the livability qualities within a 400 m radius, which potentially means that urban interventions may affect the livability of spaces not immediately close to them. A higher density of buildings with moderate height distributed among parcels with distinct sizes...
can potentially have a positive impact on economic vitality and housing affordability. The intensity and diversity of the tree canopy was important to predict active accessibility and social diversity. The inclusion of spatial diversity and network centrality measures on urban planning and design practices potentially foster more livable densification processes.

1 LIVABILITY AND THE BUILT ENVIRONMENT

Cities are complex systems composed of a large number of interconnected elements. Relations among the physical parts of these systems—blocks, plots, streets, buildings, trees, trails, furniture, etc.—are constantly changing and reshaping urban life. Spatial patterns of urban form can be identified from relations between the physical parts of cities. Such patterns affect the livability of urban spaces. Although there is no consensus over an objective definition of urban livability, it can be generally defined as the ability of cities to fulfill expectations of its inhabitants for wellbeing and quality of life. Since urban form is a consequence and a driver of urban life at the same time (Holanda 2013), urban livability is also dependent on urban form. According to Scarth (1964), livability is essentially a property of the physical environment—also an assumption of this paper—and densification should be designed to not disturb the livability of residential units. Thus, it is important for decision-makers to understand how policies that affect urban form (such as maximum allowed densities, spatial or land-use requirements for urban developments) will also affect the livability of spaces. Furthermore, the higher complexity of large metropolitan areas poses the challenge of cross-scale interactions when urban form patterns of different scales affect distinct (and sometimes contradictory) qualities.

Relations between density, livability and urban form have been intensively explored. Most researchers refer to density as a synonym of population density (the intensity of people living or working in a certain area), but it can also mean morphological density (the intensity of the built environment in a certain area). Higher population densities have been linked with economic vitality due to the intense movement of people (Montgomery 1998), improved health (Carlson et al. 2012) and lower greenhouse gas (GHG) emissions (Senbel et al. 2014) as a result of better walkability. However, high population and building density might surge housing costs (Voith & Wachter 2009), increase the susceptibility to spread diseases as a result of agglomeration (Florida 2020) and diminish the sense of human scale (Sim & Gehl 2019). Compact and dense urban design has been widely acknowledged as an effective planning tool to decrease cities’ overall carbon footprint while providing accessible amenities to urban dwellers (Senbel et al. 2014). Nevertheless, such design decisions may come with a cost of urban overpopulation, less green space per capita, traffic pollution, etc.

In order to find balances between distinct aspects of urban livability, it is relevant to understand mechanisms by which different configurations of density indicators—population density, building density, tree canopy density, etc.—and other attributes of the built environment affect various socioeconomic qualities. This paper is focused on the social and economic dimensions of livability. It investigates relations between densities of the built environment (based on metrics that describe the concentration of entities within a spatial scale, such as density of people, dwellings, buildings, floors, vegetation, parcels, floors and bedrooms) and indicators of four socioeconomic qualities of livable cities:

- accessibility
- social diversity
- affordability
- economic vitality.

The case study of the Metro Vancouver (MV) region of Canada is presented. The analysis is in two parts. The first section is focused on relations between clusters of population density and livability indicators in order to understand how densification processes might affect such qualities. It was
found that population density enhances those qualities up until a certain threshold (around 3000 people/km² in the case of MV). Above that, denser spaces start to become highly unaffordable when compared with lower density areas. The second analytical section focuses on the importance of spatial density (or intensity) of the built environment across multiple scales for predicting the socioeconomic indicators, in contrast to spatial diversity and centrality. Indicators of intensity of the built environment were more relevant to predict the qualities analyzed when compared with indicators of diversity and centrality.

The idea that livability can be assessed by urban form indicators is backed by the literature. Szibbo (2015: 32) highlights morphological attributes related to livability such as population density, diversity of land use, availability of open spaces, walkability and affordability. She defines urban livability as:

as a general measure of comfortableness, ‘neediness’ and suitability, including freedom from intrusion. It specifically outlines ‘livability’ as the ‘suitability of a place for comfortably meeting all of one’s daily and long term needs and desires’.

