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Benchmarking real and ideal cities - a multicriteria analysis of city performance based on urban form

João Monteiro [a], Nuno Sousa [b,c], João Coutinho-Rodrigues [b,e], Eduardo Natividade-Jesus [b,d,*]

[a] Research Centre for Territory, Transports and Environment (CITTA), Porto, Portugal
[b] Institute for Systems Engineering and Computers of Coimbra (INESCC), Coimbra, Portugal
[c] Department of Sciences and Technology, Universidade Aberta, 1269-001 Lisbon, Portugal
[d] Department of Civil Engineering, Polytechnic Institute of Coimbra, Coimbra, Portugal
[e] Department of Civil Engineering, University of Coimbra, 3004-531 Coimbra, Portugal

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ABSTRACT

The debate on the ideal urban layout, or form has long been an active topic of research. As cities expand and population demands rise, the quest for efficient and sustainable urban designs gains greater significance, necessitating objective and quantitative evaluation of their performance. This article adds to the debate by presenting a multicriteria analysis of city performance, based on quantitative indicators obtainable from geographic information systems calculations, which focus on sustainability and physical pleasantness issues. Indicator values were derived for a real city, its infill version, and five redrafts as classic city models existing in the literature. The city layouts were then compared using the TOPSIS multicriteria ranking method, results showing a preference for the more compact urban layouts due to the multiple advantages of having shorter distances between supply and demand points. The methodology provides quantitative insights on city performance and efficiency and can be used to compare options for city expansions or major urban regeneration projects.

1. Introduction

Cities play an immensurable role in society. For centuries, urban conglomerations have been the prime places for evolution and the development of mankind (Tellier, 2019). The way cities are planned and built directly impacts the quality of life of billions of people. Sustainable and resilient planning towards higher quality of life standards has never been more important, for example, as the COVID-19 pandemic stressed (Monteiro, Sousa, Pais, et al., 2023). However, planning cities is not an easy task, as it involves several areas of knowledge, a holistic understanding of the different city dimensions, cooperation among different decision-makers and city dwellers, and comprehensive understanding of local context and its shortcomings. The job of spatial planning researchers is to provide the necessary knowledge and tools so that, in practice and on the field, decisions are made based on sound methodologies and with the best possible outcomes in view.

Understanding urban development and how it should be planned is a research avenue which has been constantly evolving, thanks to new knowledge, socioeconomic and technological advances, and considering new challenges and goals. Urban development and spatial planning are related, among other, by urban morphology, i.e., *'the study of urban forms, and of the agents and processes responsible for their transformation'* (Oliveira, 2016), which emphasizes the spatial layout, or form of the city. A city urban form encompasses its size, shape, land uses, distribution of facilities, and transport networks, and can have a close relationship with the city function, i.e., the actual use of urban space for human activities (Chen et al., 2020; Crooks et al., 2015; Zhong et al., 2014; Živković, 2019). Studying the form and function of cities is thus pivotal towards understanding urban problems, evaluating planning strategies and supporting urban policies (Zhong et al., 2014). Gradual advances in Geographic Information Systems (GIS) technology and computing power improved our capability to map large-scale urban areas and made it possible to add quantitative arguments to urban planning, based on the city form and function (Crooks et al., 2015). GIS also allows to integrate multiple information with a spatial dimension and carry out subsequent geostatistical analyses (Majumder et al., 2023; Roy et al., 2024; Roy, Bose, Majumder, Roy Chowdhury, et al., 2023; Roy, Majumder, Bose, & Chowdhury, 2023; Roy, Majumder, Bose, &

* Corresponding author at: Institute for Systems Engineering and Computers of Coimbra (INESCC), Coimbra, Portugal.
E-mail address: ednativi@isec.pt (E. Natividade-Jesus).

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Roy Chowdhury, 2023).

This article intends to contribute to the debate by presenting a methodology to assess city performance, based on urban form and making use of GIS capabilities, and carrying out a comparative multi-criteria analysis on the results that methodology yields for a real city and five redrafts of that city as classic models and an infill version of itself. It aims to study the impact of urban form on the efficiency, sustainability, and pleasantness of the physical environment using quantitative benchmarking indicators and compare different layouts for the same city. Accessibility, active transport modal share, transport energy consumption, road network directness, mix land use, and neighborhood perceived pleasantness make up the six indicators that are evaluated in GIS, derived solely from geographic characteristics of the spatial layout of urban areas.

Throughout the centuries urban conglomerations grew to accommodate more inhabitants in ways that mostly responded to the interests of living forces of their societies, often resulting in construction by convenience and limited strategic planning. As times change and societies evolve, cities constantly face new challenges, aiming to improve the inhabitants' quality of life and create a more resilient and sustainable urban future. This has led to the development of different city models that, based on urban design, planning strategies and policies, aimed to deal with the challenges that our cities have faced, still face, and will continue to face over the next decades. The proposed multi-criteria methodology (MCM) allows benchmarking those classic models, i.e., to make a comparative study between real and ideal cities, showing what cities could look like and how they could perform if a stricter planning approach were followed instead. The methodology was put to test by analyzing and comparing seven urban layouts for a case study, the city of Coimbra, Portugal, namely the real city of Coimbra; its redraft as five classic models, the Garden City, Ville Radieuse, Compact City, Transit-Oriented Development, and Transect Planning; and one urban development approach, the Infill (Ghodsi et al., 2021). This research ultimately aims to present an understanding on how planned urbanism may compare to a real city and provide a clear path to transpose some solutions to practical contexts.

The presented MCM is also directed at policymakers, as its use only requires data that is usually readily available and provides quantitative results that can be used to analyze and compare the different urban planning solutions. Its results are easily interpreted and can be presented to city dwellers to increase collaborative planning and all stakeholders participation towards a better quality of life for everyone.

1.1. Literature review

Urban studies have long been an important research topic that aims to provide the necessary tools and knowledge to improve the inhabitants' quality of life (Kristjánsdóttir, 2019; Mumford, 2018; Tellier, 2019). Modelling cities and studying their spatial layout has been a long-term item of that topic, and its relevance has risen due to the increase of migration flows towards cities (Barthelemy, 2019; Hall, 2014; United Nations, 2018). Nevertheless, most research so far focused on a single urban layout or benchmarking indicator, aiming to find a direct resolution or model to the problem at hand (Correa, 2006; Neuman, 2005; Schrader, 1999; Transit-Oriented Development in the United States, 2004). When quantitative, these approaches usually lead to specific solutions, where the impact of a particular idea or city model is limited, not implying major changes in the city structure (Lin & Yang, 2006; Lyu et al., 2016; Ratner & Goetz, 2013). The research involved in creating and developing those models usually carries on with a deep analysis of the model itself, focusing on specific problems, policies, future sustainability and value, applicability to worldwide cities (Knowles et al., 2020; Montavon et al., 2006; Mouratidis, 2019; Randolph, 2006; Thomas et al., 2018; Yuan et al., 2014). Because of this focus, it is not yet clear how the different city models and indicators can combine to provide the knowledge and possible guidelines needed to improve the sustainability and resiliency of real cities (Sharifi, 2016). This author highlights the different classic models, their relevancy and role on the quest for sustainability in urban planning and evaluates the degree of sustainability incorporation in the different layouts.

Far-reaching and multidisciplinary comparative analyses between different city layouts are uncommon and were mostly done in a qualitative way. Past debates on the ideal spatial layout of cities include Lynch, 1960, Fishman, 1982 and Frey, 1999, the latter standing out as one of the most important pieces of research made on the study of urban and spatial planning, whose conclusions are still valid to this day. Similarly, to the present research, Frey analyzed and compared six different classic models designs based on several (qualitative) indicators. However, this qualitative nature and the need for various assumptions lead to many inaccuracies on the results, as Frey himself recognizes. The present research aims to overcome this problem and contribute to the literature by proposing *quantitative* indicators and a MCM to compare city layouts. As far as the authors are aware, other quantitative comparisons between different full-scale city models based on their urban form and resorting to objective indicators do not exist in the literature. This research fills that gap by proposing both a methodology and by carrying out an extensive benchmarking study on the best-known classic city models.

One final word to note that quantitative methodologies do exist to assess performance of the urban environment, such as e.g., LEED, BREEAM, CASBEE or the urban morphometric approach of Momepy ("BREEAM Communities - BRE Group,", 2022; "CASBEE For city scale,", 2024; "LEED certification for neighbourhood development,", 2024; Fleischmann, 2019), but these consider indicators that may diverge considerably from the scope of this study or may be intricate to encapsulate with straightforward parameters, making them unsuitable to estimate the criteria considered in this research. Space syntax (Hillier, 2007; Hillier et al., 1976; Yamu et al., 2021) is another quantitative way to analyze spatial layouts and human activity patterns in urban areas. Space syntax focuses on measuring how well connected an urban environment is and how much accessible and legible it is. While the approach shares some similarities with the methodology presented in this research, space syntax is done mostly from a social and urban vibrancy perspective, whereas this article focuses more on obtaining figures that go beyond that.

2. Methodology

The methodology to benchmark city models based on their urban form, or layout revolves around redistributing a city's geographic elements according to the alternative layouts under study (Monteiro et al., 2022). The criteria by which each layout is evaluated consists of indicator values that depend on the layouts and are calculated in a GIS environment. The set of alternatives and criteria values form the so-called decision matrix in multicriteria analysis. The outcome of this analysis may come in several guises, depending on which multicriteria method is applied. This article uses the TOPSIS method, a ranking method whose output is a quantitative figure that may be termed the "Combined Spatial City Index" (CSCI) for each layout.

The geographic elements of a city consist of three datasets: #1 origins (O), residential buildings centroids representing trip demand (endowed with inhabitants per building); #2 destinations (D), urban facilities and jobs, representing the supply of interaction opportunities; and #3 the road network, which connects origins to destinations.

This approach is now detailed and further demonstrated with a case study for the city of Coimbra, Portugal, in which its actual layout was compared to six other layouts, according to the benchmarking methodology. When redrafting Coimbra, the number of inhabitants and jobs was kept equal to that of the real city. For urban facilities similar, but smaller numbers than those real Coimbra were considered, as preserving the original numbers in the alternative layouts would just create supply redundancy. Nevertheless, the lowest distortion possible was soughtafter.

The quantitative indicators, i.e., the criteria whose scores form the decision matrix, were selected due to their importance for city planning and their intrinsic correlation with the urban layout. They also check important boxes: they are objective, calculable in GIS, and relate to efficiency, sustainability and social aspects of today's urban life. Motivation and calculational details are presented below.

