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Article

Filling in the Spaces: Compactifying Cities towards Accessibility and Active Transport

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Abstract: Compactification of cities, i.e., the opposite of urban sprawl, has been increasingly presented in the literature as a possible solution to reduce the carbon footprint and promote the sustainability of current urban environments. Compact environments have higher concentrations of interaction opportunities, smaller distances to them, and the potential for increased active mode shares, leading to less transport-related energy consumption and associated emissions. This article presents a GIS-based quantitative methodology to estimate on how much can be gained in that respect if vacant spaces within a city were urbanized, according to the municipal master plan, using four indicators: accessibility, active modal share, transport energy consumption, and a 15-minute city analysis. The methodology is applied to a case study, in which the city of Coimbra, Portugal, and a compact version of itself are compared. Results show the compact layout improves all indicators, with averages per inhabitant improving by 20% to 92%, depending on the scenario assumed for cycling, and is more equitable.

Keywords: urban layout; urban form; urban compactification; sustainability; accessibility; transport energy; active travel; 15-Minute City; GIS

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1. Introduction

Cities are the driving forces of local and global economies, generating over 80% of the world's wealth and consuming a fraction of 60–80% of all the energy produced on the planet [1]. Cities attract people by offering better housing standards, multiple job and interaction opportunities, better education, and higher health standards [2]. As a result, more than 56% of the world's population currently resides in urban areas [3], with a continuous growth trend that calls for new policies for the optimisation of territorial resources (more than 2.2 billion new urban residents are expected by 2050 [4]). Urban areas must be prepared for the future, with clear perspectives on sustainability [5,6]. The agenda includes improving accessibility and overall proximity [7–9] as well as fighting back urban sprawl by promoting a more compact urbanism [10,11].

Urban form is an essential element of urban planning that either can lead towards sustainability or unsustainability [12]. The post-war decades witnessed urban transformations due to technological and economic changes that led to urban dispersion [13]. Rapid transport, road investment, and low rents in city suburbs led to a metropolitan expansion onto suburban low-density areas [14], ultimately creating a lack of continuity and separating areas of housing, industry and offices, retail, and recreational use, i.e., urban sprawl [15–17]. Urban sprawl impacts transport and the environment due to trip distances, traffic pollution, extensive roads, excessive private car use, and low public transport ridership [16,18]. It has also negative social and economic consequences [12,14–16,18,19].

In the pursuit of more sustainable cities, urban compactification and densification policies have been widely promoted and adopted [19–21], as they counteract urban sprawl and provide tentative solutions to accessibility and walkability challenges [10,11,22,23] and avoid countryside urbanization [10,11,23]. A good urban design leads directly to better transport planning opportunities [24–27], and other high-density urban strategies such as mixing land-use, urban diversification, sustainable transport, development of green spaces, and higher population density have been suggested as means of planning for sustainability [20,23,28–31].

Together with efficiency and sustainability considerations, citizens want cities to provide them with a sense of place. "Home sweet home" is a brief sentence that summarises the importance of being able to live in a place that protects us, with the people we love. Leon Battista Alberti in his treatise *La Architettura* [32] compared the city to the house and equally compared rooms to urban blocks and corridors to streets. With this comparison, one could reformulate, following Leon Battista Alberti, for the concept of "city sweet city". To conceive the city as our home, we must get to know it and live it slowly. Slow city, 15-minute city, or an urban space that we can experience and get to know like a large and comfortable home: this is the meaning authors give to the compact city in the third millennium. Knowing built parts, and equally knowing empty parts, means reflecting on how to recreate the compact city. In *L'estetica della città europea*, Marco Romano [33] recalls two entities that make up cities: Civitas, which represents a spiritual entity or population with its desires and with pride of belonging to that specific city, and Urbs, made up of the buildings that create the image of the city. For Urbs and Civitas to cooperate in the formation of what could be called the soul of the city, or the interpretation that inhabitants have given to a certain place, citizens, buildings, and empty spaces must live together and belong to each other. Modernity has untied this union, the creed of zoning denying any value to this blend, and the futurist exaltation of speed and of the machine broke the alliance between man and his ability to design and build spaces, buildings, for himself and for others. In the compact city, habit means living knowing the city well and being certain that one's behaviour ensures the proper functioning of the city.

Modern techniques enable us to measure, interpret, and understand where and how the compact city is interrupted. The use of geographic information systems (GIS), algorithms, and the powerful tool of datafication allows us to deeply investigate those lacerations of the urban fabric that interrupt the relationship of union between the city space and citizens. Investigating the simplest and cheapest way to fill these gaps in space and communication and restore the city to its compact harmony means giving cities back to citizens.

Thanks to social media, modern communication systems, and the Internet, speed is no longer the only value, as one can travel while remaining in the same place, making the once futuristic concept of speed outdated and now replaced by the concept of connection. The compact city does not need fast means of travel but efficient travelling. Efficient public transport and its infrastructure network became more desirable than individual means of transport. Models of interpretation and study demonstrate it: urban sprawl is responsible for the segregation and gentrification that excludes, divides, and opposes citizens to each other. The compact city includes the re-use of spaces within historic cores that exist but are not known because they are not properly valorised, and this constitutes a new way of conceiving town planning.

Powerful possibilities of simulating effects and benefits of the redesign of the city, in the direction of a compact city, allow us to possess effective tools for economic and political strategies. The government of future cities passes through governance of these surveys and these simulations, which are indispensable tools for understanding social dynamics and for making the best use of potential energies of creativity, entrepreneurship, and citizen cooperation. Modelling cities to obtain reliable quantitative predictions is one major step in that direction and a key challenge of the modern world [34,35]. Accordingly, this research proposes one such modelling tool, a quantitative methodology, based on GIS, to estimate the impact that compactification can have on accessibility and active transport. Starting with the city of Coimbra, Portugal, a sprawled city that has expanded in a low-density pattern, and turning it onto a compact version of itself by filling in vacant spaces of the urban fabric while respecting the municipal master plan, quantitative indicators are proposed and evaluated for the two layouts, yielding comparative figures that give a precise notion of what can be gained from the compactification procedure.

It should be mentioned that several studies have argued that, overall, compact urban environments provide better accessibility, encourage public transport, and lead to reductions of transport energy and associated emissions [36–39]. However, to best of the authors' knowledge, the present research one of the first quantitative efforts to measure the effects of compactifying a real city, thus filling an important a gap in the field of urban planning. Other quantitative studies include ref. [10], which relates the degree of compactness with neighbourhood satisfaction, which is a different topic.

Compact urban development is not without downsides, and some positive outcomes such as less traffic, less environmental problems, or social liveability, have been questioned over the past decades [11,40–43], making it all the more important to have quantitative figures, which can help people decide in what way they want their city to develop.

2. Materials and Methods

The proposed methodology pivots on a comparative analysis between the city of Coimbra as it is, henceforth designated simply as "Coimbra" or "real Coimbra", with its compact counterpart, i.e., "Compact Coimbra". That is to say, the urban layout of real Coimbra is compared to a hypothetical, compact layout, in which Coimbra is reorganised by moving residential areas, urban facilities, and job locations from the outskirts onto vacant spaces in the real city, following municipal regulations. The comparison is carried out using four quantitative indicators: accessibility, active transport modal share, transport energy consumption, and the degree by which a city layout can be considered a 15-minute city. In transforming, or redrafting the city, the principle is followed that it should not distort the number of actors in play (inhabitants, destinations, etc.).

2.1. Indicator Motivation

The four indicators above were selected mainly because of their importance for city planning. A brief motivation for them now follows.

2.1.1. Accessibility

Accessibility is a wide-ranging concept, related to urban spatial layout, qualities of the transport and land-use systems, and to economic and environmental goals [44–46]. Providing a binding factor of urban structure key components: people, mobility, and social activities [47], accessibility is being increasingly incorporated into metropolitan transport plans and national planning guidelines [9,48,49]. It is recognised as one of the possible paths to sustainable development: by putting more emphasis on proximity rather than speed, daily living is facilitated without creating a dependency on long distance, fast, and energy-intensive transportation [8,50–52].

2.1.2. Active Modal Share

Active transport, e.g., walking, cycling, requires human muscular input for locomotion, thus providing health benefits, and is non-polluting [53–56]. It is currently one of the main focuses of transport planning also due to energy efficiency, local context, and socioeconomic factors [53,57–64]. Active travel has been strongly promoted worldwide [65–69] as a sustainable form of urban mobility that is also equitable, affordable, and inclusive [70–76]. Strategies that encourage the replacement of short-distance car trips by active travel are becoming more popular [62,77,78], e.g., redesigning streets to accommodate for pedestrian, cycling, and public transport infrastructure [79].

Active modal share is an outcome of those promotional policies but also of planning policies and urban features such as density and mixed land-use [72,79–85]. Albeit active mobility is important to today's urban society [22,86] recognise it to be a striking challenge for contemporary cities, making it important to evaluate to what degree compactification may help in this respect.