Ahmed et al. (2019: 166) mention that livability varies from place to place due its dependency on ‘community-specific values’, but claim that features of livability can be assessed by both environmental and personal subjective characteristics. For example, the meaning of livability in the US is closer to quality of life and wellbeing, but in the UK, it is more related to cleanliness, safety and greenness. In contrast, Ghasemi et al. (2018: 383) clearly define boundaries between objective and subjective dimensions of livability by distinguishing them from the idea of quality of life:

quality of life is an abstract (subjective) theme pertaining to the general wellbeing of individuals (Bérenger & Verdier-Chouchane 2007); while livability is defined as objective conditions in which social; economic; physical; and environmental requirements are fulfilled to provide the long-term comfort and wellbeing of the community.

The analysis of socioeconomic livability in the present paper is backed by Ghasemi et al.’s (2018) definition. This research focuses specifically on how social and economic conditions of the concept interrelate to the physical structure of the built environment in order to provide comfort and wellbeing for the community. Specific qualities of the livability concept are recurrent in the literature and were used to back the definition of livability adopted here. Overall, livable urban places should facilitate access to economic vitality and social diversity (Smith et al. 1997), while remaining affordable (Maschaykh 2013) and supportive of health and safety for residents and visitors (Lihu et al. 2020).

Although ‘comfort’ and ‘wellbeing’ are subjective concepts, objective indicators of urban form are especially useful to compare or predict scenarios in terms of the urban qualities they potentially generate. Such analysis holds the potential to support urban form policies and the practice of urban design since morphological attributes are present in most urban planning and design codes and can be defined in the early stages of the design process.

However, the concept embraces multiple dimensions of urban life and thus it demands a relatively large set of indicators to be analyzed, especially considering the complexity inherent to all urban systems. One way to approach this intrinsic complexity of the city is by considering multiple spatial scales in the analysis (Bourdic et al. 2012). The study of cross-scale interactions enhances the predictability of complex systems since it helps to account for spatial nonlinearities (Peters et al. 2004). Machine learning models (such as neural networks, random forests, agent-based analysis, cellular automata, etc.) can also be used to model complex spatial systems accounting for nonlinear effects of the built environment on local society, economy and environment. Such models have been successfully used to predict or classify highly subjective aspects of places, such as the beauty (Seresinhe et al. 2017), perception (Dubey et al. 2016) or meaning (Ros et al. 2016) of places. For the MV case study, a machine learning model was applied to find nonlinear relations between attributes of the built environment aggregated across multiple spatial scales and socioeconomic indicators of livability.
Another way to consider urban complexity is by using high-frequency data scraped from the web (Batty 2018). As interactions are constantly happening in complex systems, the highly interconnected urban elements are constantly changing and adapting through local interactions. Traditionally, the consideration of this fast adaptive character was limited by the little availability of reliable data. Now, data from social networks and classified advertising pages have been used to research urban systems by taking into account their intrinsic complexity. For this case study, high-frequency information from housing and job listings webpages was combined with traditional census data.

This paper explores socioeconomic dimensions of a vision of urban livability that is backed by objective conditions (Ghasemi et al. 2018), as urban form is an objectively measurable aspect of cities. Even though a degree of urban livability might be impossible to quantify, indicators can measure the progress of cities towards specific visions of it. This study addresses livability from a spatial perspective based on the assumption that relations among the physical parts of the city can support or hinder urban livability. A broader vision of this spatial character of livability can be further decomposed into spatially quantifiable qualities.

The paper is structured as follows. Sections 2.1–2.4 summarize the concepts and indicators from the literature for the four above-mentioned socioeconomic qualities of livable cities. Non-morphological indicators of accessibility, social diversity, affordability and economic vitality (dependent variables) were spatialized and quantified according to the methods explained in Section 2.5. Each quality is then represented by an index composed of normalized indicators. Such indices were then used to compare different density zones within MV (Section 3.1) and were later regressed on morphological indicators of intensity, diversity and centrality (described in Table 2) aggregated across multiple spatial scales (Section 3.2). The results and implications for policy guidelines are discussed in Section 4, and conclusions are presented in Section 5.