2.1. Accessibility

Accessibility is a wide-ranging concept that is being increasingly incorporated into city form and design (Deboosere et al., 2018; Guerra, 2017; Kompil et al., 2019). Accessibility directly relates to the urban layout, transport planning, land use, socioeconomic factors, and environmental goals (Bertolini et al., 2005; Gil Solá et al., 2018; Shen et al., 2020; Verma et al., 2019). As a sustainable development strategy, accessibility by active modes emphasizes proximity and local daily living, as opposed to long distance and energy-intensive transportation (Banister, 1995; Handy, 2002; Monteiro et al., 2024; Papa & Bertolini, 2015). The classic definition of accessibility, as the ease, or more widely, the cost of reaching destinations (Boisjoly & El-Geneidy, 2017) was considered for this research. Cost-based views of accessibility have been used on spatial and transport planning (Apparicio et al., 2008; Bruinsma & Rietveld, 1998; Geurs & van Wee, 2004; Jiao et al., 2020; Miller, 2018; Monteiro et al., 2022; Monteiro, Para, Sousa, et al., 2023; Ryan & Pereira, 2021; Shen et al., 2020; Vale et al., 2016; Zhou et al., 2018). The accessibility indicator selected for this research is akin to that used by Monteiro, Carrilho, Sousa, et al. (2023), Monteiro, Para, Sousa, et al. (2023), Monteiro, Sousa, Natividade-Jesus, and Coutinho-Rodrigues (2023c, 2023d), Monteiro, Sousa, Pais, et al. (2023), Monteiro et al. (2022), Schläpfer et al. (2021) and Sousa et al. (2018). It is given by:

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

where

i: $1, \ldots, I$ number of origins;

j: $1, \ldots, J$ number of facility types (includes jobs);

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 centroid).

w_j: weight of facility type j (destination attractiveness);

L_{kj}: freedom of choice factor for the k-th closest facility of type j; $L_{kj} > L_{k+1,j}$.

This accessibility indicator can be interpreted as the average distance from origins to destinations, weighted by destination attractiveness and by choice factor. It can be further weighted by the number of inhabitants of the origin, h_i (representing demand) to yield the (doubly weighted) average distance per inhabitant to all destinations.

Some considerations with respect to destinations are due at this point. A total of 20 destination types were considered: 19 urban facilities, plus jobs. Destination weights were assigned as according to their trip frequency. A 1–2-3 scale was used for urban facilities (Monteiro et al., 2022) and $w_j = 22, j:\text{jobs}$, in accordance to the commuting trip share for Coimbra of 37 % (Pais et al., 2022).

The choice factor is used to model supply diversity, i.e., the fact that for some facility types, inhabitants might wish to be able to choose between two or more. Since by convenience the closest ones will be preferred, the inequality $L_{kj} > L_{k+1,j}$ follows naturally. In this research the set $L_{kj} = \{70, 20, 10\}$ was used. Note that choice factor does not apply to all facilities. For some, e.g., post-offices or primary healthcare, people usually choose the closest one. These will be called "closest-only" facilities and are equivalent to using $L_{kj} = \{100, 0, 0\}$ (this is also why L has an index j, as it depends on the facility type).

Another issue, which concerns active travel modes, is as follows. The propensity to use an active mode depends on the distance to destination. For some destination types, e.g., bakeries or grocery stores, the permanence time at destination is short, and the person feels as if she effectively must travel twice the distance. Other facility types, e.g., cultural or entertainment sites, have long permanence time, allowing the person to rest at destination. This makes it more plausible that the traveler is only deterred to use an active by distance itself, not twice its value. Thus, for some facility types, the distance used to calculate active trip probability was twice the OD distance. These will be called "extended trips".

Finally, the jobs destination type requires a special treatment. Jobs require employees to go where their job is located, so the notion of "closest job" does not apply. Instead, a zone analysis was considered, as previously used in literature (Jiao et al., 2020; Wang, 2000). For each city layout, the study zone was divided according to neighborhood similarities. Then, job locations and employee count in each zone were used to obtain the geometric average job location for that zone. Accessibility to jobs was then calculated using Eq. (1) with

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

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 average job location of zone z.

Table 1 summarizes the above considerations on destinations.

The above destination types are likely to appeal to most inhabitants. Different types could be considered depending on cultural and contextual factors (see, e.g., (Roy, Majumder, Bose, & Chowdhury, 2023) for an example).

2.2. Active transport modal share

Active transport, such as walking or cycling, has been widely promoted worldwide (City Cycling, 2012; Scotini et al., 2017; United Nations Economic Commission for Europe, 2020; Wegener et al., 2017) as an affordable, equitable and inclusive means of transport that promotes energy efficiency and overall sustainable and resilient urban environments (Grow et al., 2008; Hino et al., 2014; Kahlmeier et al., 2021; Lamíquiz & López-Domínguez, 2015; Nourian et al., 2018; Vale et al., 2016; Zannat et al., 2020). Fostering active travel can also mitigate the spread of respiratory pandemics in urban environments (Monteiro, Sousa, Natividade-Jesus, & Coutinho-Rodrigues, 2023d). Strategies

Table 1
Characterization of destination types.

Destination type	Weight	Choice type	Extended trip?
Post offices	1	Closest	Yes
Sports facilities	1	*k*-closest	Yes
Cultural organizations	1	*k*-closest	No
Higher education institutions	1	*k*-closest	No
Elderly care centers	1	*k*-closest	No
Churches	1	*k*-closest	No
High schools	2	*k*-closest	No
Shopping centers	2	*k*-closest	Yes
Entertainment sites	2	*k*-closest	No
Primary healthcare services	2	Closest	No
Pharmacies	2	Closest	Yes
Restaurants	2	*k*-closest	No
Parks and green areas	2	Closest	No
Kindergartens	3	Closest	Yes
Primary schools	3	Closest	Yes
Middle schools	3	Closest	No
Grocery stores	3	*k*-closest	Yes
Supermarkets	3	*k*-closest	Yes
Bakeries and pastry shops	3	*k*-closest	Yes
Jobs	22	Job zone analysis	No

towards achieving higher active transport modal share are gaining traction worldwide and directly relate to planning policies and the urban design itself (Glazener & Khreis, 2019; Handy et al., 2002; Heinrichs & Jarass, 2020; Koszowski et al., 2019; Nielsen & Skov-Petersen, 2018; Saelens et al., 2003; Tight, 2016; Vale et al., 2016).

Estimation of active transport modal share followed the methodology of Monteiro, Carrilho, Sousa, et al. (2023) and Monteiro, Para, Sousa, et al. (2023) and was determined by transforming trip distances onto active trip probabilities using log-logistic distributions. Albeit trip probability is inversely monotonous to distance, the relation is non-linear, which justifies studying the two variables separately.

Walking and cycling were considered as the active modes. However, rather than making separate analyses for both modes, the option was made to combine both modes onto one active trip probability indicator following the method of (Monteiro, Sousa, Natividade-Jesus, & Coutinho-Rodrigues, 2023d). Its outcome is to provide a number, p^k_{Aij}, which represents the probability of active travel, i.e., walking or cycling, from origin i to the k-th closest destination of type j. With this number, the modal split can be calculated, as follows:

$$M_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} p^k_{Aij}}{\sum_k L_{kj}}, \tag{3}$$

where

M_i: active modal share of origin i;

p^k_{Aij}: active trip probability from origin i to the k-th closest destination of type j, with

$p^k_{Aij} = \sum_z f_z p_{Aiz}$ for j: jobs (p_{Aiz}: active trip probability from i to average job location of zone z).

The p^k_{Aij} was based on the log-logistic curve (Hilbers & Verroen, 1993) and depends on distance accordingly, with high probabilities and slow decay at short distances, gradual and steeper decay afterwards, and very low probabilities for long distances. Details on how p^k_{Aij} was obtained can be found on the supplementary materials, Section 1.

2.3. Transport energy consumption

Trips not made by active modes require motorized transport, which in turn consumes energy and typically produces greenhouse gas (GHG) emissions. Since the fraction of non-active trips is represented by $1 - p^k_{Aij}$, it suffices to estimate the energy consumption associated to this fraction. In Coimbra motorized trips resort almost totally to fossil fuels, with a modal split of 70 % for private cars and 30 % public transport (Metro Mondego, 2011). Thus, the following expression was used to obtain transport energy consumption (Monteiro, Para, Sousa, et al., 2023; Monteiro, Sousa, Natividade-Jesus, & Coutinho-Rodrigues, 2023c):

$$E_i = \frac{1}{\sum_j w_j} \sum_{jk} \frac{w_j L_{kj} \left(1 - p^k_{Aij}\right) \left(f_{car} F_{car} + f_{pub} F_{pub}\right) \left(d_{\overrightarrow{ijk}} + d_{\overleftarrow{ijk}}\right)}{\sum_k L_{kj}}, \tag{4}$$

where

E_i: average fuel consumption of accessibility-related trips originating in i;

f_{car}: fraction of motorized trips made using the private car;

f_{pub}: fraction of motorized trips made using public transport;

F_{car}: private car average fuel economy (MJ/passenger.km);

F_{pub}: public transportation average fuel economy (MJ/passenger.km);

$d_{\overrightarrow{ijk}}, d_{\overleftarrow{ijk}}$: 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) and trips are always considered as two-way regardless of facility type. Motorized fuel consumption is assumed to be 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport (International Energy Agency, 2018).

Note that transport energy consumption depends on the non-active fraction, which is non-linear on distance, and then gets multiplied by distance itself. Like active modal share, transport energy consumption is monotonous to accessibility in a non-linear way that twice-penalizes long distances, which again justifies treating it separately. Another source of non-linearity between accessibility, active share, and energy is that transport energy always requires consideration of the return trip, regardless of a trip being extended or non-extended. However, in calculating p^k_{Aij} for non-extended trips, the return trip distance is not considered, making non-extended trips less energy-consuming for the same distance, as they are more likely to be carried out by active modes.

2.4. Route directness

Although for most transport related analysis network distances are preferred to the straight-line, or Euclidean distances (Buczkowska et al., 2019; Mora-Garcia, 2018), the latter may be of use as a reference for network performance. Route directness (Stangl, 2019), also termed detour index or circuity (Costa et al., 2021), is the ratio of the shortest distance between two points on a network to the Euclidean distance between these points. Directness is a permeability, or connectivity, indicator, i.e., a measure of the extent to which urban form facilitates (or restricts) the movement of travelers, and a proxy for mobility (Gonçalves et al., 2014; Lu et al., 2014; Marques & Pitombo, 2021; Stangl, 2019). It has also been used to study active transport in the context of filtered permeability, i.e., different permeability for different modes (Melia, 2012; Silavi et al., 2017; Soltani, 2005).

To decouple accessibility from mobility, instead of the OD routes used in (1–2), the following procedure was used to evaluate route directness. A square mesh of neighborhood size (282 m × 282 m; diagonal of 400 m, a walkable distance) was created in GIS over the study area, together with its associated centroids. To remove squares outside the study area, those with a centroid more than 150 m away from the network were deleted (for Coimbra this threshold was lowered to 50 m to reduce computational complexity). Then network and Euclidean trip distances from each centroid to all other centroids were obtained and directness was calculated using:

$$D_{ij} = \frac{d_{ij}}{E_{ij}}, \forall_{ij} \in \text{set of mesh centroids} \tag{5}$$

where

d_{ij}: network distance between mesh centroids i and j.

E_{ij}: Euclidean distance between mesh centroids i and j.

Route directness improves as the ratios D_{ij} get closer to 1, since network distances get closer to the shortest possible distance. The average of D_{ij} can then be calculated and used as global directness indicator for each city layout.

As a proxy for mobility, directness is limited, in that it does not consider aspects such as traffic congestion or intersection turn times. However, obtaining a more representative global mobility indicator would require running traffic simulations, which are out of the scope of this research.