2.1.3. Transport Energy Consumption

An individual's transport energy consumption is a product of the travel modes used, i.e., trip distances and frequency, that in turn are directly correlated to the built environment [87]. Consumption from motorised travel is especially impactful, mainly due to greenhouse gas emissions (GHG) but also due to fuel supply issues and urban congestion [88–92]. Measures towards energy conservation and emissions reduction are becoming critical [30,93], and the urban form and land-use policies are powerful tools to achieve them. Since more compact urban forms are associated with lower consumption and emissions, and fragmentary urban forms (e.g., urban sprawl) are associated with higher consumption and emissions [90,92–97], it becomes important to have quantitative estimates of energy consumption for those urban layouts.

2.1.4. The 15-Minute City

The 15-minute city is a contemporary holistic concept for urban planning developed by Carlos Moreno, a modern interpretation of the neighbourhood unit concept and the work of le Corbusier [98–100]. Motivated by chrono-urbanism, i.e., that quality of life is inversely proportional to transportation time [99], it suggests an urban form that enables residents to carry out their daily activities within distances that would not take more than 15 min by walking or cycling [99,101,102]. The aim is not to bring people to activities but rather bring activities to people, in particularly work. It seeks to localise workplaces near people, considering that commuting represents the main and most inelastic of everyday trips [102]. The 15-minute city represents a shift in traditional urban planning, which often spatially separates city functions of residence, work, leisure, and circulation [98] towards local living [103].

It is argued that implementing the concept of the 15-minute city need not imply a complete city overhaul; some urban areas might already meet the general criteria, as studies in Barcelona, Naples, or Bogotá evidence [101,104,105]. Other cities such as Paris are making plans to adapt it [99,106]. Evaluating to what degree compactification can lead to a 15-minute city becomes an indicator of whether the methodology can achieve such objective in practice.

2.2. GIS Implementation

The bulky quantitative analyses required to calculate indicator values are carried out in a GIS environment using solely the geographic characteristics of the spatial layout of the urban areas. The GIS component of the methodology can be summarised as follows:

1. An urban area was selected for study. Three datasets are collected and curated into a GIS environment: origins (O), destinations (D), and road network. Origins represent demand (for trips) and are the centroids of buildings (endowed with inhabitant number information). Destinations represent supply and are urban facilities and centroids of job zones (see Section 2.4.1. for details on job zones). The road network connects origins to destinations. Origins and destinations are point feature classes, and the road network is a polyline feature class;
2. In a copy of the datasets, new buildings and facilities are positioned in vacant urban spaces, job zones are remade, and connecting roads are drawn. The buildings house population from the outskirts and are endowed with inhabitant information;

3. For every origin of each layout, network distances are evaluated in GIS to (a) the nearest urban facilities of each type and (b) the centroid of each job zone;
4. Four transport modes are considered: walking, cycling, private motorised transportation, and public transport. For each OD pair, trip probabilities for all those modes are obtained;
5. Indicator values for each origin are then calculated for both the real and the compact layouts based on OD distances and trip probabilities;
6. From the indicator values, statistical measures and maps are derived for the two layouts.

Steps #3 to #6 are similar to ref. [107,108]. Some further notes are as follows:

- The methodology considers only accessibility-related trips, which constitute most trips in an urban environment and can be modelled in GIS as one-way or round trips to predefined destinations, subject to supply attractiveness and demand intensity, two attributes which need be considered in accessibility [109,110];
- If the methodology is applied to a very large city, computational complexity can be reduced by defining origins as centroids of a square mesh over the study area, with associated inhabitant number given by the intersection of building centroids with mesh polygons;
- Urban facility types and respective destination attractiveness are here represented by weights as given in Table 1 below. An empirical 1–2–3 Likert scale for weights was used in the research, based on trip frequency, with three the most frequent. Higher weights mean trips to the corresponding destinations are likely to be more frequent. These weights are consistent with trip frequencies per facility type found by ref. [111];
- For some facility types, only the closest facility is relevant (e.g., primary healthcare, parks), whereas for others (e.g., restaurants), inhabitants usually want to choose between multiple facilities [112]. The closest-only facilities are marked with an asterisk in Table 1;
- If the return trip to a facility is made soon after reaching the destination, the person may experience a feeling of walking or cycling a longer distance. Therefore, in evaluating active transport probabilities (which are a function of distance), a one-way distance is considered for facilities that imply a long stay at the destination (e.g., schools, restaurants), whereas for the other facilities, a two-way distance is considered instead. One- and two-way facilities are indicated in Table 1 by the I or II;
- The four transport modes are comprehensive categories; e.g., for cycling, they include all types of cycles and not just bicycles. Likewise, public transport includes buses, subway, etc.

Table 1. Facility types and jobs weights.

Weight 1 Facilities	Weight 2 Facilities	Weight 3 Facilities
Post offices ^{*II}	High schools ^{I}	Kindergartens ^{*II}
Sports facilities ^{I}	Shopping centres ^{II}	Primary schools ^{*II}
Cultural organizations ^{I}	Entertainment sites ^{I}	Middle schools ^{*I}
Universities and institutes ^{I}	Primary healthcare services ^{*I}	Grocery stores ^{II}
Elderly care centres ^{I}	Pharmacies ^{*II}	Supermarkets ^{II}
Churches ^{I}	Restaurants ^{I}	Bakeries and pastries ^{II}
	Parks and green areas ^{*I}	

(*) Closest only, (^{I}) one-way facility, and (^{II}) two-way facility.

The Section 2.3 to Section 2.7 present implementation details and their rationale. Some of these details are presented using the ArcGIS 10.8 language, but any other GIS environment can be used provided its toolset can execute the operations described herein.

2.3. Compactification Procedure

Compactification is done in accordance with the existing municipal master plan. These plans define authorised construction zones and set rules in terms of soil impermeabilization coefficients, usable building area, gross floor area, number of floors, and zoning rules (i.e., zone land use), which must be respected in the compactification procedure. Authorised (but still construction-free) zones usually form the largest share of vacant space to be occupied. Other spaces include derelict areas and brownfields, as those zones are likely to be regenerated at some point [113–120]. No green areas are reassigned to residential or commercial use. Identifying the vacant spaces is the first step in the compactification procedure. These zones can be strictly residential, non-residential (e.g., commercial, industrial, other public facilities, etc.), or have mixed land use.

The second step is to determine how many people can be moved onto the vacant spaces that allow for residential use. From the soil impermeabilization coefficients, it is possible to determine the usable building area for each vacant space (the area that a building occupies when seen from directly above). Multiplying this area by the number of floors yields the gross floor area. After discounting 15% for building communitarian spaces (e.g., main entrance, stairways, etc.), the resulting area is what is available for apartments, i.e., private gross floor area. Apartment typologies and respective inhabitants are then distributed by the private gross floor area. This can be done following the empirical statistical distribution for the country's typologies [121] or by any other means (e.g., minimizing building unused space or maximizing number of inhabitants). As an example, Table 2 below shows the characteristics of building typologies in Portugal and can be used for the purpose.

Table 2. Building typologies in Portugal.

Apartment Typology	Fraction	Minimum Private Area * (m^2)	Average Inhabitants
T0 (studio)	2%	35	1
T1 (one bedroom)	9%	52	2
T2 (two bedrooms)	32%	72	3
T3 (three bedrooms)	36%	91	4
T4 (four bedrooms)	13%	105	5
T5+ (five+ bedrooms)	9%	122	6

(*) See ref. RGEU, 1951.

Having determined how much of the population can be moved into the residential buildings, the new buildings are drawn in GIS in the vacant spaces as follows:

1. Locate the point with best accessibility in the real city, point P;
2. Define a 100 m radius circle centred on P and draw all the possible new buildings within that circle. Assign the population farthest from P to those buildings and remove the buildings originally containing the moved population from the origins dataset;
3. Define a ring-like area 100–200 m away from P and repeat the assignment of #2;
4. Add 100 m to the ring-like area edges of #3 and repeat #3 until resulting new buildings can no longer be fully populated.

For vacant areas with mixed land use, i.e., residential and commercial, the commercial space is deducted from the private gross floor area. The deduction amount is determined by the municipal master plan.

After moving the population, urban facilities that ended up away from residential buildings are moved, starting from the farthest away, to the ring-like zones centred around P and onto vacant spaces that allow their land use and as close as possible to P. Note that some facilities can be moved onto buildings with mixed use, subject to area restrictions.

The third step is to move job locations. Jobs and job zones that already existed inside the new urban perimeter remain in their location. Employers with over 100 employees (e.g., hospitals, shopping centres) that can be moved are, and their employee count is added to the job zone they are moved to. Those that cannot be (e.g., stone quarries, chemical industries) remain in their original position, and a dedicated job zone is created for them. Smaller employers are allocated to job zones inside the new urban perimeter according to the percentage of population moved to those inside zones; e.g., if a job zone in the outskirts held 1000 jobs and the population of that zone was moved 70/30% onto inside zones A and B, then A gains 700 jobs in its centroid, and B gains 300. Edge zones, i.e., zones that have a part (but not all) of their population and jobs moved, are redrawn and centroids recalculated based on the jobs that remained inside. Note that job zone centroids are geometric averages of actual job locations of that zone, weighted by employee count (see Section 2.4.1.).