2 SOCIOECONOMIC LIVABILITY

The four main elements that embrace social and economic dimensions of urban spatial livability are shown in Figure 1. According to Ducas (2011: 147), ‘it is essential that the definition of livability consist of factors that are universally agreed upon and non-negotiable’.

As cities are complex systems, these qualities are directly and indirectly interrelated by constant nonlinear feedback loops. Spatial indicators themselves are not sufficient to define if a place is livable or not. Nevertheless, they might provide a way of understanding which attributes support or hinders the livability of certain places.

MV is one of the few cities in North America that is constantly assigned high livability rankings. The city is bounded by mountains and waterfronts, but these features limit greenfield densification processes. However, despite being highly ranked, it presents serious socioeconomic issues that affect certain aspects of livability that might not be captured by such rankings. Population density is highly concentrated around the central business district and a shortage of housing supply contributes to affordability and homelessness crisis. Density is mainly concentrated along transit corridors. However, there is still room for transit-oriented densification (especially in the northeast side) (Figure 2) that should address multiple socioeconomic aspects of livability discussed in this paper, especially the housing affordability crisis.

In order to assess relations between attributes of the built environment and livability, each quality was represented by an index composed of normalized indicators represented in Table 1. In order to understand how urban livability is influenced by morphological factors, such indices were then used to compare different density zones within MV (Section 3.1) and were interpreted as dependent variables (Table 1) in a regression model (Section 3.2) along with the explanatory variables representing intensity, diversity and centrality of urban form (Table 2).
Figure 1: Social and economic qualities of spatial livability.

Figure 2: Population density (census dissemination areas—DAs) and the regional transit network in Metro Vancouver (MV).
2.1 ACCESSIBILITY

Associations between spatial accessibility and other qualities of urban livability have been widely studied in the literature. ‘Accessibility to essential services, such as employment, education, health care, and recreation, is a key component of livability’ (Ducas 2011: 20). High accessibility usually means greater vitality and walkability. It has been linked to better quality of life and health (Carlson et al. 2012; Frank et al. 2010). Transit-oriented developments policies usually increase urban livability since they significantly increase spatial accessibility of communities (Murakami 2010).

Accessibility has been a central concept in quantitative studies that relate urban form to social behavior. Some approaches quantify it based on how much time is needed to reach a certain number of destinations, others based on the proximity of elements along the street network (intersection density; street to intersection ratio; proximity to services). Some non-morphological indicators of accessibility are: frequency of public transit, travel demand, counts of pedestrians and bikers along streets, and mode shares. Given that several studies have demonstrated that dwellers of neighborhoods where people drive more seem to have a poorer quality of life (Frank et al. 2010), active transportation mode shares (walk, bike) and frequency of public transit were analyzed as non-morphological indicators (dependent variables) of accessibility for the MV case study (Figure 3).

Some morphological approaches rely on an abstraction of the street network to assess potential movement patterns. Hillier et al. (1993) claim that the configuration of the street network is the main driving force behind pedestrian movement in urban settlements. The extent to which this configuration can predict such movement flows is what they call ‘natural movement’. Hillier et al. propose to decompose spaces into smaller elements to assess the topological relationships among them. By dividing the street network into a series of straight axial lines, it is possible to derive a network graph based on the interconnectivity of these lines. Each axial line is represented by a node in the network, and the intersections between axial lines become the links between
such nodes (Figure 4). Network centrality measures calculated based on this technique have been found to be correlated with pedestrian movement (Hillier & Iida 2005), walkability (Koohsari et al. 2016), and bikeability (Liu et al. 2016; Manum 2013).

Centrality measures commonly calculated are: closeness centrality, which measures the proximity of nodes to the network as a whole and highlights central places in the system; and betweenness centrality, which measures the overlapping of shortest paths among nodes and highlights the main transportation corridors of the system (Figure 5). Recently, other network measures have been applied to the study of street networks, such as eigenvector (Agryzkov et al. 2019), hits and Katz centrality (Akbarzadeh et al. 2018), which measures the influence of nodes in the overall network.

