Beyond land use mix, walkable trips. An approach based on parcel-level land use data and network analysis

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ABSTRACT

Land use mix is one of the cornerstones for urban sustainability, in opposition to functional segregation and zoning policies. Land use mix is a prerequisite for urban proximity dynamics, healthier lifestyles and public space vitality. However, methodological shortcomings to its measurement remain and are responsible for the unexpected weak association with pedestrian activity. This study puts forward a novel method to reframe, measure and map land use mix as ‘walkable trips’, a closer approach to its benefits based on functional and spatial complementarity. The method draws on newly available cadastral microdata at the parcel-level that, combined with trip generation rates and network analysis tools, enable a detailed assessment and mapping of potential for walkable trips, as well as a proxy to the spatial patterns of urban vitality, in line with the principle of the 15-minute city. The method is applied to the case of the Madrid metropolitan area.

1. Introduction

Urban planning and policy regulate the distribution of land use and urban activities in space. By doing so, they define the distances that citizens have to travel between those activities, resulting in mobility needs (Wegener & Fuerst, 1999). Short distances encourage walking, while long distances require the use of a private vehicle or public transit. Thus, mixing a diversity of land uses and urban activities has been long considered a strategy to achieve multiple benefits for urban environments that result from the pedestrian activity. The possibility of walking enables a more active, healthier lifestyle associated with lesser car dependence and the reduction of negative environmental impacts. The presence of people on streets has a positive impact on the perceived safety and natural surveillance (Jacobs, 1961), the development of neighbourhood social ties, the sense of community and enhanced local economy (Dovey & Pafka, 2017; Gehrke & Clifton, 2015; Song et al., 2013). Today the emerging principle of the ‘15-minute city’ (Pisano, 2020; Willsher, 2020) insists on land use mix as the cornerstone for urban sustainability.

However, despite half a century of vindication, land use mix remains underachieved. We put forward a new method to measure and visualise land use mix with a threefold contribution. First, land use mix is quantified as a closer proxy to its benefits, understood as the facilitator of walkable trips, or the co-presence of origins and destinations at a walking distance. This measure draws on the notions of functional and spatial complementarities (Hess et al., 2001) and well-consolidated trip generation techniques. Second, this approach to measuring mix is deliberately not relative, as a closer proxy to local urban vitality. Third, this method is based on parcel-level cadastral microdata and network analysis tools that enable to control the conceptualisation and visualisation of land use mix as walkable trips in a flexible, readable and attractive way.

2. Background

Empirical studies on the link between land use mix and active travel rates have been disappointing. Statistical results do not confirm an otherwise quite evident relationship, and this has been attributed to methodological shortcomings, such as data availability, the type of measure or the scale of analysis (Gehrke & Clifton, 2015; Hess et al., 2001).

Crucial first questions are land use categorisation and the very definition of mix. Some have focused on the mix of residential and non-residential uses, while others have recovered the rationalist triad and Le Corbusier’s mantra – living, working and recreation – (Dovey & Pafka, 2017; 2008; 2012; Ye & Van Nes, 2014). With regards to how to quantify land use mix, some authors have stuck to a descriptor of...
each land use relative weight – usually a percentage –, with mixed-use areas considered those with non-pre-
dominant uses representing more than 10% (Dovey & 
Pafka, 2017; 2008; 2012; Ye & Van Nes, 2014). This 
kind of approach does not consider the further implic-
tions of specific land uses, which is a shared short-
coming with more elaborated types of measure. This 
is the case of those measures imported from fields 
like sociology – dissimilarity measures (Cervero & 
Kockelman, 1997) – or ecology – entropy measures 
(Cervero, 1989; Frank & Pivo, 1994) –. The detailed 
analysis of all of these measures of mix for at least 
two land use types shows symmetry (Song et al., 
2013), which invalidates them to represent mobility 
implications. If we imagine two urban areas, one 
with a residential-commercial mix of 80%-20% and 
another one with the inverse 20%-80%, the mobility 
patterns taking place are most probably very different.