The final step is to add road strips alongside new buildings and non-residential land-use plots that become occupied with facilities or jobs.

2.4. Accessibility

This research uses the classic definition of accessibility as the ease or, more widely, the cost of reaching destinations [7,122], measured as averaged distances from origins to destinations (OD). Recent examples of cost-based approaches to accessibility include [51,123,124]. The use of distance is justified because of its flexibility and ease of interpretation, an important attribute for planning purposes since measures need to be well understood by policy makers [125] and also because distance can be used as a proxy to other measures, as will be seen below.

The accessibility measure selected in this research is similar to that used in refs. [107,126]. It is given by the following:

$$A_i = \frac{\sum_{jk} w_j L_{kj} d_{ij}^k}{\sum_j w_j \sum_k L_{kj}}, \tag{1}$$

where

i: $1, \ldots, I$ number of origins;
j: $1, \ldots, J$ number of facility types;
k: $1, \ldots, K$ number of closest facilities (when it applies), and in this article, $K = 3$;
A_i: accessibility score of origin i;
d_{ij}^k: network distance from origin i to the k-th closest facility of type j (or job zone);
w_j: weight of facility type j;
L_{kj}: freedom of choice factor for the k-th closest facility of type j; $L_{kj} > L_{k+1,j}$.

This indicator can be interpreted as the average distance from origins to destinations, weighted by destination attractiveness and by choice factor. Formally, freedom of choice factors for closest-only facilities can be defined as $L_{kj} = \{100, 0, 0\}$.

2.4.1. Accessibility to Jobs

Accessibility to jobs requires a different treatment because people have fixed job locations; hence, the concept of "closest job" does not apply. In other words, contrary to facilities where people can choose where to go, for jobs, employees must go where their job is located. To deal with this issue, a zone analysis is carried out instead, as follows in refs. [107,127,128]: identify job locations and employee count, divide the city into zones (considering population density, buildings, job density, and orography), count jobs in each zone, and find the geometric average job location of each zone. Finally, for each origin, calculate distance to each average job location, and ponder it by the percentage of jobs in the respective zone. Mathematically, this can be expressed by the following:

$$d_{ij}^k = \sum_z f_z d_{iz}, \quad j : \text{jobs}, \tag{2}$$

where

$z : 1, \ldots, Z$ number of job zones;
f_z: fraction of total jobs in zone z;
d_{iz}: distance from origin i to the z-th job zone centroid.

Jobs are of "closest-only" nature, and their weight can be set by, e.g., the percentage of commuting trips on the study area.

2.5. Active Modal Share

This research estimates the walk/cycle/car/bus modal split by the methodology of ref. [103], which is based on the following ideas:

- The active mode share is estimated from transforming accessibility-related trip distances onto active trip probabilities using log-logistic distributions. Separate walk and walk/cycle probabilities are obtained, the latter by combining walk and cycle probabilities, yielding two types of analysis;
- After discounting the active trip probability, the remaining probability corresponds to motorised trips, which are split onto bus/car trips according to the empirical percentages.

The above analysis is applied to each origin and OD pair. The modal split for origin i is then as follows:

$$M_i = \frac{\sum_{jk} w_j L_{kj} p^k_{\mathrm{A}ij}}{\sum_j w_j \sum_k L_{kj}}, \quad (3)$$

where

M_i: active modal share of origin i;
$p^k_{\mathrm{A}ij}$: active trip probability from origin i to the k-th closest destination of type j, with $p^k_{\mathrm{A}ij} = \sum_z f_z p_{\mathrm{A}iz}$ for j: jobs ($p_{\mathrm{A}iz}$: active trip probability from i to job centroid z).

The separate scenarios for walk and walk/cycle is justified because many cities do not provide adequate support for the cycling mode (e.g., lack of bikeways and/or lack of mechanical aid devices in hilly cities [126]), causing users to steer away from this mode. Because of this, two $p^k_{\mathrm{A}ij}$ actually exist, each corresponding to an active mode scenario.

Methodological details on the active mode estimation are lengthy and are thus presented in the Supplementary Material, Section S1, for the interested reader.

2.6. Transport Energy Consumption

Transport energy consumption is defined as fossil fuel usage on motorised trips. It is estimated for each origin and OD pair and can be obtained from the motorised modal split using the following [103]:

$$E_i = \frac{\sum_{jk} w_j L_{kj} \left(1 - p^k_{\mathrm{A}ij}\right) \left(f_{\mathrm{car}} F_{\mathrm{car}} + f_{\mathrm{pub}} F_{\mathrm{pub}}\right) \left(d^{\rightarrow}_{ijk} + d^{\leftarrow}_{ijk}\right)}{\sum_j w_j \sum_k L_{kj}}, \quad (4)$$

where

E_i: average fuel consumption of accessibility-related trips originating in i;
f_{car}: fraction of motorised trips made using the private car;
f_{pub}: fraction of motorised trips made using public transportation;
F_{car}: private car average fuel economy (MJ/passenger.km);
F_{pub}: public transportation average fuel economy (MJ/passenger.km);
$d^{\rightarrow}_{ijk}, d^{\leftarrow}_{ijk}$: one-way distances from origin i, respectively, towards/away the k-th closest destination of type j.

The E_i is measured in MJ/passenger-trip (at the tank). Note that in Equation (4), trips are always considered as two-way regardless of facility type.

2.7. 15-Minute City

Rather than checking which origins belong to a 15-minute city, the attainable fraction for each origin is calculated instead. For this purpose, network arcs are endowed with walk and cycle speed information (walk speed: 1.14 m/s [129]; cycling speed: 5.00 m/s for facilities [130]; 6.01 m/s for jobs [131]) and network junctions with delay (turns) information. New OD routes are derived, minimizing time and accumulating this variable (call it t^k_{ij}).

Then, for each OD pair, a binary score is applied depending on whether the trip is (or is not) achievable in 15 min. The OD pairs are then doubly weighted and summed using the following:

$$C_i = \frac{\sum_{jk} w_j L_{kj} B_{ij}^k}{\sum_j w_j \sum_k L_{kj}}, \quad (5)$$

where

C_i: attainable fraction of 15-minute city for origin i;
B_{ij}^k: 1 if the trip from origin i to the k-th closest destination of type j is possible within 15 min using active modes $\left(t_{ij}^k \leq 15\right)$; otherwise, 0. For jobs, $B_{ij}^k = \sum_z f_z B_{iz}$ (B_{iz}: 15-min binary score from i to job centroid z).

Again, two sets of C_i exist depending on whether or not cycling is considered in the active modes. If it is, the trip time t_{ij}^k refers to cycling time.

Both walking and cycling times are calculated not considering terrain slope. Hilly cities reduce active mode speeds; considering the effect of hilliness is possible, but it requires having network datasets with altimetry information and is left for future research.

3. Case Study Results

Coimbra is a mid-sized city with 104,643 inhabitants located in the centre region of Portugal [132]. Founded in the Roman age, Coimbra grew mostly in an unrestricted way, owing to its long history of occupation by different cultures, ideals and needs. Coimbra had a compact layout during its origin and medieval times and up to the twentieth century, having then developed onto a sprawled, low-density, and low-mix pattern of land use, with long and wide streets to accommodate the motorised traffic that came in the wake of the cheap fuel boom of the second half of the twentieth century. This spatio-temporal trend left plenty of unused urban space, which the city can now reclaim. Figure 1 shows the evolution of Coimbra urban perimeter and population; Table 3 summarises the associated sprawl. The figure was based on data from refs. [133,134] and the table on data from refs. [133–137].

Table 3. Population and area of Coimbra.

Year	Population	Population Increase	Area (ha)	Area Increase	Population Density (inhab./km^2)
17th Century	Circa 12,000	N/A	43	N/A	27,907
1930	36,021	200%	170	295%	21,189
2021	104,464	190%	8700	5018%	1201

As can be seen from the table, sprawl increased throughout the centuries, with area increases being greater than the homologous population increases.

Detailed Coimbra datasets were available from previous projects, and compact Coimbra datasets required only minor changes of the former, carried out manually on GIS. Survey data show circa 19% of trips use active modes, of which only 0.2% are cycling [138], mostly due to poor cycling network suitability (i.e., lack of cycling infrastructure and overall safety) [139] and high inclines [122]. Motorised trips are split 30/70% between public transport and private car, respectively [138]. The low cycling share is, however, expected to rise significantly if the cycling network were upgraded and deterrents mitigated, again justifying the two-scenario approach [108]. The commuting trip sharing of Coimbra is 37% [139], which translates to $w_j = 22,\ j:$ jobs, and all the analyses used $L_{kj} = \{70, 20, 10\}$ for non-closest-only facilities. Parameterization of active-mode trip probabilities can be found in the Supplementary Materials, Section S1. Motorised fuel consumption was assumed to be 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport [140].