Accessibility can have negative effects on other livability qualities, such as affordability or environmental comfort. Diversity is a quality that might help to mitigate some of these negative externalities of accessibility. A higher diversity of dwelling types or plot shapes, for example, tends to make urban land more affordable (Marcus et al. 2019; Talen 2008). Talen (2008: 115) states that, ‘housing mix is needed to ensure that social mobility does not require geographic mobility’.

2.2 SOCIAL DIVERSITY

Social diversity is the quality of being composed of different people. Places can be socially diverse based on its composition of ages, genders, income categories, etc. Jacobs (1961) was one of the
pioneers in identifying morphological indicators of livable neighborhoods, and diversity is in the core of her ideas. Jacobs indicates four conditions for diverse vibrant cities: diversity of functions at different times of day and night; short urban blocks; diversity of buildings, in terms of ages and forms; and a good concentration of people and buildings (150–151). According to Jacobs, ‘big cities are natural generators of diversity’ (145), and the diversity of land uses is the upholder of urban civilization itself. Furthermore, diversity also supports a set of urban qualities, such as safety, vitality, economic activity and public contact (144). The more diverse a city is, the more diversity it generates. This natural generation of urban diversity should be stimulated and not constrained by forces that shape the character of urban spaces, such as governments and developers. Netto et al. (2012) found correlations between pedestrian movement and the morphological indicators pointed by Jacobs. Sung et al. (2015) also provide statistical correlations between Jacobs’ morphological patterns and pedestrian activity, finding that Jacobs’ conditions of diversity play a key role in pedestrian activity. De Nadai et al. (2016) also confirm Jacobs’ theory based on the tracking of mobile phone data.

Diversity plays a key role in the livability of spaces. Rastegar et al. (2014) interviewed residents of cities in Malaysia and found that a significant number of residents think that diversity is a critical element of the area’s livability. Rastegar et al. also point out that ‘both diversity and accessibility are the effective parameters to have a livable area’ (373). Rosner & Curtin (2015: 32) suggest that ‘mixed-use and dwelling density are perhaps the most important of the four individual parameters in terms of their contribution to the overall livability of the built environment’. Ruth & Franklin (2014: 22) point out how diversity is a character that makes systems more resilient and thus more livable, but this same character is also one of the main reasons why it is so difficult to grasp a global definition of urban livability.

Thus, even though there is this assumption that morphological diversity leads to social diversity, authors point out the challenges in prescribing a set of defined urban characteristics that enhances diversity. Talen (2008: 194) summarizes the difficulties in defining normative goals for diversity. Even though ‘attention to design seems to be particularly relevant in areas struggling to hold on their diversity’, it is actually impossible to have a precise design plan that is able to maintain the diversity of a community in the long run. The diversity mentioned by Jacobs is a result of spontaneous and voluntary interactions among individuals. In order to maintain the character of cities as natural generators of diversity, a certain degree of spontaneity is necessary, so that each urban settlement organizes itself around its own local needs. Thus, there is no such thing as a global prescription of what should be the form of diverse cities and neighborhoods. Different societies at different times have different needs. For the analysis of MV, four non-morphological indicators (dependent variables) of diversity based on census data were analyzed: diversity of education degree, of ages, of income category and of ethnic origins (Figure 6).

Accessibility and diversity encompass a social dimension of livability. As these urban qualities are intrinsically interrelated, diversity is also related to the urban economy. Marcus (2010: 32) also found correlations between accessibility, diversity and land price reinforcing that social and economic effects of space are affiliated:

\[
\text{urban form generates variations in spatial accessibility and diversity with direct effects on social accessibility and diversity, which are possible to measure, whereby, in turn, it is possible to measure variations in urbanity as a socio-spatial category.}
\]