2.5. Pleasantness

Urban pleasantness is a concept with social, proximity, and physical aspects (Skifter Andersen, 2011). Proximity aspects were included in the accessibility indicator and social ones tend not to depend on the urban layout. Thus, this indicator concentrates on physical pleasantness. Human perception of the pleasantness of the physical urban environment is related to well-being, better quality of life and sustainable development (Mouratidis, 2021) and has been an active topic of research (Alexander et al., 1977; Cullen, 1995; D'Acci, 2019; Lee, 2021;

LI et al., 2022; Monteiro, Carrilho, Sousa, et al., 2023; Sousa et al., 2023; Wang et al., 2021; Yaran, 2016; Zhang et al., 2021).

As a quantitative indicator was needed, this research evaluated the perceived physical pleasantness following (Sousa et al., 2023), an ordinal regression model based on geometric and land use qualities of the urban environment, evaluated at the neighborhood level. The model has five explanatory variables, namely green area percentage, street width, number of floors, building distance, and existence of green private area, which estimate perception of pleasantness in a 1–5 Likert scale. Details on this model can be found in Section 2 of the supplemental materials. The results of (Sousa et al., 2023) show that people tend to prefer higher percentages of green areas, wider streets, a lower number of floors, small building distances, and having green private areas.

Similarly to the calculation of route directness a neighborhood-size square mesh was used to evaluate the explanatory variables for each layout. Neighborhood-scale values were extracted for each explanatory variable, from which neighborhood pleasantness expectation values were derived. Squares with no inhabitants were removed from the calculations.

2.6. Mix land use

Mix land use is an important attribute of the urban built environment (Handy et al., 2002) and a common topic in urban planning for sustainability (Abdullahi & Pradhan, 2018; Bibri, 2020; Cheng et al., 2015; Roo & Miller, 2020), since higher degrees of this indicator lead to better proximity life, vibrancy, environmental quality, and comfort. Indeed, neighborhoods with high mix land use have many activities going on, both simultaneously and sequentially throughout the day, ranging from work to services to cultural offer. This leads to vibrant, busy streets and people circulating all the time, which, together with proximity, creates a sense of belonging and of safety (Ding et al., 2017, 2014; Glazener & Khreis, 2019; Handy et al., 2002; Kirdar & Cagdas, 2022; Koszowski et al., 2019; Li & Zhao, 2017; Meng & Xing, 2019; Sousa et al., 2023; Vale et al., 2016; Wu et al., 2022; Zahabi et al., 2012).

A square mesh of neighborhood size was again used as unit to evaluate mix land use. For each city layout, neighborhoods were evaluated for the existence of eight different types of possible land use: residential, educational, entertainment and cultural, commercial, parks and green areas, industrial and offices, healthcare, and governmental and institutional (Song et al., 2013). A neighborhood unit can have up to eight different land use types (highest score) or only one (lowest score). Neighborhoods without dwellings or facilities, i.e., whose land use does not correspond to any of the type above, were deleted, as these correspond to rural or otherwise non-urbanized land parcels.

2.7. Multicriteria methodology

The six urban layout benchmarking indicators are criteria representing different dimensions of reality. When comparing alternatives against multiple, often conflicting, dimensions, a multicriteria method is the appropriate assessment tool. It is important to note that multicriteria analysis does not necessarily yield a "optimum solution"; it merely offers the decision-maker a viewing window for the trade-offs that occur when choosing between the different alternatives, in this case the city layouts. Multicriteria methods also imply setting parameters. Some may relate to technical aspects of the method, while others, such as e.g., criteria weights, reflect different perspectives of the decision-maker. Multicriteria analysis has been widely used in urban and spatial planning and is an important day-to-day tool for municipal authorities (Coutinho-Rodrigues et al., 2011a; Criado et al., 2017; Kabir et al., 2014; Kutty et al., 2023; Marull et al., 2023; Mosadeghi et al., 2015; Nijkamp et al., 2013; Schetke et al., 2012).

The rank multicriteria method selected was TOPSIS, one of the most widely-used methods of this kind in the literature and frequently applied in urban and spatial planning research (Aragão et al., 2023; He et al., 2017; Komasi et al., 2023; Masoumi & Genderen, 2019; Ogrodnik, 2019; Stachura & Kuligowska, 2021; Zhang et al., 2020; Zinatizadeh et al., 2017), including its integration with GIS environments (Coutinho-Rodrigues et al., 2011b; Janssen & Rietveld, 1990; Panagopoulos et al., 2012; Yang et al., 2008). TOPSIS was especially recommended for public sector procurement by Adil et al. (2014). TOPSIS works by measuring criteria weighted distances of the alternatives (city layouts) to two reference points: the ideal and anti-ideal. These are two hypothetical alternatives whose criteria values are the best (respectively worst) scores of each criterion among the set of all alternatives under consideration. The result is a rank for each alternative, in a [0,1] interval scale, with 0 (worst) to 1 (best). Details on the method, including formulas and the calculation procedure, can be found in Triantaphyllou (2000).

3. Case study: a real city vs. its redrafts as six different city models

The methodology proposed to benchmark the different layouts was applied in a comparative analysis between the real city of Coimbra, Portugal, with its redrafts as six different city models. For this purpose, the geographic elements of real Coimbra were redisposed following the above-mentioned city models for a total of seven layouts to be compared. Of the six models, five represent classic city models and were chosen based on their impact on urban planning and policies. These models span circa a century of trends in the planning field and have, directly or indirectly, been considered on the urban development of cities worldwide.

Each of the six hypothetical layouts was obtained by moving residential areas, urban facilities, job locations, and redesigning the road network, all according to the principles guiding each city model. As noted before, in these redrafts of Coimbra, the number of actors in play, i.e., inhabitants, urban facilities, and jobs, was preserved as much as possible, to keep a baseline for comparison. To redraft the real city as an classic model, a comprehensive analysis was carried out for each model's blueprints, general urban form and design, land-use features, inhabitants' distribution and general population density, mobility considerations, policies, and underlying ideas. This in-depth analysis also involved some trial and error and, moreover, as some of the classic models, e.g., the Garden City, are over a century old, the redraft had to consider adaptations to the 21st century. When redrafting, provisions for walking and cycling were considered, namely street space would be wide enough to ensure adequate separation for cycleways and sidewalks. The consideration of widespread active infrastructure in the redraft versions of Coimbra is justified because those redrafts are modern interpretations of classic models and thus should cater for sustainability issues of today. Existence of adequate infrastructure fosters active travel and greatly mitigates its main deterrent, the lack of safety from traffic (see, e.g., Monteiro, Para, Sousa, et al., 2023). When active travel is safe and pleasant, people are more likely to adopt it. The following subsections motivate and give procedural details for each layout. Original GIS datasets for Coimbra were available from previous projects of the research team, updating where needed. Datasets for the redrafts were drawn on a per-case basis by the team.

3.1. Coimbra, Portugal

Coimbra is a mid-sized city in the center of Portugal with 106,768 inhabitants, founded in the Roman age (Instituto Nacional de Estatística, 2021), with higher education and healthcare as its main economic activities. Due to its occupation by different cultures, Coimbra grew mostly in an unrestricted way. Coimbra had a compact layout in its origin and the medieval times, mostly concentrated on a hill for defensive reasons. In the modern era, and similarly to many cities at the time, Coimbra grew and evolved in the wake of the cheap fuel boom of the 1950s onwards, developing onto a low-density, low-mix pattern of land use and sprawled urban environment, with wide streets to accommodate the motorized traffic. Fig. 1 shows the city evolution towards sprawl. Between 1930 and 2021 the population increased 190 %, but the urban area of the city increased 5018 %, demonstrating the sprawling.

The origins, destinations, and road network GIS datasets for Coimbra were available from previous team projects. Survey data relating to daily trips shows circa 19 % active mode share, of which only 0.2 % is cycling. Motorized transport complements the remaining percentages, from which a 30/70 % split between public transport and private car, respectively was observed (Metro Mondego, 2011). Commuting trips in Coimbra represent 37 % of total trips (Pais et al., 2022).

3.2. Infill Coimbra

The sprawling of Coimbra resulted in many spaces left unurbanized, as well as spaces that became derelict over the years. The Infill redraft, presented in Monteiro, Para, Sousa, et al. (2023), made use of those available spaces by filling them with new residential buildings, urban facilities or jobs located on the outskirts of the city, in full compliance with the current municipal regulations, the development master plan and codes of practice. New land plots were infilled with residential, commercial and mix use buildings that would house inhabitants moved in from the city peripheries. Results showed that 40 % of Coimbra's current population could migrate inside the city's new perimeter. Urban facilities located on the outskirts were also moved inside while retaining their original business volume. The total urbanized area of the city was reduced from circa 142,000 m^2 to 16,700 m^2, a reduction of 88 %, as Fig. 2a and b show. This reduction also impacted accessibility, active modal share, and transport energy consumption. Exact figures for these indicators are given in the results section. The reader is referred to Monteiro, Para, Sousa, et al. (2023) for more information on the infill procedure.

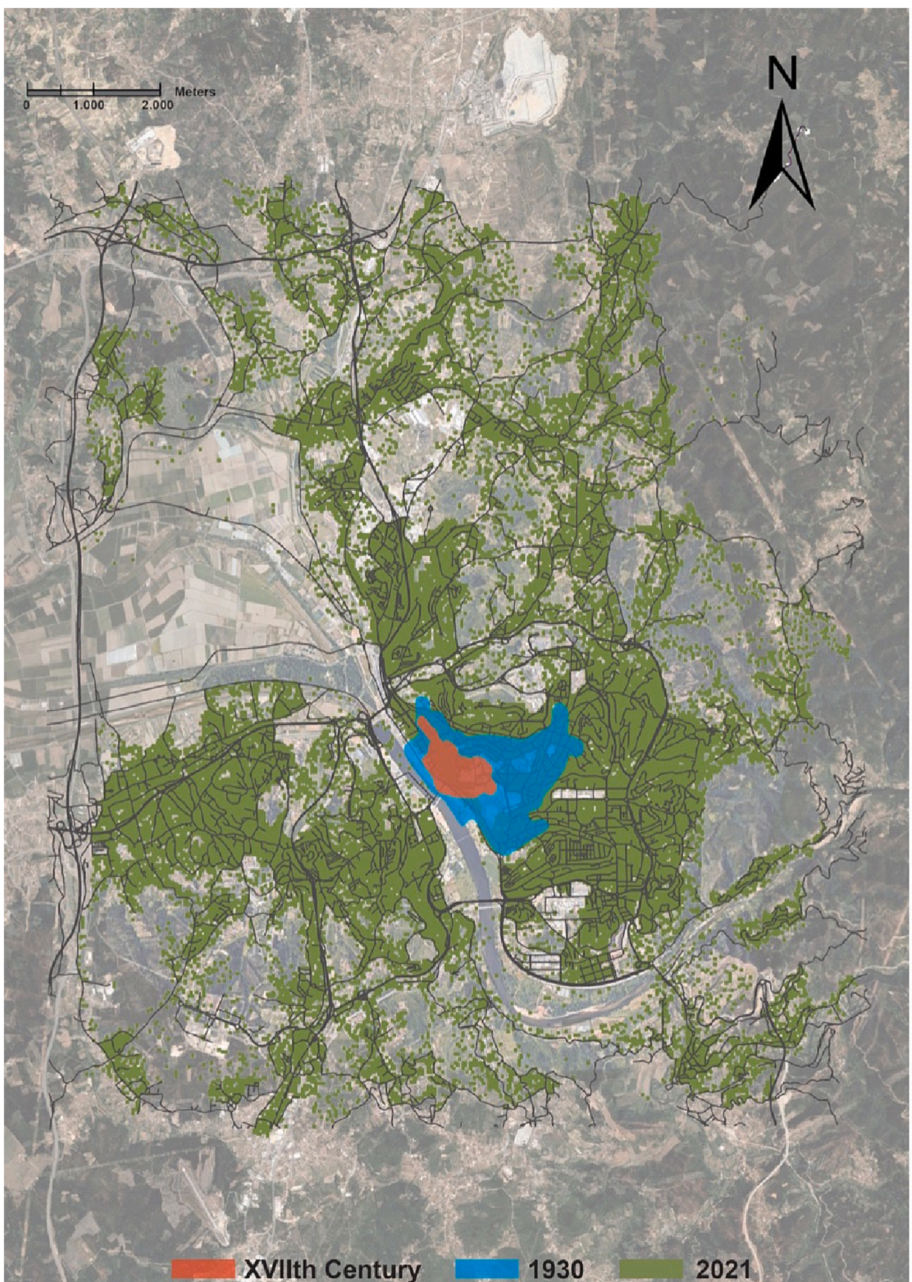

Fig. 1. Evolution of Coimbra's urban perimeter and population (Monteiro, Para, Sousa, et al., 2023).