Also, questions arise on the scale and extent of the 
geographies that should be considered when measur-
ing land use mix, as the perceived patterns of its distri-
bution may significantly vary when different 
combinations of spatial data sources and scales of 
analysis are used (Cervero & Kockelman, 1997; 
Frank & Pivo, 1994). The use of detailed data descri-
ning land use, avoiding the modifiable areal unit pro-
blem (MAUP), and explicitly considering the scale 
effects on the results, have been generally encour-
ged in the literature (Batty, 2009; Talen & Anselin, 1998).

Addressing some of these concerns, Hess et al. (2001) 
defended the use of a totally different type of measure, 
capable of describing the level of land use 
complementarity regarding mobility. In line with 
transport planning techniques, these authors proposed 
translating all the residential into trip origins and all 
other land uses into trip destinations.

They exposed two notions:

- Functional complementarity, defined by the co-
presence of possible trip origins and 
destinations.
- Spatial complementarity, as long as the distance 
between origins and destinations is walkable.

We draw on these ideas to propose a new measure 
of land use mix as the number of walkable trips.

3. From land use to people on streets: 
walkable trips

One walkable trip is defined by the co-presence of one 
trip origin and one destination at walking distance. 
Previously, the number of origins and destinations 
can be calculated using well-consolidated trip gener-
ation rates (Institute of Transportation Engineers, 
2012; Ortúzar & Willumsen, 1990) – Figure 1. This 
approach goes one step further towards more precise 
weighting, in comparison with previous land use 
mix proposals (Dovey & Pafka, 2017; Pushkarev & 
Zupan, 1975). Then, by comparing the numbers of 
origins and destinations, we can deduce the number 
of walkable trips and the number of ‘unpairable’ ori-
gins or destinations, which constitute an imbalance as 
non-walkable trips and transport demand. The num-
ber of ‘unpairable’ origins/destinations is related to 
the ‘captive demand’ that must use private/public 
transport modes due to the impossibility of walking.

To illustrate this approach, Figure 2 represents four 
urban contexts: a residential-only area (A), a com-
mercial-only area (B) and two mixed-use areas (C & D). 
All land use in monofunctional areas (A & B) creates 
imbalance and transport needs, while there are some 
possible walkable trips in mixed-use areas. However, 
it is worthy of note that areas C & D have the same 
land use types at the same proportion, which means 
that they have similar levels of entropy, dissimilarity 
and other relative land use mix measures. Neverthe-
less, D’s density is twice C’s and these results in 
more walkable trips, potentially more people on the 
streets and a proxy to a higher urban vitality. This is 
an essential advantage of our approach in comparison 
with relative measures of mix.

It is important to note that land use complementar-
ity and the number of walkable trips express only the 
potential derived from the built environment 
configuration. However, many other causes may influ-
ence citizens’ choice of not walking, as developed in 
the long-standing scientific discussion on the impor-
tance of the built environment versus socio-econ-
omic-personal factors affecting walking. This 
misleading opposition was overcome by Ma and Ban-
ister (2006), who distinguished quantitative imbalance 
(land use ratios) and qualitative imbalance (charac-
teristics of the individual, such as age, gender, race, 
income or car ownership), and acknowledged the 
importance of both for modal choices. Thus, our 
approach may be partial to predict actual pedestrian 
flows, but of the greatest relevance for urban planning 
and design.