### 2.3 AFFORDABILITY

Affordability means the quality of a place to be financially affordable to live for the majority of citizens. It has become a significant issue in most big cities across the world. Specifically, in MV, households have increasingly been priced out of the ownership market for the past years, which also increased the demand for rented housing (Coriolis & Wollenberg Munso 2019). Authors have found significant correlations between the configuration of spatial networks and land price (Chiaradia et al. 2013; Marcus et al. 2019). Generally, there is a high demand for living in central places and a small supply of buildable land. Marcus et al. (2019: 14) argue that, ‘the reflection of relative location in the housing market is causal, not only correlational’.
Studies have been using multiple spatial variables and machine learning models to predict housing prices (Chen et al. 2017; Yoo et al. 2012). Chen et al. (2017: 278) predict housing price based on ‘district characteristics, transportation infrastructure and neighborhood amenities’. Yoo et al. (2012) perform a similarly successful, but more detailed, analysis based on the distance to urban amenities, such as schools, parks, etc.

However, indicators of housing affordability should consider not only the cost of buying or renting a piece of land, but also how it relates to other socioeconomic aspects. Stone (2006) explains that housing affordability is not a characteristic of housing per se, but a relationship between the cost of housing and people’s income. Building maintenance, taxes and capital costs are other factors that can affect the financial accessibility of urban housing and some of the reasons why it is problematic to discuss affordability solely based on land price (Leishman & Rowley 2012). The ratio of a household that spends more than 30% of its income on housing and building maintenance costs is measured by the census of the population in Canada (Statistics Canada 2016), and was considered as a non-morphological (dependent) indicator of affordability in this research.

The availability of high-frequency datasets tends to facilitate the assessment of housing costs, and thus of affordability, more accurately. Boeing & Waddell (2017) used 11 million posts scraped

Figure 6: Social diversity indicators in Metro Vancouver (MV) (see Table 1).
Note: Data were aggregated within 400 m from the centroids of dissemination areas (DAs).
Data source: Statistics Canada (2016).
from Craigslist, a classified advertising webpage popular in North America, to contrast the rental housing markets in different US cities. Such fine-grained data enable an assessment of urban affordability that allows decision-makers to better adapt their decision to the constant adaptations intrinsic to the urban dynamics. For the analysis of MV, more than 200,000 real estate rental posts were collected and cleaned in an attempt to measure housing affordability. Census data were also used to consider land market value and maintenance housing costs. Figure 7 displays the non-morphological affordability indicators (dependent variables) analyzed at the DA level.

2.4 ECONOMIC VITALITY

Most of the value of a land is not given by the material estate of the property itself, but by its location. The vitality in the vicinity of a property, in terms of urban life, also tends to affect land prices. Economic vitality means the capacity of a place to facilitate the exchange of small-scale goods and services generating local wealth and jobs. Vitality is frequently linked to urban livability. Rastegar et al. (2014) state that vitality in streets is a prerequisite to create livable urban environments. Cui & Mao (2018) claim that vitality is an indicator of a city’s livability.

Figure 7: Affordability indicators in Metro Vancouver (MV) (see Table 1).
Note: Data were aggregated within 400 m from the centroids of dissemination areas (DAs).
Data sources: Craigslist (2020); Statistics Canada (2016).
Montgomery (1998: 97) indicates that density and mixture of uses are essential ingredients to generate urban vitality: ‘Vitality is what distinguishes successful urban areas from the others.’ Jacobs (2016) also mentioned the role of cities as generators of wealth and indicated urban form attributes that might contribute to this vitality, such as block size and mixed use. Long & Huang (2017: 1) analyzed some of the urban form attributes mentioned by Jacobs and found, ‘that these urban design indicators have a significant and positive relationship with levels of economic vitality for cities at every administrative level’.

High-frequency data about where and when jobs are located help to compare different urban regions in terms of their economic vitality. Job listings webpages have been proven to be a good resource for this type of urban analysis. Mayaud & Nuttal (2019) gathered around 5000 job posts for Vancouver, Portland and Seattle to evaluate disparities between the accessibility to jobs on different income groups. Posts from Craigslist and Indeed, a popular job listings webpage in North America, were used as non-morphological indicators of affordability and vitality, respectively, for the analysis of MV. Data from the census and BC Assessment (2019) on land use and employment rate were also used. Figure 8 shows the economic vitality indicators analyzed.