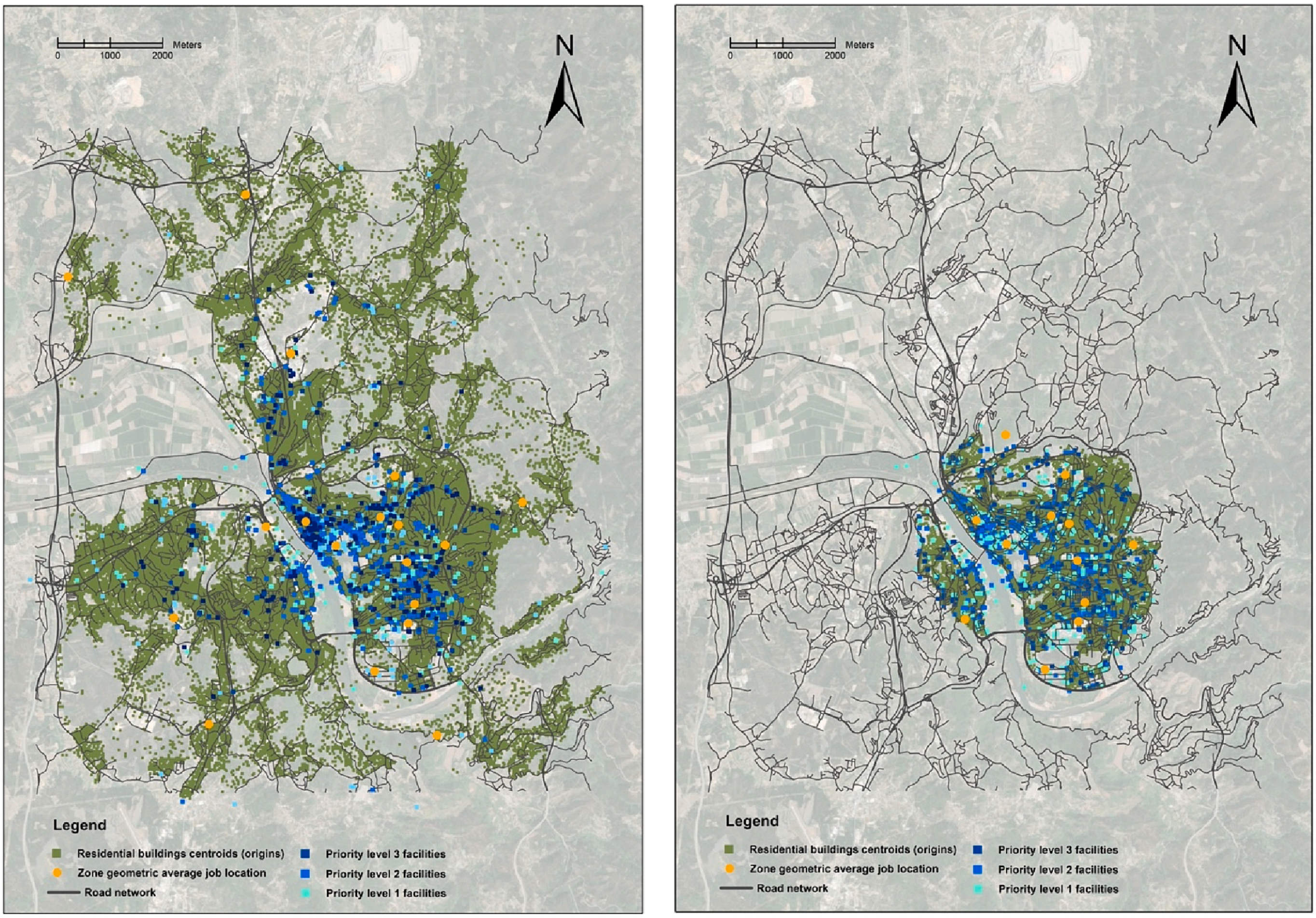

Fig. 2. Origins, destinations, and road network. (a) Layout of Coimbra; (b) Layout of Infill Coimbra (Monteiro, Para, Sousa, et al., 2023).

3.3. The Garden City

The Garden City concept was created by Ebenezer Howard amid the New Town movement in the turn of the XIXth to the XXth century as an alternative to the overcrowded, and industrialized cities like London (Gillette, 2010; Hügel, 2017a). According to Howard's plans (Howard, 2010), the city would house around 30,000 inhabitants, in its hallmark circular shape of ring-like concentric zones, with clear land-use specifications encompassing residential areas, green parks, and a full range of industrial, cultural, and commercial facilities. City expansions would be achieved via the creation of hexagon-like clusters of Garden Cities that together would form the Social City (Howard, 2010). More than a century later, the Garden City is still present in academic research (Hügel, 2017b; Monteiro et al., 2022; Sharifi, 2016; Yuan et al., 2014) and is considered as a valid solution for the expansion or the development of new cities (Blundell, 2019, p. 3; Duxbury, 2019; GOV.UK., 2019).

Coimbra's redraft as a Garden City followed Howard's descriptions and blueprints which, considering the population of Coimbra, led to a cluster of three Garden Cities (Fig. 3). The distribution of facilities was made in two stages: in the first stage the smaller facilities were placed in an equal number throughout the three Garden Cities; in the second stage the larger facilities (e.g., regional hospitals) were distributed according to their actual location in Coimbra. The original Garden City and Coimbra's redraft as this model are presented in Figs. 3 and 4. For more details on the redraft, see Monteiro et al. (2022).

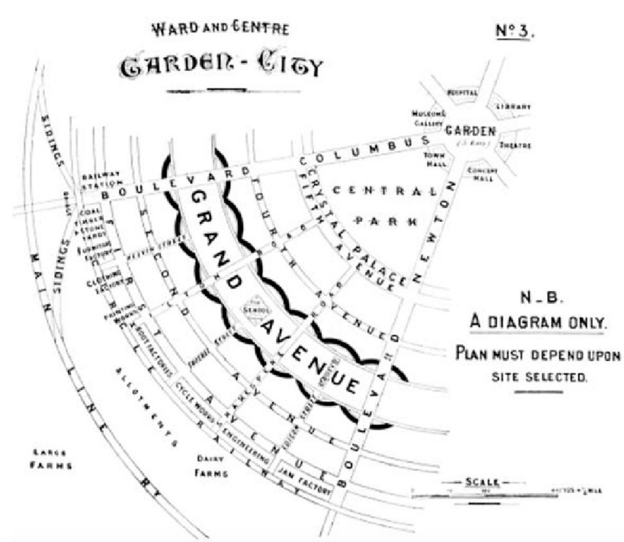

Fig. 3. The Garden City model: layout of a ward of the Garden City (Howard, 2010).

3.4. Ville Radieuse

Ville Radieuse was a project of Le Corbusier developed between 1920 and 1940 (Cirlot, 1971; Fishman, 1982), to be implemented in cities such as Moscow or Paris. The Ville Radieuse layout main characteristic is its landmark skyscrapers. In its larger version, the skyscraper could hold around 100,000 inhabitants and expansion plans would be implemented by adding new skyscrapers (Blake, 1996; Cirlot, 1971; Corbusier, 1987).

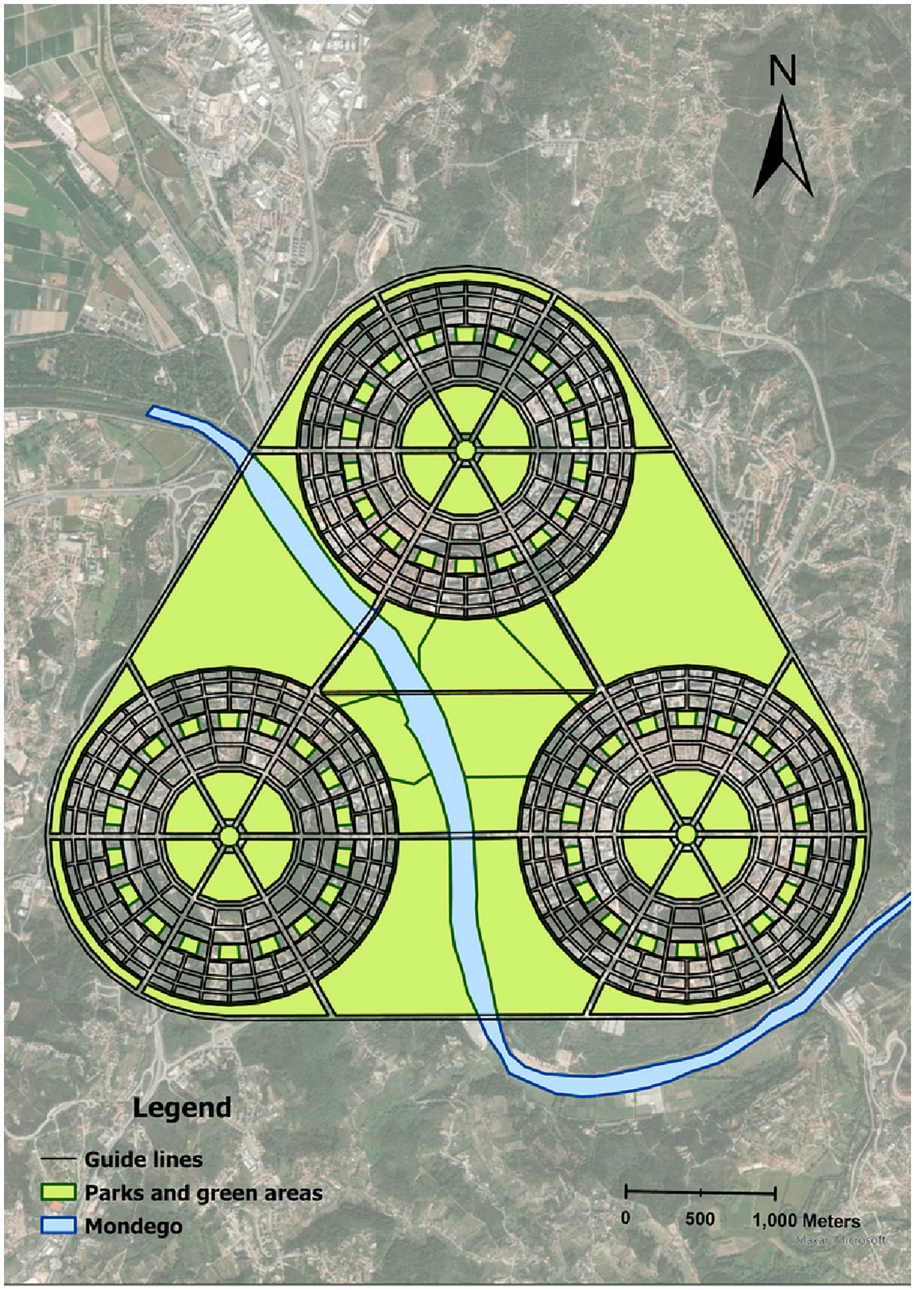

Fig. 4. Coimbra redrafted as the Social City (Monteiro et al., 2022).