4. Methodology

4.1. Case study

Madrid Metropolitan Area (MMA) integrates 28 
municipalities, with a total population of 5,557,365 
inhabitants as for 2017 (2018), and a total area of 
193,588 hectares. MMA includes a wide variety of 
urban fabrics, with a diversity of density levels and 
land use combinations (Bataller Enguix et al., 2004). 
Mixed-use town- and neighbourhood-centres coexist 
with residential-only suburbs and specialised central-
ties, resulting in a very diverse caseload of urban tis-
sue samples to illustrate the proposed method.
4.2. Data sources

Cadastral data is available online from the Spanish Cadastral Direction (Dirección General de Catastro, 2017). Its datasets include a full description of built surfaces and land uses registered at the parcel-level, and the official address assigned to each item. This dataset contains many different variables to capture the physical reality (floor area, construction date, maintenance, etc.) and land use (for detailed descriptions, see e.g. Dalmau et al., 2014; Romero et al., 2014).

We have geolocated this database and blended it with the MMA Streetmap, a road-centre line (RCL) network geometry that includes the official names, validated and enhanced to sufficiently represent all possible pedestrian routes. Built on a RCL dataset depicting only one central axis for each street segment, any nuance differentiating ‘sidewalks’ (such as tree shading, lighting and pavement quality or design) needs to be cautiously left out of the picture. However, our metropolitan-scale approach makes this simplification pertinent.

Trip generation rates are adapted from Madrid Home-based Mobility Survey (2014) and the detailed rates by the Institute of Transportation Engineers (2012).

4.3. Data Preparation

Data for individual real estate properties in the cadastral database consists of up to 4,323,486 units in the MMA. This dataset is aggregated at the parcel-level, resulting in a database of 386,224 points that contain the number of properties and total square footage for each land use category.

The cadastral address field is used to geolocate this data, first by looking up the same name at the MMA Streetmap spatial point data for addresses. The unmatched addresses (~20%) are then sent to a public Web Processing Server (CartoGeocoder).

Regarding the network modelling approach, for scope reasons, we choose the Primal Graph Approach (Crucitti et al., 2006; Porta et al., 2006), among all the available approaches to modelling movement in urban space through network analyses (Marshall et al., 2018). This approach uses undirected planar graph edges to represent the street network (streets axes as edges, junctions and dead-ends as nodes). The network edges are built from the RCL map, with corrections to include pedestrian connections like tunnels, pathways and footbridges; using aerial and street-level imagery for validation. The final network consists of 683,068 nodes and 718,240 edges. The network is topologically validated following best practice (Cooper, 2016).

Parcel-level cadastral data, previously converted to origins/destinations, is loaded to the network edges (Figure 3). Calculating and mapping the land-use variables on the street network are decisions in line with our will to visualise land use mix as the trigger of pedestrian travel and the vitality of public space, which is acknowledged as the arena for social interaction in urban environments.

4.4. Network measures

After the network validation, the Reach Centrality measure developed by Sevtsuk et al. (2013) is used to calculate the total number of origins and destinations that can be reached by foot from each network node (Figure 4). Due to computer power limitations, the measure is implemented using NetworkX Python library (2008). The Reach Centrality of a node \( i \) in a graph \( G \) sums the total weight \( W[j] \) of the nodes reachable from \( i \) at a path distance of at most \( r \):

\[
\text{Reach}[i]^r = \sum_{j \in G-\{i\}, d(i,j) \leq r} W[j]
\]

‘Reach’ is a network distance-based cumulative opportunity type of measure (Vickerman, 1974; Wachs & Kumagai, 1973), which represents the sum of opportunities (total number of origins or destinations in our case) within a given distance. The reason to choose this type of measure is its clarity and direct interpretability, which increases its applicability in real-world planning and policy (Geurs & van Eck, 2001; Geurs & van Wee, 2004; te Brömmelstroet et al., 2016).