Figure 8: Economic vitality indicators in Metro Vancouver (MV) (see Table 1).
Note: Data were aggregated within 400 m from the centroids of dissemination areas (DAs).
Data sources: Census (2016), Indeed (2020), BC Assessment (2019).
2.5 MEASURING LIVABILITY AND URBAN FORM ACROSS SCALES

Morphological attributes have been frequently used as indicators of urban qualities. Methods in machine learning that grasp some of the non-linear relations between form and character might help one to understand the effects of urban form on human behavior and bridge the gap between humanistic and positivistic urban studies. A broad vision of socioeconomic livability defined as the ability to facilitate access to diversity by remaining affordable and economically lively can be decomposed into spatially measurable qualities to assess which attributes of the built environment affect urban livability. This paper is focused on finding spatial attributes of the built environment that correlate with social and economic indicators.

The analysis was divided into two parts: (1) Section 3.1 shows a clustering analysis aiming to assess to extent to which large-scale density clusters (aggregated at 4800 m radius) perform in terms of local (400 m) livability qualities; and (2) Section 3.2 describes a statistical analysis to find which morphological attributes aggregated at multiple scales (Figure 9) can influence local livability qualities. The non-morphological livability indicators (dependent variables) (Table 1) were used in both analyses. Data were aggregated at a 400 m radius from the centroid of each DA (the red network on Figure 9) and summed into indices according to the metrics described in Table 1. Simpson and Shannon indices were applied to calculate the diversity of categories. Indicators were chosen based on the literature about urban form and livability and on the availability of clean datasets (Table 1).

Morphological attributes at the surroundings of spaces tend to affect the behavior of urban dwellers and passersby. Although a relatively large body of the literature applies spatial network analysis to aggregate data that potentially represent behavioral patterns (Frank et al. 2017; Manum 2013), there is no consensus over a defined set of parameters (such as radius or distance-decay function) to which such attributes become more or less relevant to assess livability-related qualities. For the statistical analysis (Section 3.2) the indices (as described in Table 1) were regressed on the explanatory variables of urban form (as described in Table 2) aggregated across multiple spatial scales (as exemplified in Figure 9) to understand the extent which morphological attributes are able to predict and thus represent such qualities. Attributes of intensity, diversity and centrality were analyzed (Table 2).

Figure 9: Network buffer radii for a sample dissemination area (DA) in Vancouver.
Data sources: Census (2016); OSMF (n.d.).
To understand how different density zones perform in terms of socioeconomic livability, DAs with a minimum density of 300 people/km² were clustered into five density categories using the Jenks natural breaks method (Chen et al. 2013). To maintain the spatial continuity of clusters, the breaks were based on the average density within 4800 m from each DA and not only on the density of the DA itself.

In order to assess contrasts between different densities and spatial relations between form, society and economy, non-morphological indicators were aggregated at 400 m radius into four indices (dependent variables) representing local qualities of social and economic livability (Figures 10 and 11). To compare the performance of each density group in terms of non-morphological indicators, the average index of each cluster was calculated (Figures 12 and 13). Results were normalized between 0.2 and 1 for visualization purposes. Figure 13 indicates the livability indicators on each density cluster from the lowest density cluster (0) to the highest (4). The blue bars represent the number of DAs in each density category. DAs within the second lowest density category are the majority.

Accessibility, diversity and vitality indicators are correlated with population density and among themselves. Affordability is inversely correlated with density and to the other indicators. Higher densities seem to support these three aspects of urban livability whereas lower densities also present low accessibility, diversity and vitality. Lower densities are more affordable in contrast with higher density clusters. The highest density cluster performs well in almost all indicators, except for age diversity, rent price/ft² and population that spends more than 30% of its income on rent.