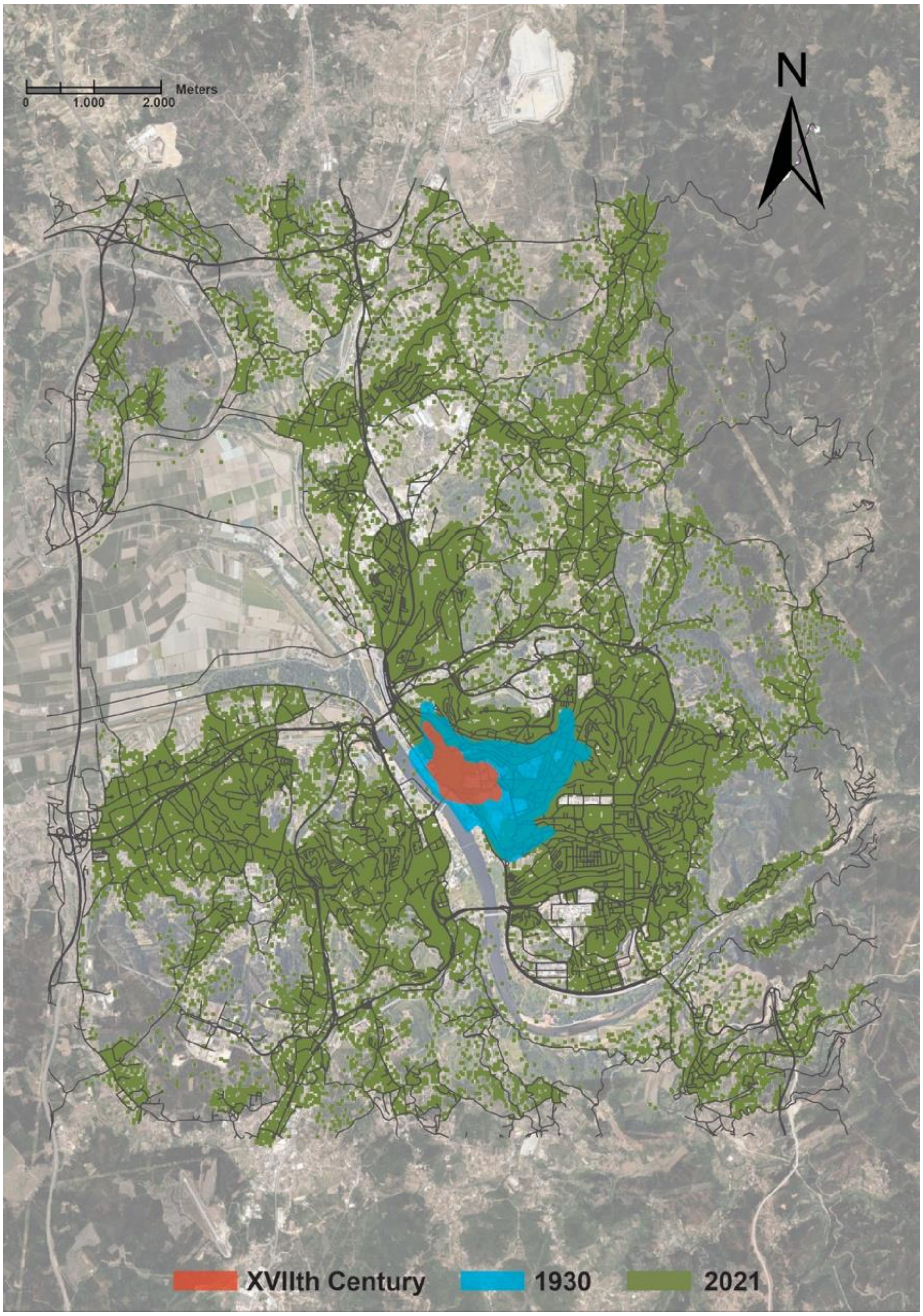


Figure 1. Evolution of Coimbra's urban perimeter and population.

3.1. Compactification of Coimbra

As mentioned above, Coimbra's urban sprawl left many spaces unurbanised, and others that were once occupied became derelict. New buildings occupying the vacant spaces were drawn in GIS in full compliance with the current regulations of the municipality of Coimbra using the up-to-date municipal master plan, as prescribed by the methodology. Compliance with those plans makes it possible to operationalise the compactification, should municipal authorities and civil construction contractors wish to do so.

After applying the municipal regulations to new buildings, a layout of flats per floor was chosen that maximised the available surface area for the number of inhabitants accommodated. This gave rise to T1 to T4 typologies in percentages of 0.1/45.8/46.5/7.6, respectively. In total, 196 new land plots were idealised, and 636 buildings created that were able to house 54,469 inhabitants, meaning that around 40% of the Coimbra's population would be moved. With respect to urban facilities, each relocated facility would be given the same area it currently occupies.

Figure 2 depicts the arrangement of new buildings that are needed to realise a compact Coimbra, and Figure 3 shows the location of buildings, facilities, job zone centroids, and the road network pre- and post-compactification. Supplementary Materials Figure S1 shows the full job zones.

At the end of this compactification process, the total urbanised area of the city was reduced from 141,720 m^2 to 16,732 m^2, a reduction of about 88%, as Figure 3 and Table 4 show. The living space per inhabitant in the new buildings is rather small (24 m^2): about half the actual value. However, it should be noted that some dwellings of real Coimbra have very generous areas, which biases the result towards large average areas.

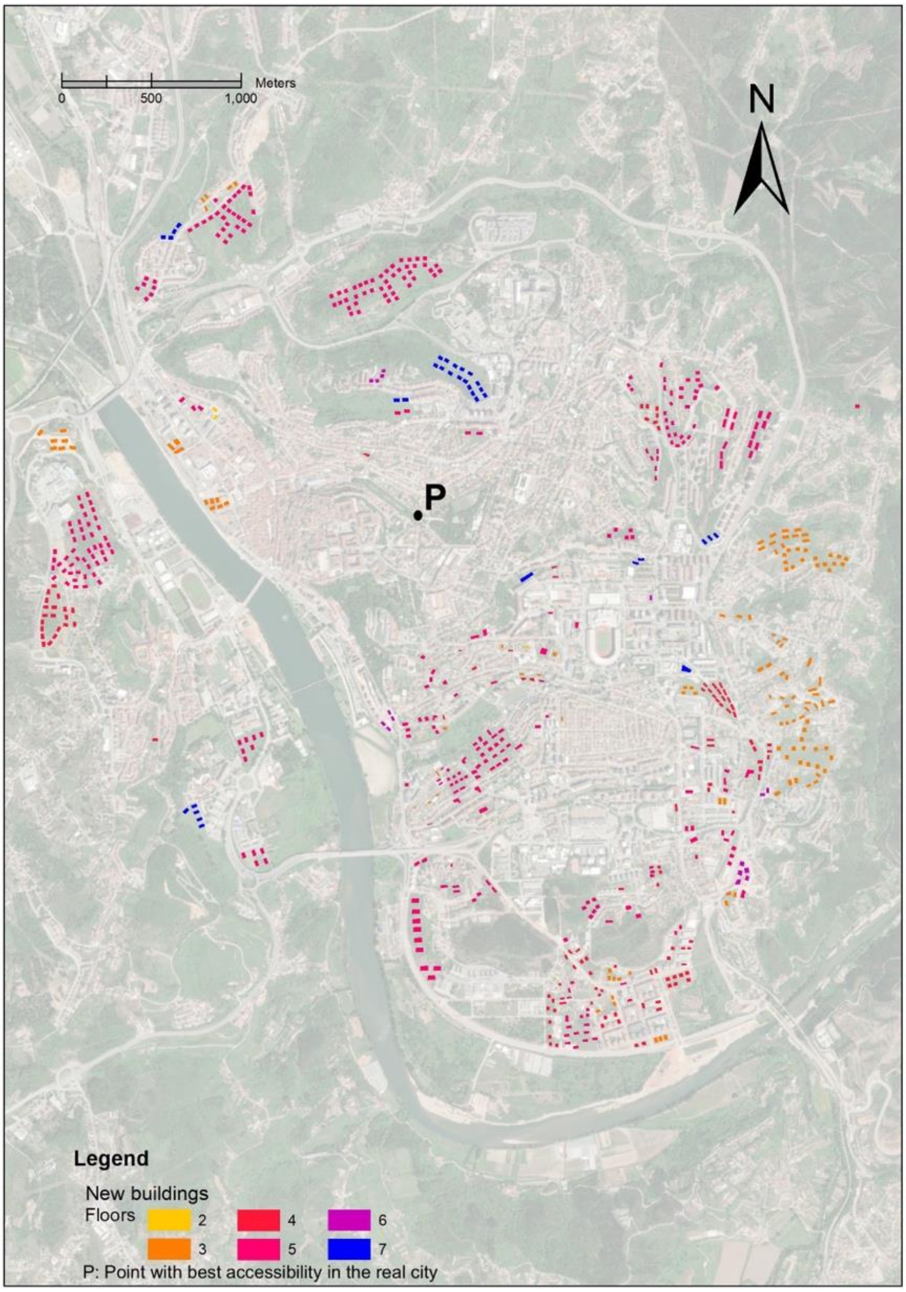


Figure 2. New buildings arising from compactification.