Its main limitation is the strong impact of the distance threshold. The choice of specific radii for network-based calculations is somehow arbitrary due to the current lack of consensus on the matter (Batty, 2009). However, we have chosen two different walkable

![Figure 1. From land use to walkable trips. Source: Authors.](image-url)
cutoff distances to capture reasonable, relevant limits for human walking: 600 metres (as a standard proxy to a 10-minute walk) and 1200 metres (as a proxy to a 20-minute walk). The literature has considered the 600-metre distance (or 1/3 mile) as a reasonable representative walking distance (Carpio-Pinedo & Gutiérrez, 2020; Sevtsuk, 2014; 2003) since it captures most of pedestrian activity according to empirical studies (Handy & Niemeier, 1997; Pushkarev & Zupan, 1975). The second threshold (1200 m) is a better proxy to consider people with reduced mobility, tests the sensitivity of the approach and the degree of land use imbalance overcome by increasing the walkable distance, and captures the idea that urban spatial network configuration might have different (yet complementary) functioning at local and global scales (an approach to our knowledge initiated Hillier et al., 1986).

4.5. Trip generation

To translate the number of housing units into origins, we use the ratio deduced from the Madrid Transport Authority Home-based Survey (2014). For the other land uses, we calculate ratios from the tables produced by the Institute of Transportation Engineers (2012). The use of the latter is not ideal, as this source is from the USA and considers private vehicles only. A more empirical-based precise adaptation is necessary for more multimodal and complex urban environments (Curran & Clifton, 2015). The ten-category land-use classification of the Spanish Cadastre conditions the approach. However, our trip generation approach (Table 1) goes one step forward in comparison with those reviewed in the literature.

4.6. Spatial-functional complementarity variables

Following the rationale presented in Section 3, we calculate two key variables. First, the number of walkable trips (WT), as previously defined. This absolute, non-relative measure captures the land-use-based potential pedestrian flow per each street segment and is a good proxy to the potential vitality of an area.
Second, we calculate the number of ‘unpairable’ origins or destinations (O/D), as the imbalance (difference) between the number of origins and destinations, with the sign identifying the type of imbalance produced. The higher the number of ‘unpairable’ origins or destinations, the more people with no possibility to walk every day and becoming captive demand of private vehicles or public transit (approximately one motorised trip for every 2 ‘unpairable’ origins/destinations at the metropolitan scale).

4.7. Data visualisation

We have created two sets of maps, one for each distance-threshold: maps 1, 2 and 3 for the 600-metre threshold, and maps 4, 5 and 6 for the 1200-metre threshold. The two distance thresholds spatialise the sensitivity of the approach, showing that the 1200-metre distance results in much more extensive, homogeneous areas.

Each set contains three maps:

- Walkable Trips – Madrid Metropolitan Area (Maps 2 & 5)
- Walkable Trips – Zoom in Madrid city central area (Maps 1 & 4)
- Unpairable O/D – Zoom in Madrid city central area (Maps 3 & 6)

The two sets of maps come with basic definitions and diagrams of the concepts proposed so that the maps could be used as self-explained documents.

5. Results and discussion

A first look at the walkable trip maps confirms that this novel methodology efficiently highlights the most vibrant areas of Madrid metropolitan area, corresponding with central places at different scales (city/town/district/neighbourhood). Among them, Madrid city centre is by far the top area and the prominent metropolitan central place. Maps 2 & 5 clearly show the dense, vibrant centres of other towns in the metropolitan area, while the metropolitan west (low-density residential suburbs) appear with minimum levels of walkable trips.

The results on ‘unpairable’ O/D are less intuitive and thus more surprising. A first remarkable result is the huge difference in absolute numbers between the areas with an imbalanced number of origins and the areas with imbalanced destinations (see Figure 5, where the black line represents perfect balance). The latter represent an enormous

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**Figure 4.** Reach tool example. Source: Authors.