Accessibility rises as density increases, potentially because people tend to walk more in denser areas, and investments in frequent/rapid transit are planned in conjunction with densification.
processes. On average social diversity is lower on medium-density clusters. It is possible this is because it was hard to find spatial patterns for the educational diversity indicator (Figure 6). Affordability and vitality being inversely correlated confirms the findings from the literature that the housing market is fairly efficient in pricing neighborhood amenities.
Relationships between accessibility, vitality and affordability seem to corroborate with the hypothesis that accessibility tends to generate vitality and increase costs, thus diminishing housing affordability. Medium to high densities (clusters 2 and 3 in Figure 13, around 2500 inhabitants/km² on average) tend to balance different aspects of socioeconomic livability.

Figure 11: Indices mapped at the dissemination area (DA) level.
Note: Yellow represents the highest and purple the lowest values.

Figure 12: Map of Metro Vancouver (MV) showing the location and density range of each cluster.
Figure 13: Density clusters in Metro Vancouver (MV).  
Note: Left-hand scale = number of dissemination areas (DAs) in each cluster; and right-hand scale = calculated livability index score for each quality.

Figure 14: Prediction results for the testing set.  
Note: Scatter plots compare the actual value of each index (x) and the value predicted by the model (y).
3.2 PREDICTING LIVABILITY FROM URBAN FORM

Random forest is a machine learning method that uses multiple decision trees to improve predictive performance while avoiding overfitting (Ho 1995). It has been successfully applied to predict livability-related qualities (Sarram & Ivey 2018). A random forest model was trained on 80% of the dataset to predict each index based on urban form attributes. All relations analyzed had $p < 0.05$ using linear ordinary least squares regression. The importance of each attribute was assessed using the Gini importance index. Figure 14 summarizes the predictions of the 20% testing set.

The Accessibility and Vitality indices were the most accurate predictions. Figure 15 represents the sum of the importance index for all the livability predictions broken down by type of morphological attribute (density/intensity, diversity or centrality), by the attribute itself, by the radius in which was aggregated (400, 800, 1600, 3200 or 4800 m), and by the type of distance-decay function analysed (flat or linear).

Overall, morphological indicators of intensity had the most statistically significant correlation with the indices, especially parcel area, number of rooms and number of dwellings. Centrality indicators were highlighted by the model, which means that the influence of certain streets in the regional network were important for local qualities. Among the diversity indicators, the Simpson index of building age diversity had the highest importance index. In terms of scale, the indicators aggregated at the 4800 m scale were more statistically significant than the indicators aggregated at smaller scales. Indicators aggregated with no distance-decay function were more important than those aggregated with a linear distance-decay function.

Although random forests can be deemed as black box models, the analysis of partial dependence plots can help to identify relations assessed by the model (Goldstein et al. 2014). Zhang et al. (2017) used this type of plot to analyze the power of user-generated data from OpenStreetMap. For the analysis of MV, the dependencies of the most important features to achieve the prediction results were plotted (Figure 16).

The plots display the marginal effect of the most important features on the predictions. Figure 16 shows how much the prediction changes when a predictor is changed. Thus, the x-axis represents the independent datasets (urban form attributes) sorted from smallest to largest, and the y-axis displays the change in the predicted result. When $y$ increases as $x$ does, it means that this relationship is positively related, as the urban form attribute ($x$) increases in value, the prediction

Figure 15: Statistical importance of the indicators used for predictions.
Note: Values are grouped by: type of socioeconomic indicator; type of morphological attribute; morphological attribute; aggregation radius; and distance-decay function.
(y) increases as well. Correspondingly, if y decreases as x gets higher, the relationship is negative. *Table 3* summarizes the relations between dependent and independent variables assessed by the model.

The plots confirm some of the results from the literature, such as centrality measures being positively related to economic vitality (Marcus 2010; Martino et al. 2019; Ribeiro & Holanda 2015). However, building age diversity, a feature commonly mentioned as an indicator of affordability and diversity, was inversely related to social diversity and affordability. Parcel area was positively

*Figure 16*: Partial dependence plots.

Note: The x-axis represents the independent variables of each feature from smallest to highest; and the y-axis displays the dependency of the prediction for that section of the independent dataset.
related to affordability and vitality and negatively related to social diversity. While the density of buildings had a positive influence on economic vitality, other density indicators, such as the ‘number of stories’, had a negative impact on affordability. Diversity of parcel sizes was also positively related to affordability. Densification processes should be planned to deal with trade-offs between different effects of urban form.