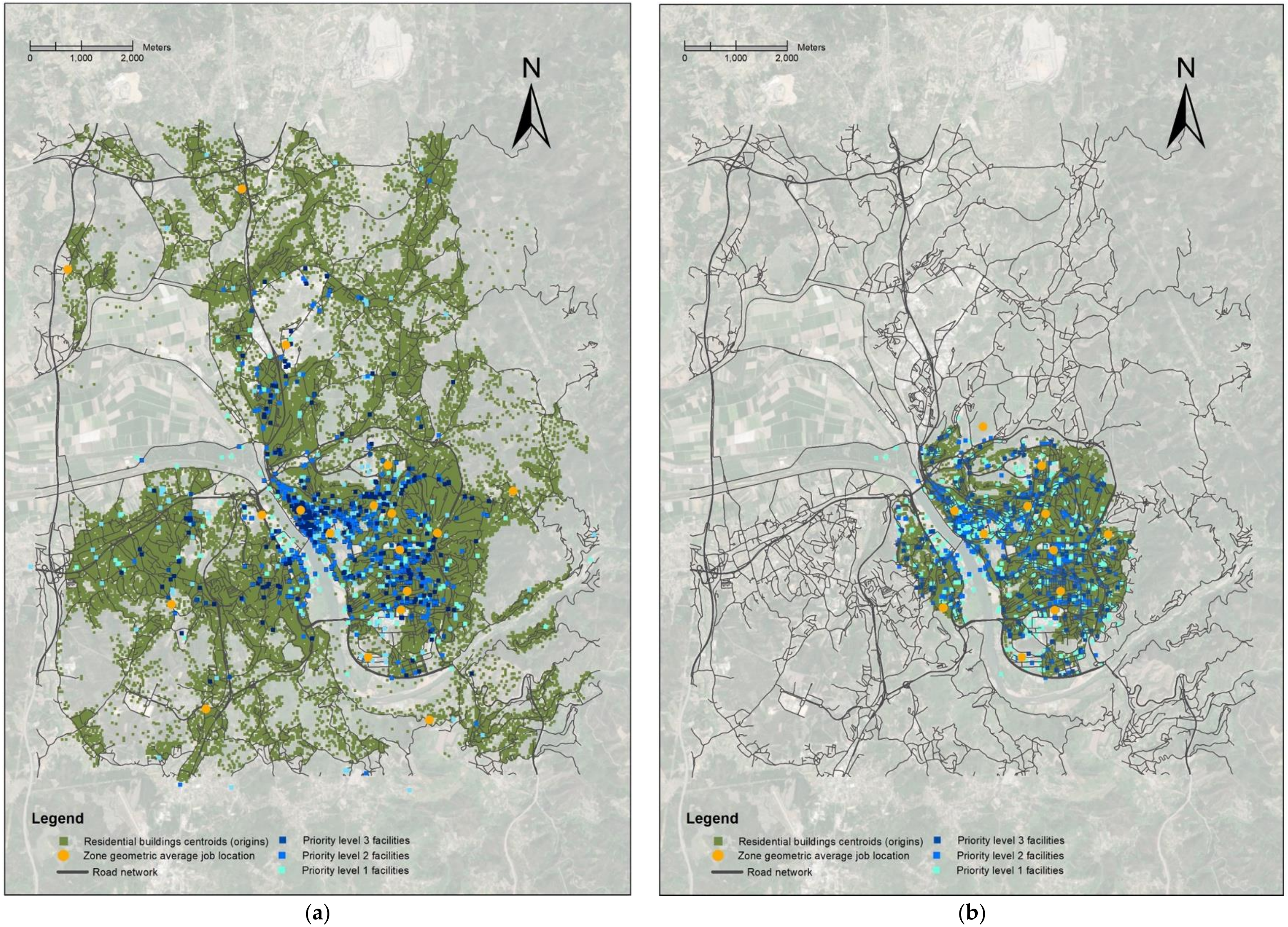


Figure 3. Origins, destinations, and road network. (**a**) Layout of Coimbra; (**b**) layout of compact Coimbra.

Table 4. Compactifying procedure statistics.

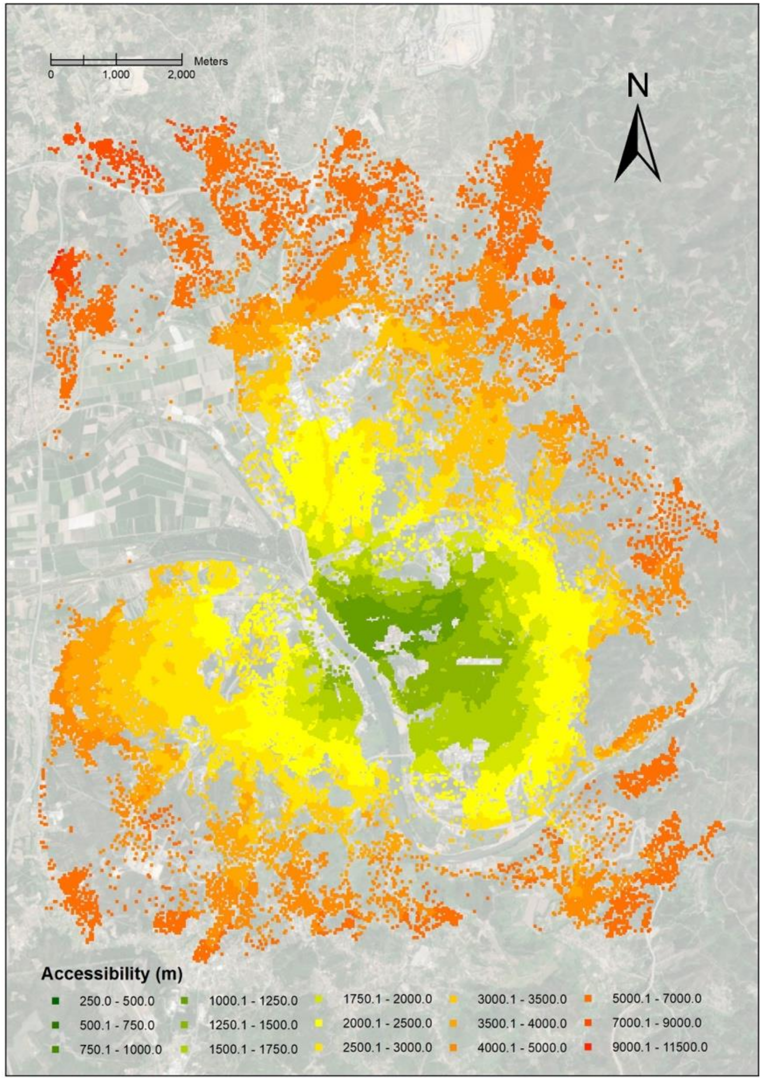
Indicator	Compact Coimbra	Notes
City area	16,732 m^2	Coimbra: 141,720 m^2
New buildings	636	New land plots: 196
New building area	296,910 m^2	Gross floor area: circa 1,300,000 m^2
Moved population	54,469 inhab.	52% of total population
Average residents per building	86	
Average building floors	4.5 floors	
Living space per inhabitant	24 m^2	Coimbra: 47 m^2

3.2. Accessibility and the 15-Minute City

Applying the methodology to obtain the accessibility and 15-minute city indicators yields the results of Figures 4 and 5 and Table 5. In all results tables, statistics are carried over the set of origins *i* except for the average per inhabitant line, which is weighted to origin population (h_i), i.e., $\frac{\sum h_i A_i}{\sum h_i}$. As seen from Figure 4, and as expected, compactification increases the accessibility scores. That increase is felt overall and is substantial even in the more central areas, which already had good scores before compactification. Accessibility scores also become more homogeneous as the city becomes denser and more compact. Statistically, Table 5 shows a reduction in the average OD travel distance per inhabitant of 38%—from 2533 m to 1570 m on average. If jobs are taken out of the equation, that difference reaches 56%—from 1440 m to 638 m on average. It is interesting to note that the average per-inhabitant distances of compact Coimbra are actually higher than the per-origin averages. This happens because much of the population is moved into zones with slightly subpar accessibility, but this effect is very small.

Table 5. Accessibility (m) and 15-minute city statistics (%).