The Ville Radieuse city center would encompass an intermodal station, streets with wide sidewalks, parking spaces, and roads of four lanes on each direction. Above the streets, perpendicular concrete bridges formed two axes of arterial roads for fast one-way traffic. Ville Radieuse was idealized for mobility and a central role for the car. The city center skyscrapers would house offices, services, and commerce. From the center, three sides would be filled with residential buildings, with space for local business, surrounded by green areas. Residential skyscrapers could be adapted to fit from a few hundred to thousands of people. The remaining side of the city would be reserved for public buildings, such as universities, city hall, and library. Before reaching a perpetual green belt, two to three stories high residential buildings with private gardens were planned for the higher classes of the society. The city would be complete with an industrial, commercial, and service area on the outskirts. Fig. 5 illustrates the city layout. Ville Radieuse was grounded on four principles: de-congested city center; high density of residential and services; ample means for moving around the city; and generous areas of parks and open spaces (Corbusier, 1987; Le Corbusier and Boesinger, 1955).

The redraft of Coimbra as a Ville Radieuse was carried out following blueprints and the author's notes. The model was adapted to suit Coimbra's population numbers, with population density, facilities location and green areas matched to the original work, resulting in a symmetric urban layout, as Fig. 6 shows.

3.5. *Compact City Theory*

The Compact City Theory was put forward as a planning solution towards urban sustainability (Adelfio et al., 2018; Bibri, 2020; Burton, 2000). One of the first approaches to the Compact City Theory was made by Burnham in Burnham et al., 1909 with the Plan of Chicago, presented in Fig. 7. The model was based on a set of policies that aim for more a compact environment (van Stigt et al., 2013), such as: mix and fine grain of land use, low open-space ratio, high degree of accessibility and street

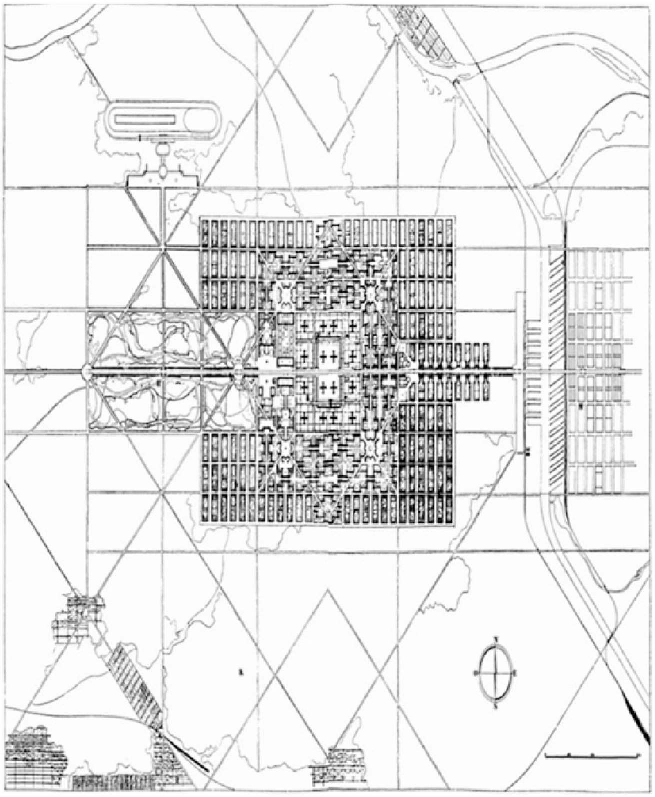

Fig. 5. The Ville Radieuse layout (Le Corbusier and Boesinger, 1955).

connectivity, contiguous development, multimodal transportation, and its hallmark high residential and jobs density (Bunker et al., 2017; Neuman, 2005; OECD, 2012). It stands on the opposite part of the spectrum of urban sprawl with higher proximity, accessibility, decreased car dependency and commuting time, reduced transport energy consumption, and conservation of surrounding natural areas (Bibri, 2020; Kotulla et al., 2019; van Stigt et al., 2013). Downsides of Compact City Theory urbanism come mainly from conflicts between its proclaimed efficiency and citizen well-being due to excessive density (Adelfio et al., 2018; Burton, 2000; Neuman, 2005; Pradhan, 2017; Salingaros, 2006; van Stigt et al., 2013; Williams & Jenks, 1996).

As Compact City Theory is not based on any blueprints or detailed design rules, but rather on a set of planning policies, the redraft of Coimbra as a Compact City Theory layout merely followed those policies. This led to an extremely compact urban environment on both river banks of the Mondego river that crosses Coimbra, a decision made based on the classic evolution of cities, which tend to side river banks (Tellier, 2019). The layout, shown in Fig. 8 was drawn as a grid-like system, similar to the Plan of Chicago.

3.6. Transit-Oriented Development

Despite the relationship between land use and transport planning, many cities have treated these as separate processes (Banister et al., 2007; Boussauw, 2023; Geerlings & Stead, 2003; Lee, 2020), usually with transport planning as a subsidiary (Holz-Rau & Scheiner, 2019; Mattioli, 2014). The lack of assessment tools that combine these two planning aspects left cities without a way to estimate the impact that decisions on one aspect have on the other and on overall sustainability and resiliency (Ainsworth, 2009; Guiliano, 2004; Papa et al., 2008). Transit-Oriented Development (TOD) integrates both transport and spatial planning in a concept that aims at improved sustainability and smart growth (Barton, 1998; Calthorpe, 1993; Cervero, 2009; Tong et al., 2018). The TOD model was developed by Peter Calthorpe (Fig. 9),

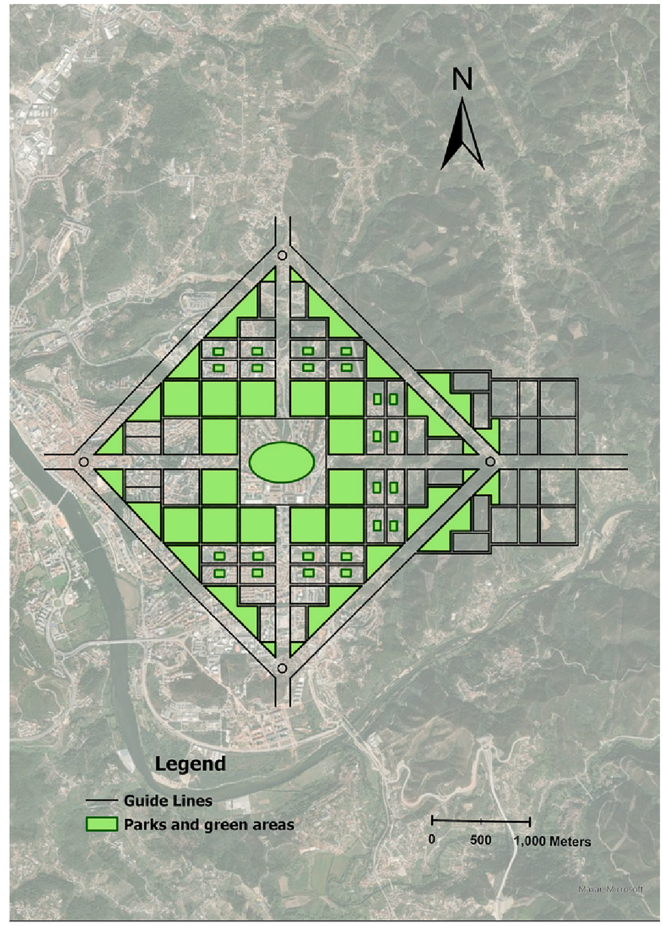

Fig. 6. Coimbra redrafted as a Ville Radieuse model.

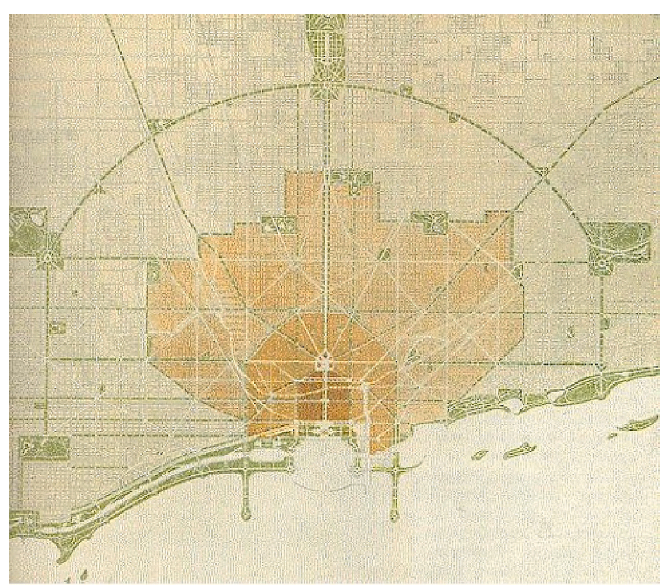

Fig. 7. The Compact City Theory layout: the plan of Chicago (Burnham et al., 1909).

who described it as the integration of the transit system with a compact land use pattern of moderate to high-density housing (Calthorpe, 1993; der Ryn & Calthorpe, 2008). Its policies and strategies target mix land use development, reduction of private motorized transport, provision for