4 DISCUSSION: URBAN FORM, SCALE AND SOCIOECONOMIC LIVABILITY

Indicators of intensity of the built environment were found to be statistically more significant for socioeconomic livability indicators than indicators of centrality and diversity. This result highlights the importance of considering the socioeconomic effects of urban form when planning urban densification processes. Density is a positive characteristic for generating economic vitality, but it needs careful consideration in relation to other livability aspects. Results from both clustering (Section 3.1) and regression (Section 3.2) analyses show that density can have a considerable negative impact on housing affordability—an aspect usually neglected in global livability rankings. Nevertheless, it is important to bear in mind that relationships between urban form and socioeconomic qualities are bidirectional. This is, if a certain morphological attribute were correlated with a socioeconomic quality, it does not necessarily mean it is causing it. Socioeconomic qualities may also affect urban form.

The same morphological indicator might have distinct socioeconomic effects and it is necessary to balance trade-offs among them. As the density of buildings contributes to economic vitality, parcel diversity contributes to affordability and number of stories had a negative impact on affordability, policymakers and planners in MV might consider a higher density of buildings with moderate height distributed among parcels with distinct sizes. This can potentially have a positive impact on both economic vitality and housing affordability.

Those trade-offs should be carefully discussed with all urban stakeholders. Public consultation and transparency are necessary when planners and designers address such challenges.

The model also revealed that attributes aggregated at the 4800 m radius were more important to predict local livability indices than those aggregated at smaller radius. This result seems to corroborate with the thesis that global attributes of the built environment have a significant influence over local qualities (Hillier et al. 1976). Furthermore, the network centrality indicators were highly important to predict the accessibility index, which also reflects Hillier et al.’s (1976) idea that the configuration of the street network is highly related to movement patterns.

The idea that spatial diversity is related to socioeconomic indicators is commonly found in the literature (Rosner & Curtin 2015; Talen 2008), but still to be examined in depth. For this case study, attributes of morphological diversity were important to predict both social diversity and affordability. The model revealed that building age diversity had a negative influence on predicting social diversity, which goes against the hypothesis that creating a mix of building ages leads to social diversity (Talen 2008: 25).

5 CONCLUSIONS

The research shows that it is feasible to link morphological attributes with livability outcomes. However, the transferring of this knowledge to policymaking may take into account the ease with
which such morphological attributes are affected by decision-makers. Street network and building age indicators are harder to manipulate and it thus should be directed towards large-scale long-term planning processes. The number of stories and parcel area are relatively easy to control in areas that are in their early stages of densification. On the other hand, impervious surfaces and tree canopy indicators are easy to control even in already densified areas. In this case, as parcel area was shown to be a highly important feature to predict affordability, for example, it could be relevant to municipalities or developers to consider how parcel assembling processes may affect the overall urban livability. Further studies could look in more detail at how local-specific densification processes perform among different aspects of socioeconomic livability.

Models hold the potential to support policymaking by assessing the socioeconomic impact of changes in urban form. Intensity indicators were the most important influence on socioeconomic qualities. Intensity indicators are already frequently used in the urban design processes involving density control, maximum footprints, maximum height, etc. However, spatial diversity and network centrality indices are relatively underused. The inclusion of such features on urban decision-making could support design solutions that potentially foster the emergence of livable densification processes.

ACKNOWLEDGEMENTS

This research was not possible without the support from elementslab.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

Data sourced from OpenStreetMap are open data, licensed under the Open Data Commons Open Database License (ODbL n.d.) by the OpenStreetMap Foundation (OSMF, n.d.). Census data are open data, licensed under the Statistics Canada Open Licence (Government of Canada, Statistics Canada 2012). Data sourced from BC Assessment are private and conceded under the Commercial Data License Agreement Number [One (1)] between the British Columbia Assessment Authority and the University of British Columbia.

FUNDING

This research was partially funded by the University of British Columbia.

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