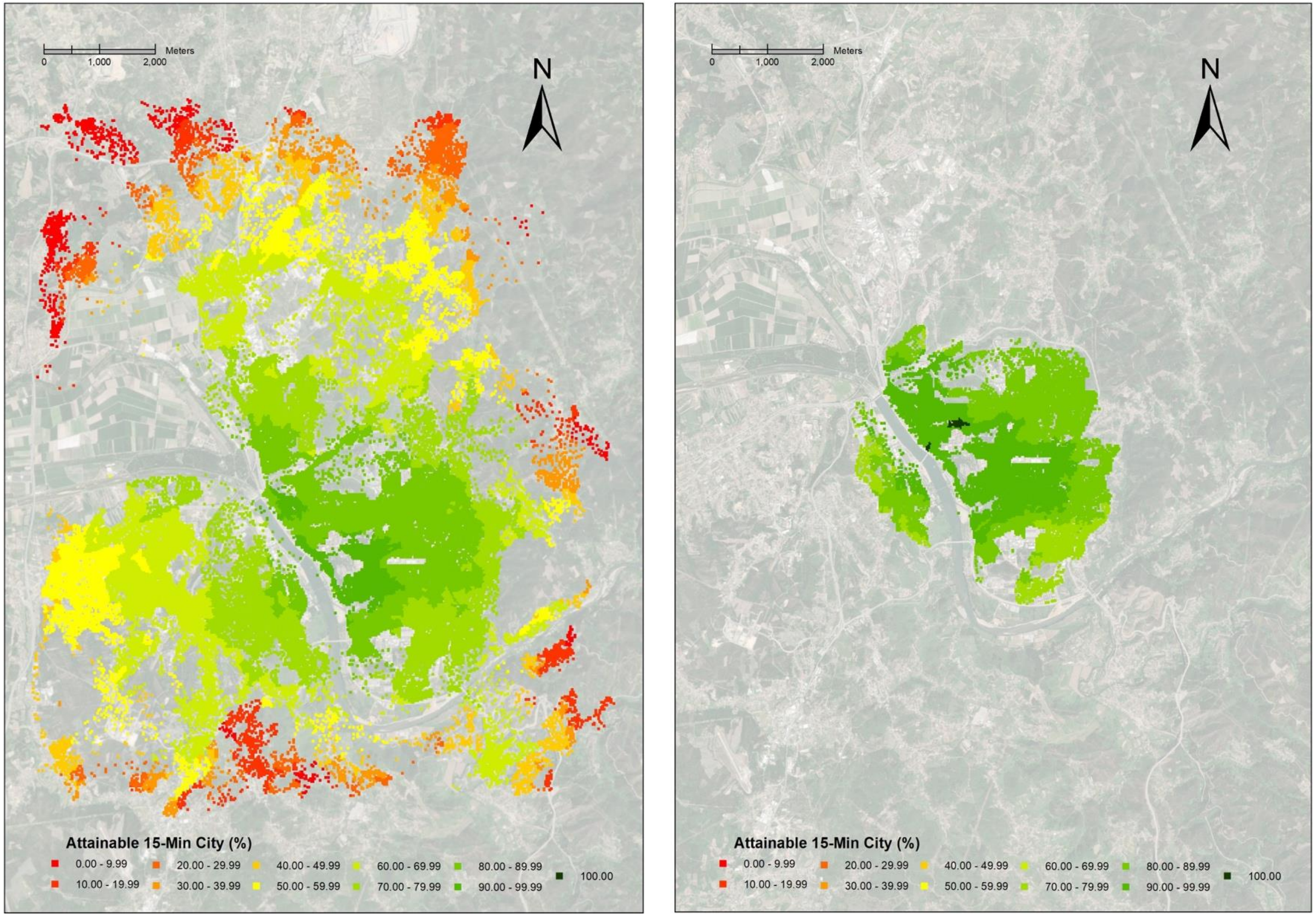
Accessibility (m)	Urban Facilities		Urban Facilities Plus Jobs	
	Coimbra	Compact Cbr.	Coimbra	Compact Cbr.
Min	268	252	1063	948
Max	8099	1746	9329	3092
Average	1936	594	3088	1491
Average per inhabit.	1440	638	2533	1570
Standard deviation	1352	188	1483	280
Coeff. of variation	70%	32%	48%	19%
15-Min City (%) (Facilities Plus Jobs)	**Walking**		**Walking and Cycling**	
	Coimbra	**Compact Cbr.**	**Coimbra**	**Compact Cbr.**
Min	0.0	6.7	0.0	69.1
Max	71.3	76.3	91.8	100
Average	22.5	61.6	66.3	88.5
Average per inhabit.	30.2	58.0	71.1	85.0
Standard deviation	20.1	8.9	19.7	5.7
Coeff. of variation	95%	15%	30%	7%



(**a**)

(**b**)

Figure 4. Accessibility to urban facilities plus jobs (m): (**a**) Coimbra; (**b**) compact Coimbra.



(**a**) (**b**)

Figure 5. The 15-minute city for walking/cycling to urban facilities plus jobs (%): (**a**) Coimbra; (**b**) compact Coimbra.

Assuming walkable distances of 700 m [141,142] or 800 m [143], compact Coimbra is largely a walkable city, especially if only facilities are considered. This is in sharp contrast to real Coimbra, whose average distance per inhabitant to facilities of 1440 m, 2533 m if jobs are added, makes it far from walkable. As for cycling, assuming cyclable distances in the range of 3800 m [141], both cities are cyclable for the average inhabitant. However, while compact Coimbra is clearly cyclable for all its inhabitants, in Coimbra, that cyclability is restricted to the more central areas.

Figure 5 and Table 5 present the results in a 15-minute city perspective. Average walking and cycling speeds mean that for 15 min, a person can walk up to 1026 m or cycle up to 4500 m, which are slightly higher values than the current literature standards.

Looking at Figure 5a reveals that Coimbra achieves a reasonable fraction of being a 15-minute city but only on its central region and only if cycling is considered. Outskirts are heavily penalised, and in practice, cycling is marginal. The Supplementary Material Figure S6a, which considers only walking, is thus a more precise picture of the current situation: only a few select locations in the centre achieve 50%+ of being a 15-minute city. In contrast, as shown by Figure 5b, a cyclable compact Coimbra manages attainability scores of over 70% almost everywhere, with percentage averages in the high eighties. Considering only walking greatly decreases those scores (Figure S6b, Table 5), once again highlighting the importance of cycling in an urban environment and the opportunities that it creates.

However, from the theoretical viewpoint of a 15-minute city, defined as a city with 100% active travel, the locations of compact Coimbra that reach the paradigm are very few (Figure 5b), proving that the 15-minute city may be an extremely difficult objective to achieve in practice, at least within the current municipal master plan. This result makes it tempting to speculate that, in general, achieving a 15-minute city is likely to remain a utopia except for, perhaps, by using very aggressive compactification designs (possibly requiring a change in the municipal master plan) or extremely dense, purposedly built urban layouts. However, such a claim needs quantitative validation, e.g., by developing and applying a modified version of the present methodology.

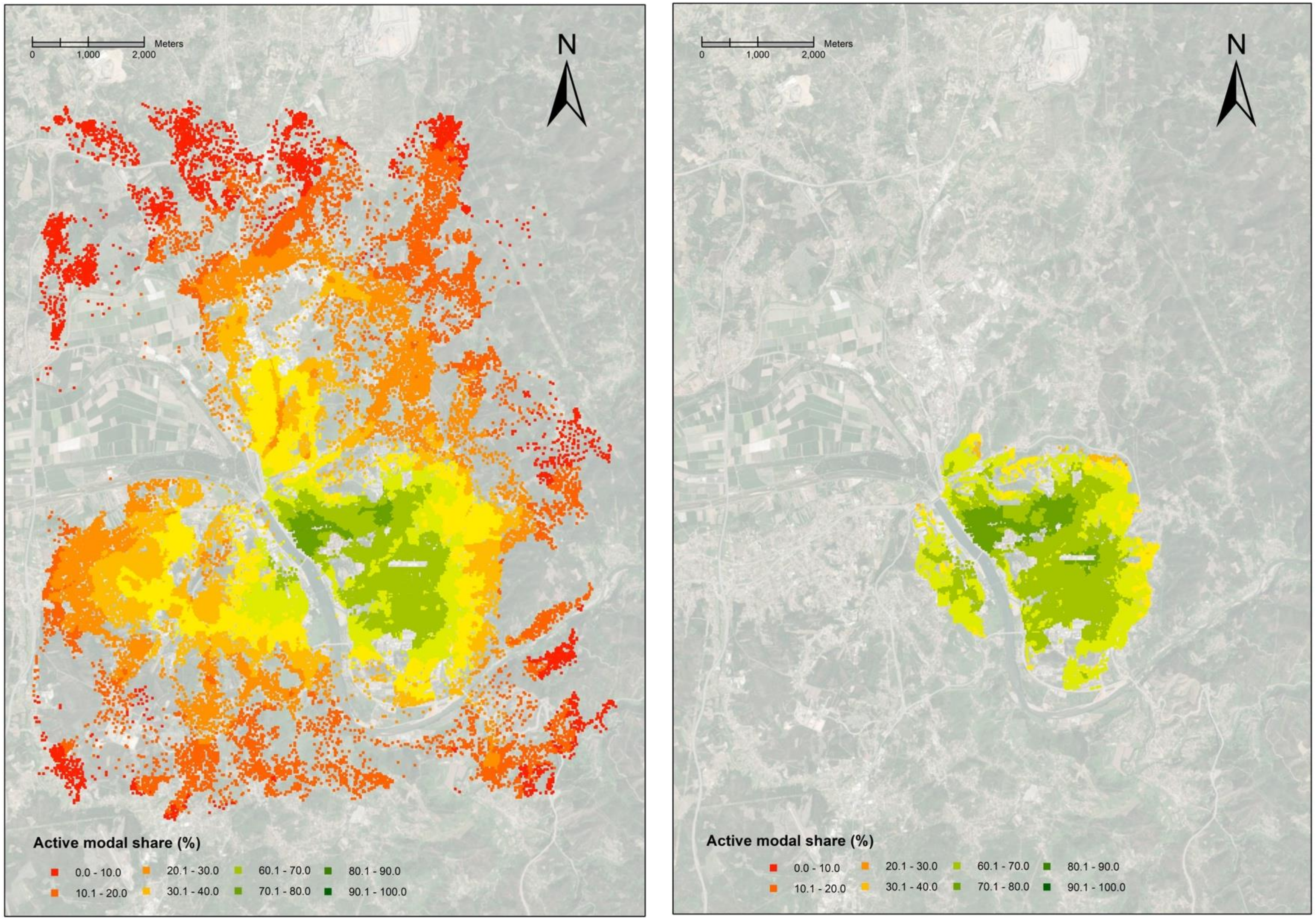
It should be noted that Coimbra is a hilly city, and although in situ observations confirm feasibility of a walking speed averaging 1.14 m/s [144], cycling speed did not reflect slopes. Still, the appearance of affordable pedelec cycles [145–147] and public aid devices [126] can mitigate this effect, making it reasonable to assume that, given adequate cycling infrastructure, slopes can be overcome. Ongoing research to evaluate slope impact on bicycle ridership in Coimbra is being developed by the team.