**Table 1.** Trip Generation Ratios. Source: Authors.

| Land use category | Ratio     |
|-------------------|-----------|
| Origins           | Destination |
| Residential       | 3.0625    | Per housing unit |
| Industrial        | 0.005     | Per sq.m         |
| Offices           | 0.019     |                   |
| Commercial        | 0.165     |                   |
| Sports            | 0.017     |                   |
| Show business     | 0.061     |                   |
| Leisure and hospitality | 0.351 |                   |
| Health            | 0.025     |                   |
| Cultural          | 0.024     |                   |
| Religious         | 0.006     |                   |
imbalance in terms of unwalkable trips in comparison with the former. These results deny such a negative impact of large extensions of dense, residential-only areas. Thanks to Spanish Planning standards and guarantees, high residential density typically involves a fair number of destinations in proximity, namely an array of public facilities (e.g. schools and sports centres) but most often local shops too. Looking at the maps (Maps 3 & 6), it is true that extensive areas of ‘bedroom suburbs’ and ‘commuter towns’ are more common than the imbalanced concentration of destinations. However, the areas with a high number of destinations and little origins (large trip attractors, like retail parks or specialised office areas) exist and involve a more significant imbalance in absolute terms than the ‘bedroom suburbs’. Interestingly, the highest levels of imbalance take place in the most vibrant areas (with many walkable trips too), so the two phenomena are not mutually exclusive. The fact that some of the most vibrant, densest areas are also far from balance regarding land uses may relate to the co-presence and sum of locals (walking from origin to destination) and people from other areas walking the first/last mile only.

Further, the connectivity of the network explains why, by increasing the distance-threshold, some locations gain access to a greater number of origins and destinations, while others get stuck (Figure 5).

6. Conclusions, applicability and next steps

This study puts forward a new method to measure and visualise land use mix by explicitly addressing its implications for pedestrian travel and, thus, for public health and urban vitality. As such, this new approach may trigger further research linking the built environment, active travel and public health.

‘Walkable trips’ identify the elements of the street network where functional and spatial complementarity support walking. In terms of scale, the use of parcel-level cadastral data along with the pedestrian network provides an opportunity to consider land use mix at an unseen level of spatial granularity -the street segment-, avoiding boundary biases. Further, the varying window of distance-thresholds helps understand the impact of urban forms and street connectivity patterns on land use mix from the pedestrian perspective.

This approach can be applied by: (a) city and regional authorities evaluating the implications of urban planning proposals; (b) transport authorities and city planners requiring decision-support tools to inform land use-transport coordination policies; and (c) practitioners aiming at improving their projects and designs using cutting-edge, evidence-based spatial analysis. Indeed, the approach can be useful to assess both new development plans and existing urban fabrics.

The first task for future research will be to evaluate the degree of correlation between ‘walkable trips’ and
`actually walked trips` (on-street pedestrian flows) and between the `unpairable O/D` and motorised transport demand. Socio-demographic variables like age, income or employment rates will most likely play a role in the equation (Ma & Banister, 2006). Further, future research could explore different ways to weight destinations beyond their floor area, e.g. considering the popularity and symbolic dimension of places (Carpio-Pinedo & Gutiérrez, 2020). Further research must also evaluate the possibility of using different walking distances for different land-use types, other types of accessibility measures (e.g. betweenness or gravity-type considering distance decay) (Crucitti et al., 2006; Sevtsuk et al., 2013), and other types of impedance (e.g. topological or angular, instead of metric) (Hillier & Iida, 2005). In the future, our approach may consider diverse factors for impedance tuning including footway quality, the perception of safety based on active frontages (Carpio-Pinedo et al., 2019) or topographic heights and slopes (Daniel & Burns, 2018). However, data quality and availability still require further development to address these factors at the metropolitan scale.

**Software**

Python, Pandas, GeoPandas and Numpy were used to prepare the data from .csv sources (dgc minhap), geocode them (calling the GeoCoder server) and perform network calculations along with NetworkX.

QGIS 3.8 was used for data edition, consolidation (Disconnected Islands, Topology Checker), and for mapping.

**Geolocation information**

Projection: EPSG:25830 – ETRS89 / UTM Zone 30N – Projected.
X Extension: 411179.12 – 475951.44.
Y Extension: 4450071.49 – 4509271.72.

**Disclosure statement**

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