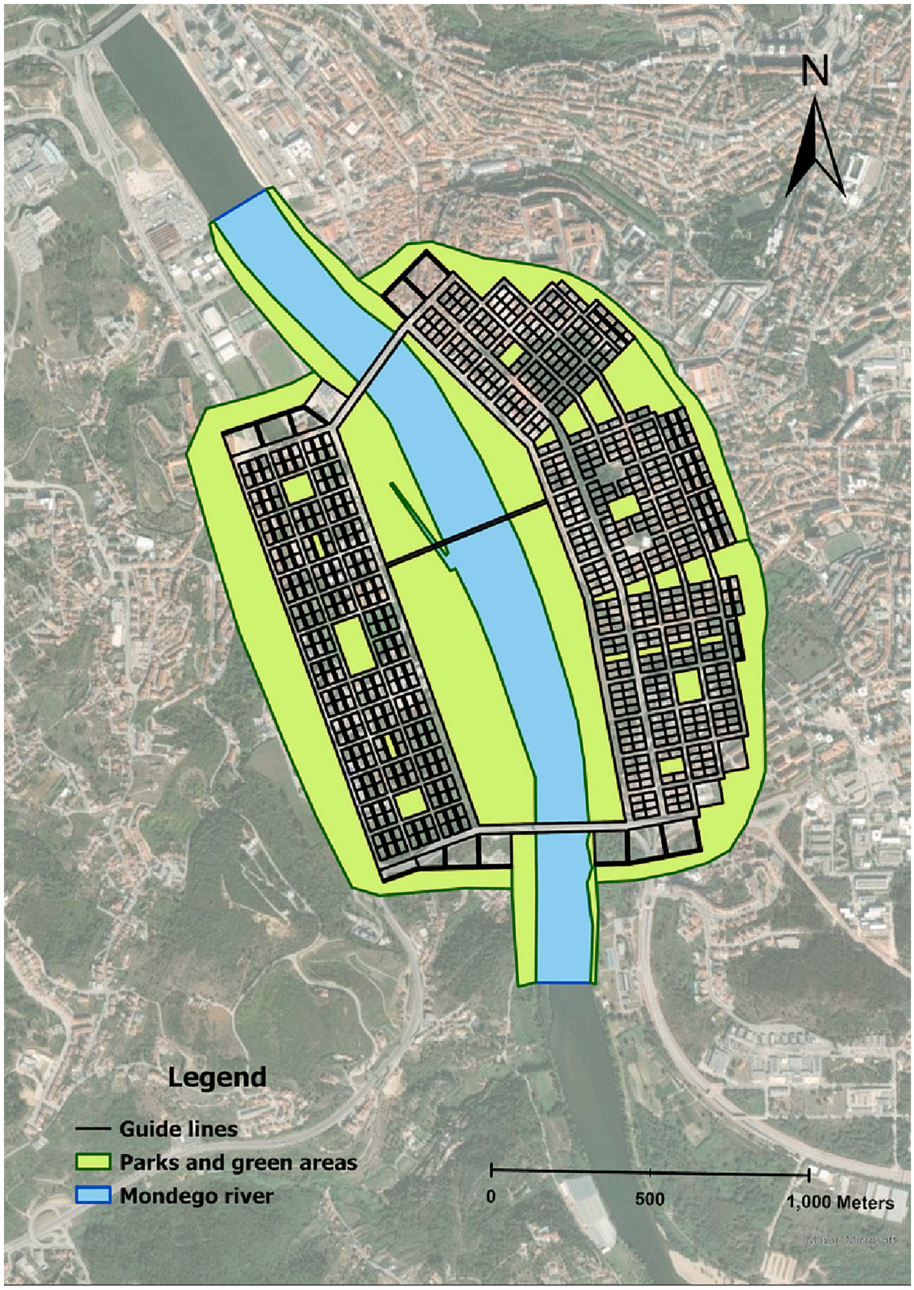

Fig. 8. Coimbra redrafted as a Compact City Theory model.

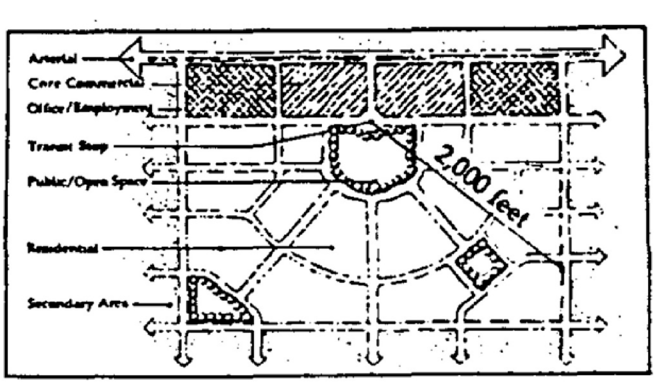

Fig. 9. TOD original blueprints from San Diego guidelines (Calthorpe Associates, 1992).

high-quality pedestrian and cycling infrastructure, and allocation of civic spaces near public transport stations (Bernick et al., 1996; Calthorpe, 1993; Strong et al., 2017). Albeit TOD sometimes gives rise to fuzzy interpretations and practical applications (Singh et al., 2017; Strong et al., 2017; Vale, 2015), overall it is viewed as a city model that deploys both transport and land use interventions combinedly. TOD ideas are present in several urban design models of the past century, namely the work of Howard, Soria y Mata (linear city) or Le Corbusier. TOD has been one an active research avenue in spatial and transport planning, with worldwide cities implementations (Cervero & Sullivan, 2011; Chrisholm, 2002; Knowles et al., 2020; Li et al., 2019; Nasri & Zhang, 2014; Papa & Bertolini, 2015; Parker et al., 2002; Vale, 2015; van Lierop et al., 2017).

Coimbra's redraft as a TOD (Fig. 10) followed Calthorpe's manual for the city of San Diego. The manual contains TOD strategies and policies, blueprints, and detailed analysis on how develop a TOD city (Calthorpe, 1993; Calthorpe Associates, 1992; der Ryn & Calthorpe, 2008). Coimbra

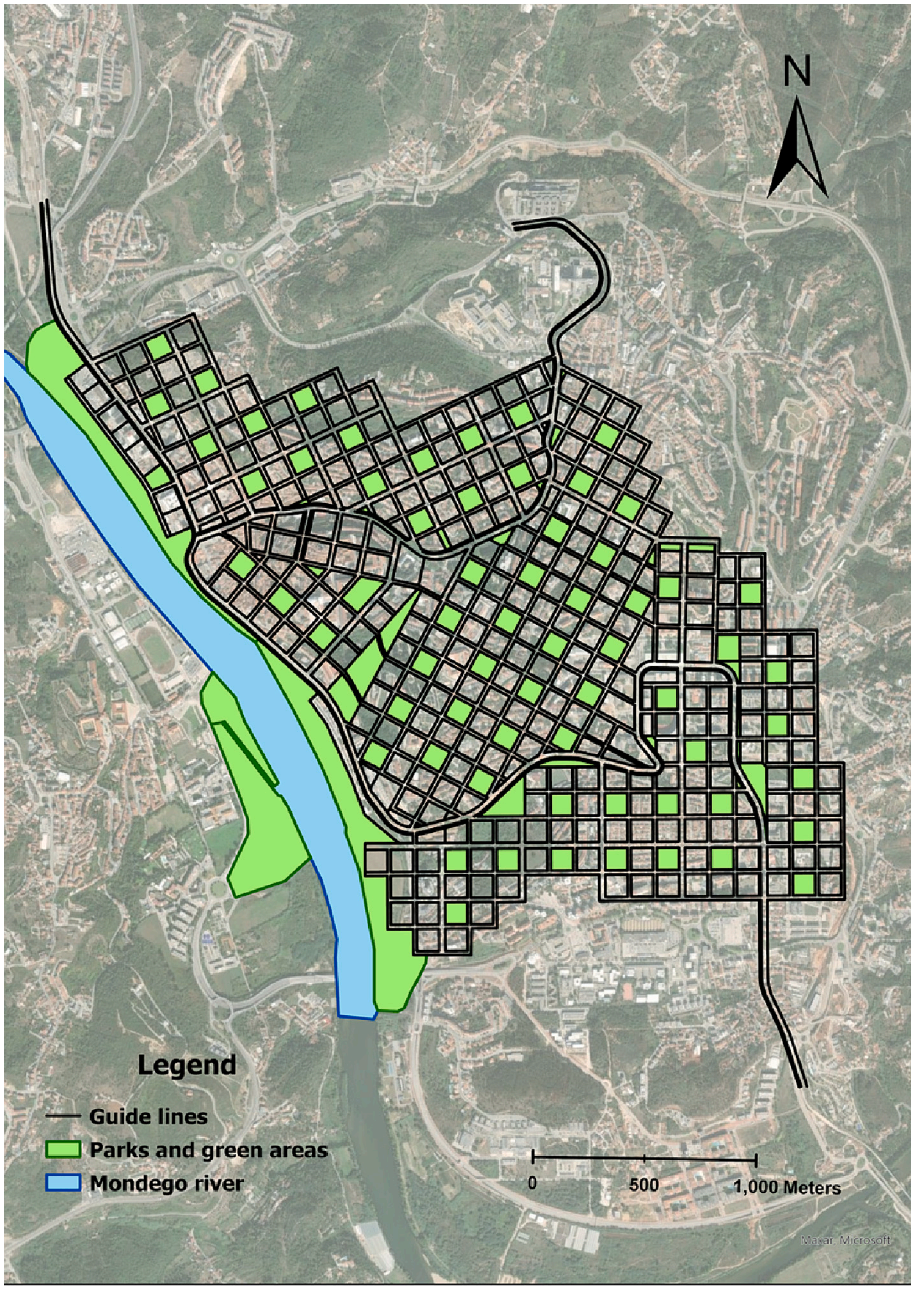

Fig. 10. Coimbra redrafted as a TOD model.

is soon due to upgrade to a Bus Rapid Transit system (BRT), which is expected to become the main mobility option for most inhabitants. The two BRT main lines were considered as basis for the redraft of Coimbra as a TOD city. These lines took into consideration the location of inhabitants, urban facilities, and jobs. As in TOD transit lines take precedence, the city was disposed around them, keeping the main residential zones and urban facilities in situ as much as possible. The redraft itself followed a grid-like network, ensuring that all inhabitants and facilities were kept within a 600 m buffer from a BRT station.

3.7. Transect planning

A transect is a cut or path through a landscape (CATS, 2023a). This concept originated in the biological sciences and was demonstrated by Patrick Geddes in 1909 with a representation of the Valley Section (Bohl & Plater-Zyberk, 2006; CATS, 2023a, 2023b). In the context of urban planning, Andrés Duany proposed Transect Planning as a gradual change from the natural environment towards an urban center, with a wide-range of habitats of increasing degree of urbanization (CATS, 2023a). Many cities worldwide already exhibit transect characteristics. However, the implementation is incoherent, with sprawl along highways, single land use, and a lack of infrastructures for active mobility (Bohl & Plater-Zyberk, 2006; Duany & Talen, 2002; Salingaros, 2006). Transect planning aims at improving this status-quo, giving it a systematic and consistent organization that naturally interpolates between nature and urban center. CATS (CATS, 2023a) developed the SmartCode in 2003, a municipal master plan for Transect Planning which presents the necessary policies, strategies, and layouts for a successful urban design based on a compact, walkable, and mixed-use urban environment (Fig. 11). The SmartCode is adaptable to local context and up to 2007 over one-hundred urban areas have adopted it (Sorlien, 2007).

The SmartCode provided all the necessary guidelines and blueprints necessary to redraft Coimbra as Transect Planning. Urban facilities and job locations were adapted to the code regulations and the redraft,

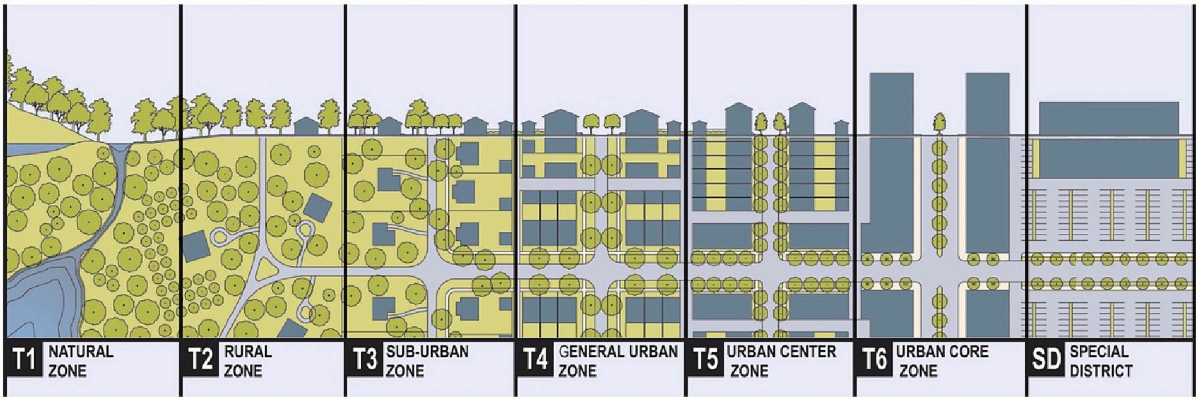

Fig. 11. Transect concept applied to urban planning (CATS, 2023a).