3.3. Modal Share

Figure 6 and Table 6 display the active modal share results.

Table 6. Active modal share (%) statistics.

Active Modal Share (%) (Facilities Plus Jobs)	Walking		Walking Plus Cycling	
	Coimbra	**Compact Cbr.**	**Coimbra**	**Compact Cbr.**
Min	0.5	5.6	3.5	28.9
Max	48.0	48.7	73.7	76.3
Average	12.7	28.1	35.6	61.6
Average per inhabit.	16.8	25.6	42.6	58.0
Standard deviation	10.6	7.4	18.7	7.2
Coeff. of variation	83%	26%	53%	12%



(**a**) (**b**)

Figure 6. Active modal share (%): (**a**) Coimbra; (**b**) compact Coimbra.

The impact on active modal share of compactifying Coimbra is significant, and if all the necessary conditions to cycle are provided, that impact is even greater. Considering all trips, i.e., facilities plus jobs, compactifying Coimbra can increase the modal share by 35% to 50%. For real Coimbra, while it is possible that the bicycle can still be a valid means of transport for the average citizen, the farther-away inhabitants are clearly outside the cycling range for many trips. The outskirts are low-density areas with insufficient connection to the city's public transport network, forcing the resident population to use private cars, another problem that compaction can help solve.

3.4. Transport Energy Consumption

The active modal share has a direct but non-linear impact on energy consumption. It is non-linear because of the log–logistic relationship between active trip probability and OD distance. Figure 7 and Table 7 summarise that impact of compactifying Coimbra. The compact layout reduces average per-inhabitant transport energy consumption by 62% considering walking only and up to a staggering 76% for walking/cycling. Note that reductions for the furthest-away inhabitant ("Max" on Table 7) are even greater (~80%), underlining how deeply urban sprawl impacts transport energy consumption.

Table 7. Transport energy consumption (MJ/passenger.trip) statistics.

Transp. Energy (MJ/p.t.) (Facilities Plus Jobs)	Active: Walking		Active: Walking Plus Cycling	
	Coimbra	Compact Cbr.	Coimbra	Compact Cbr.
Min	0.690	0.605	0.190	0.132
Max	36.340	7.365	35.370	5.491
Average	8.180	2.056	6.700	0.954
Average per inhabit.	5.901	2.254	4.533	1.103
Standard deviation	6.210	0.830	6.170	0.578
Coeff. of variation	76%	40%	92%	61%

The map of Figure 7 shows that many residents living in the urban sprawled outskirts face high levels of transport energy consumption. Changing the city form by bringing everything and everyone closer together provides from the start a significant reduction in energy consumption. Along with the cycling infrastructure promotion, such policies could improve energy savings even further. Additionally, it provides a more equitable urban environment that is able to provide similar opportunities to everyone.

It would be interesting to estimate the effect of compactification on building energy consumption, which constitutes a share of total city energy consumption comparable to that of transport. If reductions can be found in the same order of magnitude of those of transport energy, compactification can arguably be presented as possibly one of the most impactful political decisions that can be taken to mitigate emissions.

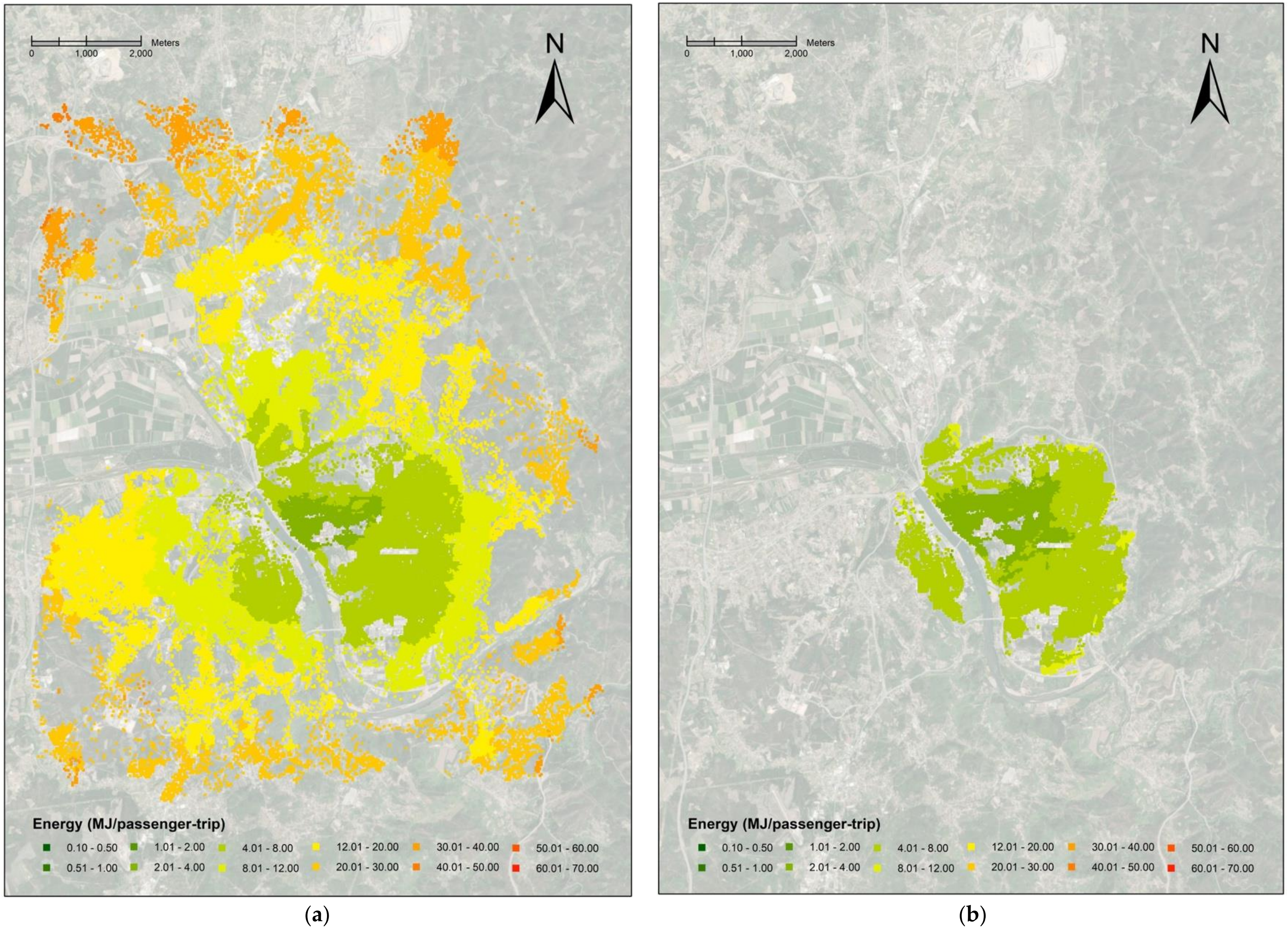


Figure 7. Transport energy consumption (MJ/passenger.trip): (**a**) Coimbra; (**b**) compact Coimbra.