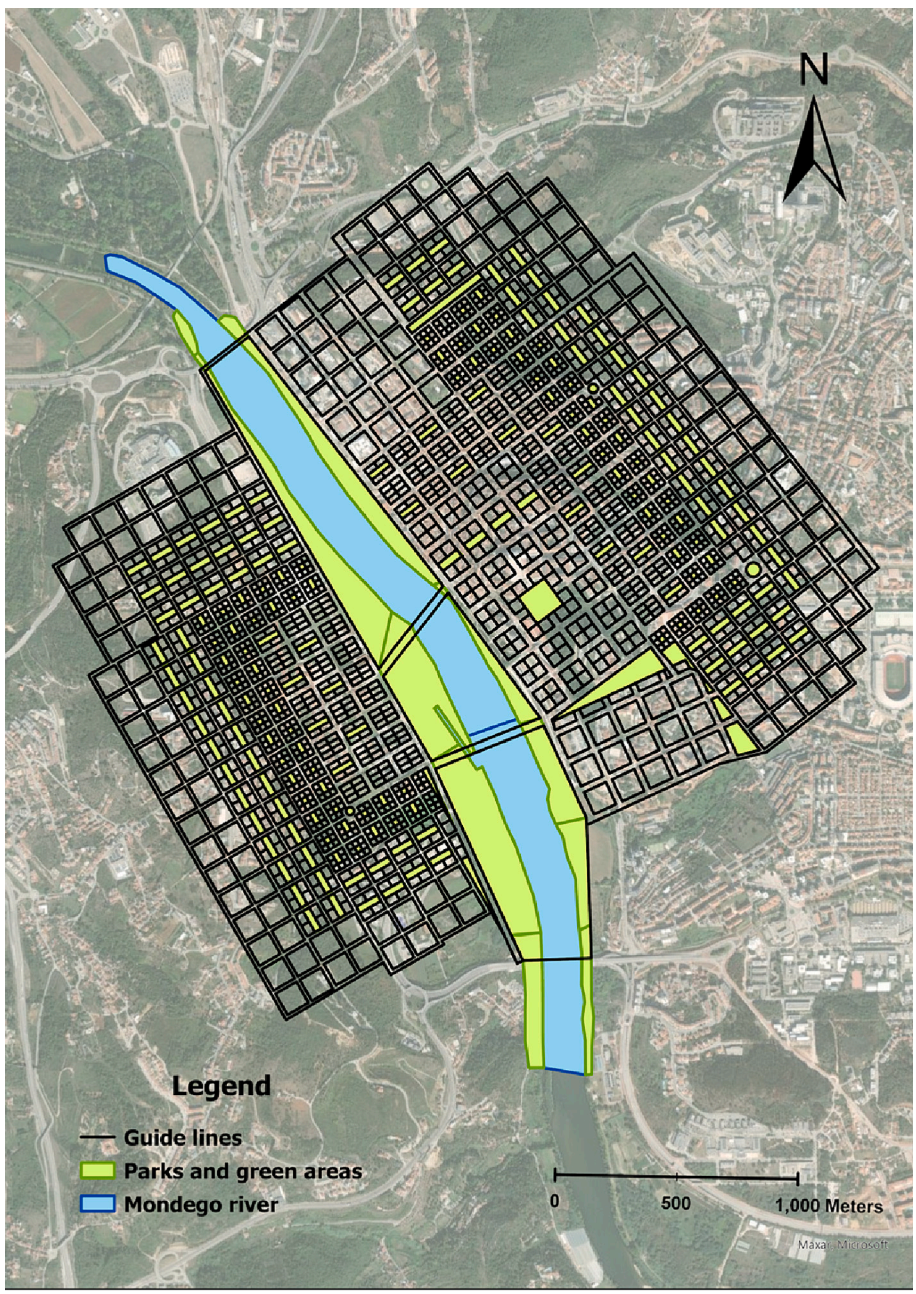

Fig. 12. Coimbra redraft as transect planning.

Fig. 12, turned out similar to that of Compact City Theory, with a city is built on both riverbanks in a grid-like system.

3.8. Summarizing characteristics

Table 2 summarizes the global geographical characteristics of Coimbra after each redraft.

Due to sprawl, the real city of Coimbra has the largest urban area and perimeter, and consequently also requires the longest road network length. Infill Coimbra is smaller, reducing the urban area in 84 % and the perimeter in 65 %. Its road network is similar to real Coimbra, just cut short and with small additions in the new infill sites. On the opposite of the spectrum, lies the Compact Theory, whose redraft has a very small urban area in comparison to the other layouts. The TOD and Transect Planning redrafts are very similar in most characteristics, just as the Garden City and Ville Radieuse are similar in size and perimeter and have the highest areas dedicated to parks and green areas. In general, all redrafts are smaller and more compact than the real city, while managing to keep a better ratio of green area to constructed area.

4. Results

Results are firstly presented and discussed for each indicator, after which the TOPSIS multicriteria analysis is carried out to compare all the layouts. TOPSIS requires normalization of the decision matrix and a ratio normalization was used, as this preserves the proportions between criteria values.

4.1. Accessibility

Accessibility statistics are presented Table 3. Statistics were run over the set of origins *i*, except for the average per inhabitant column, which is given by $\frac{\sum_i h_i A_i}{\sum_i h_i}$.

All redrafts improve accessibility considerably. To test statistical significance of the layout differences a one-way non-parametric factorial analysis at 5 % significance was carried out over the set of origins, namely a Kruskal-Wallis test, followed by post-hoc Dunn tests with Benjamini-Hochberg correction. This yielded an accessibility ranking that can be loosely written as:

$$\text{Compact} = \text{TOD} = \text{Transect} < \text{Ville} < \text{Garden} = \text{Infill} < \text{Coimbra}$$

with "=" standing for statistically equivalent and "<" for statistically different, shorter distances (better accessibility). When considering population weighting, the Infill, Garden City and Ville Radieuse layouts reduce average per inhabitant distances by around 40 % and the more compact layouts, Compact, TOD and Transect, by around 75 %, showing the high impact sprawl has on the real city.

The dispersion measures, which can be seen as a benchmark of equity, improve very considerably for all redrafts of Coimbra, evidencing a striking difference between the inhabitants of the real city that live close to the center and those far away from most urban facilities and job locations.

Table 3
Accessibility statistics.

Layout \measure (m)	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of Var.
Compact Theory	459	572	572	745	61	0.107
Transect Planning	448	748	649	1484	168	0.224
TOD	481	664	623	1008	123	0.185
Ville Radieuse	1010	1337	1230	1819	207	0.154
Infill Coimbra	948	1491	1602	3092	280	0.188
Garden City	1194	1486	1487	1914	171	0.115
Coimbra	1063	3088	2578	9239	1483	0.480

4.2. Active modal share

Table 4 presents the statistics for active modal share. All redrafts double or triple their active transport modal share with respect to Coimbra, with the more compact layouts achieving very high active modal shares, over 85 % per inhabitant averages.

The one-way factorial analysis post-hoc tests reveals an active share statistical rank similar to that of accessibility, namely:

$$\text{Compact} = \text{TOD} = \text{Transect} > \text{Garden} = \text{Ville} = \text{Infill} > \text{Coimbra}, (\text{Garden} > \text{Infill})$$

where the "Garden > Infill" means the differences between those layouts are significant, but not when compared in sequence with Ville. This happens because statistical equivalence is not transitive (i.e., A = B = C does not imply A = C). Considering population weighting the active share tends to improve slightly, as people concentrate on the central locations.

It must be mentioned that the cycling mode requires adequate provisions for its feasibility, i.e., properly designed and maintained cycleways. That is not the case for real Coimbra: the existing cycleways are scattered, fail to link origins to destinations and serve mostly recreational purposes. Consequently, the actual cycling share of Coimbra is far from the 30–40 % it could theoretically aspire to, representing currently only the aforementioned 0.2 %. This might suggest suppressing the

Table 4
Active transport modal share statistics.

Layout \measure	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of Var.
Compact Theory	0.821	0.878	0.878	0.918	0.020	0.022
Transect Planning	0.564	0.817	0.851	0.918	0.059	0.072
TOD	0.702	0.844	0.858	0.910	0.044	0.052
Ville Radieuse	0.440	0.612	0.666	0.730	0.077	0.126
Infill Coimbra	0.289	0.616	0.591	0.763	0.072	0.118
Garden City	0.533	0.624	0.623	0.683	0.029	0.047
Coimbra	0.035	0.356	0.433	0.737	0.187	0.526

Table 2
Redrafts summarizing characteristics.

Summarizing characteristics	Urban area (km^2)	Urban perimeter (km)	Road length (km)	Road density (m/m^2)	Green areas (km^2)	Green areas (%)
Compact Theory	3.7	7.4	36.2	10.5	0.7	18.4
Transect Planning	9.2	11.8	110.0	11.9	1.1	12.0
TOD	9.5	12.7	94.7	10.0	1.2	12.1
Ville Radieuse	17.7	16.4	80.8	4.6	3.8	21.3
Infill Coimbra	20.3	16.7	320.1	15.8	1.2	6.0
Garden City	24.6	21.4	135.6	5.5	8.6	35.0
Coimbra	129.4	47.2	873.0	6.8	1.5	1.2

cycling mode from the calculations. However, the redraft layouts were all designed with cycleway provisions and sized according to engineering guidelines and best practices (Parkin, 2018). If ideal layouts are to be implemented, it would not make sense to disregard this very important active mode. Because this research is about layout geometry, to put all layouts on the same footing, the option was made to assume that cycling provisions will exist for all, regardless of the investment necessary to implement those provisions. Results for the walk mode only can, nevertheless, be derived. These are presented in the supplemental materials and reveal that removing the bicycle reduces the active modal share by about one-half to two-thirds for all layouts, a difference that should not be overlooked.

4.3. Transport energy consumption

Qualitatively, transport energy consumption results are similar to those for accessibility and active modal share, as Table 5 shows.

The one-way factorial analysis again yields statistical equivalence between the more compact layouts and a clear hierarchy over the remaining layouts:

Compact = TOD = Transect < Ville < Infill < Garden < Coimbra

Slight differences emerge on weighting to inhabitants, but an interesting feature is that if the Ville, Infill and Garden City layouts are considered as a group, the ratios between the compact layouts, this group and Coimbra are approximately 10/5/1, which are far larger than the same ratios for accessibility, at approximately 4/2/1. This difference is due to the relation between accessibility and energy, the latter raising quickly and with distance because of the non-linear decrease of active modal shares. In a sense the impact of distance on transport energy is greater than distance itself, once again emphasizing the importance of minimizing urban sprawl.