4. Discussion

The case study results give an objective measure of how compactifying Coimbra impacts its accessibility, attainability of a 15-minute-city status, active modal share, and transport energy consumption, revealing improvements on all indicators. Table 8 below summarises these improvements.

Table 8. Effects of compactification in Coimbra: indicator improvements.

Indicator	Statistics							
	Facilities				Facilities + jobs			
Accessibility (m)	Coimbra	Compact Coimbra	Reduction (m)	Reduction (%)	Coimbra	Compact Coimbra	Reduction (m)	Reduction (%)
Avg. Avg. per inhab.	1936 1440	594 638	1342 802	69% 56%	3088 2533	1491 1570	1597 963	52% 38%
	Walking				Walking + Cycling			
15-min city (%) (Facilities + jobs)	Coimbra	Coimbra compact	Increase	Increase (%)	Coimbra	Coimbra compact	Increase	Increase (%)
Avg. Avg. per inhab.	22.5 30.2	61.6 58	39.1 27.8	174% 92%	66.3 71.1	88.5 85	22.2 13.9	33% 20%
	Walking				Walking + Cycling			
Active modal share (%) (Fac. + jobs)	Coimbra	Coimbra compact	Increase	Increase (%)	Coimbra	Coimbra compact	Increase	Increase (%)
Avg. Avg. per inhab.	12.7 16.8	28.1 25.6	15.4 8.8	121% 52%	35.6 42.6	61.6 58	26 15.4	73% 36%
	Walking				Walking + Cycling			
Transport energy (MJ/p.t.) (Fac. + jobs)	Coimbra	Coimbra compact	Reduction (MJ/p.t.)	Reduction (%)	Coimbra	Coimbra compact	Reduction (MJ/p.t.)	Reduction (%)
Avg. Avg. per inhab.	8.18 5.901	2.056 2.254	6.124 3.647	75% 62%	6.7 4.533	0.954 1.103	5.746 3.43	86% 76%

The compact version of Coimbra shows improvements on all indicators, ranging from 20 to 174% (20 to 92% if only averages per inhabitant are considered). Accessibility values, being distances, are readily interpreted by decision makers for planning and make it clear that the compact version is mostly walkable. The 15-minute city is a modern benchmark of urban sustainability not fully attainable for Coimbra with the present compactification procedure (but may be possible with other procedures). Active modal share is another such benchmark. A high modal share has health and environmental benefits and reduces congestion. Again, for Coimbra, compactification increases this indicator considerably. Finally, transport energy is a measure of both efficiency and sustainability, which improves considerably as well with compactification.

Comparing the compact version with real Coimbra shows that urban sprawl posed a toll on all measures, in line with similar results found in the literature [148,149]. It is worth noting that the compactification procedure did not require any radical measures, such as, e.g., skyscrapers or vertical development, excessive densification, or excessive land-use mix. All the new construction was proposed in line with the municipal master plan that was already authorised for implementation, proving practical feasibility of the compactification procedure.

The high accessibility of compact Coimbra is due to shorter OD distances, and this has an objectively positive effect at various levels, as described in the previous section and above. Along with these also come subjective effects such as, e.g., sense of place and liveability [150] or higher level of travel satisfaction, as active modes are arguably more pleasant than motorised ones [151]. Less energy spent on travel results in lower greenhouse gas emissions (GHG), but in the same way that active modal share is non-linearly related to energy consumption, GHG emissions are also non-linearly related to fuel consumption, as internal combustion engines typically have lower efficiency at warm-up than at cruise regimes [152,153]. Further research is necessary to quantify this effect, which becomes more important as distances are reduced.

Compactification also has non-tangible effects on public transport network and ridership, as recognised by refs. [10,38]. Urban sprawl makes it difficult to properly organise a public transport service: serving distant, low-density locations requires bus lines that are inefficient or unprofitable. Moreover, buses that connect frequently to the final destination are necessary, which discourages their use and pushes users to the private car. Compactifying reduces trip distances, leading to less time spent on public transport and fewer stopovers, a decrease on the number of bus lines, and consequently, an opportunity to increase the frequency of the remaining lines. Compactness also leads to more users within reasonable catchment areas of public transport stops, potentially leading to higher rates of ridership.

Equity and gentrification are growing concerns of the modern city and urban planning [154]. By observing the statistical dispersion measures of the results (standard deviation and coefficient of variation) for all indicators and both city layouts, it is seen that the city of Coimbra in its compact version has improved equity. In the real city of Coimbra, there a clear difference between those who live close to most of the facilities and those who live far away. In its compact counterpart, this difference is substantially smaller, with similar accessibility and transport opportunities for those who live in the centre and those who live at the furthest distances. Regardless of the social levers that led to inequity in the current city, its compact version presents itself as a possible instrument to fight this status-quo and ensure a more equitable and fair development.

Overall, results show that the idea of compactifying a city by filling in the available spaces is likely feasible for many cities and could be used as an urban regeneration and development tool. With the right set of urban policies and adequate promotion, new construction undertakings can bring back to the city centre residents that once left or even bring new people to the city. It is not about completely rebuilding a city area or destroying what is already there to build something completely different. It is about efficiently using urban areas that for different reasons are yet undeveloped or have been forgotten. There is no need to create new places to build but rather build on the free spaces that are already there, compactifying a city by filling in the spaces.

5. Conclusions

This article presented a quantitative methodology to estimate the impact of compactifying a city by urbanizing its vacant spaces and applied it on a comparison between the real city of Coimbra, Portugal, and its redraft as a compact version of itself. The methodology is based on indicators of accessibility, active modal share, transport energy consumption, and the degree to which it can be considered a 15-minute city, all of which can be evaluated using a GIS environment and the necessary datasets.

The case study results showed the compact version has very considerable improvements in all indicators (from 20 to 91%), in line with previous research hat advocated compactification as a possible way to reduce the environmental and societal impact of urban sprawl. Furthermore, the compactification of Coimbra can be completed in strict adhesion to municipal master plan, thus attesting to its practical feasibility to implement the reurbanisation agenda and deliver on the desire for closer, more intense social interaction.

As far as the authors know, the proposed methodology is one of the first attempts to provide quantitative measurements of the impact of compactifying a city. The fact it considers the current municipal master plan was not previously tested, and it revealed that, despite the lack of changes in planned land use, a very small space is necessary to accommodate all the suburban citizens and concomitant facilities.

Insights from the case study provide urban planners with valuable information. By showing the plus values of compactifying a city in a quantitative manner, authorities are alerted to the advantages of developing urban planning policies that mitigate sprawl and incentivise the consolidation of city centres, e.g., urban regeneration projects. The implications of these findings go beyond the decrease of travelling and commuting times or the reduction of energy spent on transport. Better public transport operability and ridership and more walkable and cyclable opportunities can lead to a healthier, more sustainable, equitable, and efficient lifestyle. More tangible future objectives include use of the results to estimate city transport energy or emissions savings on a more global, e.g., monthly or annual, basis.

Nevertheless, the quantitative measures presented are not the only ones needed to analyse or compare different urban layouts. A more holistic view may require other measures to be implemented, such as urban environmental pleasantness (e.g., ref. [155]), land-use analysis, or to extend the energy considerations to the building sector. Such putative measures would need to be defined in a way that they can be calculated in a GIS environment, which is a fundamental prerequisite for applying the methodology proposed in this research given its quantitative nature. The growth and development of a city is unlikely to follow predefined theoretical patterns, but this research provides quantitative elements with intuitive map representations, allowing everyone to understand, judge, predict, and make decisions regardless of what the future may bring.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi12030120/s1, Table S1: Log-logistic parameters for walking, Figure S1: Job zones, Figure S2: Accessibility to urban facilities, Figure S3: Accessibility to jobs, Figure S4: Total accessibility (facilities plus jobs), Figure S5: 15-Minute City by walking [jobs only], Figure S6: 15-Minute City by walking (facilities plus jobs), Figure S7: 15-Minute city by active modes (walking/cycling) (jobs only), Figure S8: 15-Minute city by active modes (walking/cycling) (facilities plus jobs), Figure S9: Walk modal share to facilities, Figure S10: Walk modal share to jobs, Figure S11: Walk modal share to facilities plus jobs, Figure S12: Active modal share (walking/cycling) to facilities, Figure S13: Active modal share (walking/cycling) to jobs, Figure S14: Active modal share (walking/cycling) to facilities plus jobs, Figure S15: Transport energy spending to facilities (active: walk only), Figure S16: Transport energy spending to jobs (active: walk only), Figure S17: Transport energy spending to facilities plus jobs (active: walk only), Figure S18: Transport energy spending to facilities (active: walking/cycling), Figure S19: Transport energy spending to jobs (active: walking/cycling), Figure S20: Transport energy spending to facilities plus jobs (active: walking/cycling).

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