4.4. Road network directness

Road network directness results are shown in Table 6. As mentioned, directness statistics did not consider population weighting.

The high maximum values of directness correspond to locations that are close to each other, typically within pedestrian range, but road network configuration force the traveler to take a large detour. These routes cause the directness distribution to be right-skewed. For this reason, median values were used in the multicriteria analysis, as they are less prone to skewness distortions. Note that for origins and destinations that are close-by, people are likely to take Euclidean-like pathways shortcuts rather than using the network, which further justifies using the median.

The one-way factorial analysis over all routes per layout yields the ranking:

TOD < Garden ≤ Compact = Ville = Transect < Coimbra < Infill

where the ≤ sign indicates that the Garden City is equivalent to the Compact Theory, albeit marginally so (p-value = 6.9 %), but better than the Ville and Transect layouts. Indeed, it would seem that sprawl and otherwise unrestricted growth create mobility inefficiencies rather than solutions.

Concerning the good result for the Garden and Compact cities, for the Garden City this may be due to its radial-hexagon structure, which leads to less 90-degrees angles and consequently straighter, less Manhattan-like paths between blocks. The same applies for the TOD angled grain mesh structure. For the Compact City the good score is likely to relate its elongated rectangular shapes.

Table 5
Transport energy consumption statistics.

Layout \measure (MJ/pass.-trip)	Min	Average	Avg. Per inhabit.	Max	Std. Dev.	Coef. of Var.
Compact Theory	0.459	0.845	0.845	1.346	0.226	0.267
Transect Planning	0.372	1.480	1.059	4.778	0.740	0.494
TOD	0.388	1.034	0.866	2.575	0.522	0.505
Ville Radieuse	2.487	4.012	3.681	6.269	1.006	0.250
Infill Coimbra	2.563	5.163	5.745	14.250	1.461	0.283
Garden City	3.667	5.336	5.341	7.922	1.066	0.200
Coimbra	3.296	13.542	10.876	46.165	7.870	0.581

Table 6
Road network directness results.

Layout \measure	Min	Median	Average	Max	Std. Dev.	Coef. of Var.
Compact Theory	1.00	1.263	1.360	3.545	0.369	0.271
Transect Planning	1.00	1.294	1.313	4.824	0.220	0.167
TOD	1.00	1.219	1.239	3.121	0.136	0.110
Ville Radieuse	1.00	1.282	1.352	8.209	0.393	0.291
Infill Coimbra	1.00	1.581	1.767	19.453	0.779	0.441
Garden City	1.00	1.264	1.332	18.086	0.361	0.271
Coimbra	1.00	1.337	1.412	24.738	0.350	0.248

4.5. Mix land use

Table 7 presents the mix land use scores.

Again, the best scores are achieved by the planned layouts, but this time the infill version of Coimbra is competitive. Coimbra's low score is due to sprawl, single land use and derelict land plots. Its infill version corrects these inefficiencies, resulting in average scores comparable to the planned layouts.

A one-way factorial analysis over the unweighted set of neighborhoods confirms that TOD is statistically superior to all other layouts, while real Coimbra is inferior to all. The other layouts are in-between those two and on par with each other, for a ranking TOD < other < Coimbra. When weighting to inhabitants, the more compact layouts, Compact Theory, TOD and Transect, further improve their status, as they concentrate more people in the denser neighborhoods.

While it could be argued that the better scores of the planned layouts is due to their more compact nature, the higher mix land use appears by design, not because of compactness itself. Planned layouts were designed with vibrancy and proximity activities in mind, which requires a good mix land use, so it is natural they have good scores in this criterion. That is the case of TOD: from its origins, this model has clear guidelines, enforcing horizontal mix land use and considering vertical mix land use to be a bonus (Calthorpe Associates, 1992).

4.6. Pleasantness

The pleasantness scores are presented in Table 8.

Physical pleasantness is one criterion where the real city is

Table 7
Mix land use statistics.

Layout\measure (uses/neighb.)	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of var.
Compact Theory	1	4.673	7.310	8	2.968	0.635
Transect Planning	1	4.213	6.416	8	2.569	0.610
TOD	1	5.406	6.008	8	1.764	0.326
Ville Radieuse	1	3.110	4.306	6	1.536	0.494
Infill Coimbra	1	3.294	3.674	7	1.713	0.520
Garden City	1	3.453	3.907	6	1.606	0.465
Coimbra	1	1.506	2.606	7	1.126	0.748

Table 8
Pleasantness results.

Layout \measure	Min	Average	Avg. per inhabit.	Max	Std. Dev.	Coef. of var.
Compact Theory	2.123	2.470	2.331	2.715	0.266	0.108
Transect Planning	2.248	3.169	2.867	4.093	0.407	0.128
TOD	2.057	2.680	2.514	4.093	0.470	0.176
Ville Radieuse	2.442	2.792	2.900	2.989	0.193	0.069
Infill Coimbra	1.962	2.635	2.439	3.951	0.496	0.188
Garden City	3.083	3.637	3.620	3.976	0.264	0.072
Coimbra	1.988	3.187	2.698	3.951	0.460	0.144

competitive with the other layouts, albeit only moderately so when population weighting is considered. This is a benefit of urban sprawl, which allows for constructing many detached homes with few floors and large bodies of green areas in the surrounding space. In the infill version, those sprawled areas reduce considerably, leading to worst scores. The one-way factorial analysis over the unweighted scores yields the ranking Garden $<$ Coimbra $=$ Transect $<$ other, confirming the status of Coimbra as a front-runner, second only to the Garden City.

Since high pleasantness scores tend to require wide spaces, short buildings and abundant green areas, it is difficult to achieve such scores with the more compact layouts, as the table shows, and the factorial analysis concurs. Note that these contrasts between independent dimensions of reality are what justifies a multicriteria approach, because it can yield an aggregated preference. The overall reduction of scores in the population weighted average is due to the denser zones having taller buildings and narrower streets, which degrade the pleasantness scores. Statistically, and realistically, compact layouts with tall buildings can be made more pleasant with very wide streets, as other forms of compensation, such as, e.g., high green area percentage or reserving space for backyards can be challenging to achieve in those types of layouts. Mitigating the oppressive presence of vertical construction with wide streets could be one way to compromise between the benefits of compactness and its poor physical pleasantness.

The Garden City was originally created to be a wide, enjoyable urban environment, while being compact enough that active transport is still possible; it looks to be a compromise between accessibility and pleasantness. Its design has the largest portion of parks and green areas, wide streets, and the tallest buildings have only four floors, so it has the best pleasantness scores. More than a century old, this classic city model remains a paradigm in that respect. It is in fact surprising that no more proposals focusing on pleasantness appeared in so much time.

4.7. Multicriteria analysis

Table 9 below summarizes the decision matrix for the multicriteria analysis.

The a priori decision matrix for the multicriteria analysis consists of seven alternatives (layouts) and six criteria (indicators). Before proceeding with the application of TOPSIS, it is important to realize that three of the criteria are very highly correlated, namely accessibility, active modal share, and transport energy, as the latter two are built off the first (Pearson correlations exceeding 97 %). In multicriteria analysis the criteria should be as independent as possible and non-redundant, to avoid giving undue importance the concept they represent (Keeney & Raiffa, 1993; Zeleny, 2014). If the three criteria were to be considered in the decision matrix, a sizeable bias towards distance dependence would emerge in the results. Two possibilities exist to solve this issue: in the decision matrix, consider only one criterion or a combination of the three. If a combination is the choice, it must be determined which one, and the natural candidate would be the principal component of the three criteria. However, this would introduce negative values in the decision matrix, requiring a change of the preferred ratio normalization scheme. Since most normalization schemes that deal with negative numbers tend to magnify the spacing between alternatives, a feature that is undesirable (most criteria are on a ratio scale, so the ratio normalization is the most natural choice), the option was made to consider only one of the three criteria. Accessibility, the most basic of the three, was thus chosen, leaving the decision matrix with seven alternatives and four criteria. For completeness, an analysis replacing accessibility with active modal share and transport energy was carried out. Differences related to the non-linearity between accessibility, active modal share, and transport energy get reflected in the results with replacement, but as expected, these were very similar to those of accessibility and did not provide additional insights, so they are not reported in this article.

It is worth mentioning that using active modal share as replacement criterion leads to less discrimination among the three compact layouts because of the slow decay of the active modal share for short distances. If instead transport energy were used as replacement, the situation for compact layouts would be similar (for the same reason), but then the discrimination between those layouts and the remaining ones would be higher because of the effect of multiplying non-active trip probability with distance itself. Still, as mentioned, those non-linear effects end up not affecting the layouts' TOPSIS ranks significantly.

Running TOPSIS requires setting one parameter, namely criteria weights. Weights reflect different judgements by the decision maker on the relative importance of the criteria and can be used to analyze the trade-offs between these. Rather than selecting a particular set of weights for the analysis, it is more elucidative to explore the weight space, and this was the preferred approach. Several ways exist to do it (Danielson & Ekenberg, 2017; Jiménez et al., 2021; Keshavarz-Ghorabaee et al., 2021; Pajer et al., 2017); for this research a combination search was carried out: each criterion weight took the value 1 or 2 and all possible combinations were evaluated. After weight normalization, i.e., division by $\sum_i w_i$, one duplicate combination was removed, leading to the weight sets summarized in Table 10 below.

This weight space exploration procedure was selected because it gives a complete overview of what may come out when putting a given emphasis on each criterion: set 1 has equal weights, i.e., same emphasis in all criteria. Sets 2–5 put emphasis on one criterion, sets 6–11 put emphasis on two criteria, and sets 12–15 de-emphasize one criterion, i.e., put emphasis on three criteria. The procedure can be refined by extending the possible weight values to, e.g., 1–2-3 or higher (and normalizing), but the combinations rapidly increase, and statistical methods would be required for the subsequent analysis.

Running TOPSIS for all 15 sets of weights yields the scores and final

Table 9
Decision matrix.

Layout\criterion	Accessibility	Active share	Transport energy	Directness	Mix land use	Pleasantness
Compact Theory	572	0.878	0.845	1.263	7.310	2.331
Transect Planning	649	0.851	1.059	1.294	6.416	2.867
TOD	623	0.858	0.866	1.219	6.008	2.514
Ville Radieuse	1230	0.666	3.681	1.282	4.306	2.900
Infill Coimbra	1602	0.591	5.745	1.581	3.674	2.439
Garden City	1487	0.623	5.341	1.264	3.907	3.620
Coimbra	2578	0.433	10.876	1.337	2.606	2.698

Table 10
Weight sets for sensitivity analysis.

Weight sets	w_{access}	w_{direct}	$w_{pleasant}$	w_{mix}
Set 1	1/4	1/4	1/4	1/4
Set 2	2/5	1/5	1/5	1/5
Set 3	1/5	2/5	1/5	1/5
Set 4	1/5	1/5	2/5	1/5
Set 5	1/5	1/5	1/5	2/5
Set 6	1/3	1/3	1/6	1/6
Set 7	1/3	1/6	1/3	1/6
Set 8	1/3	1/6	1/6	1/3
Set 9	1/6	1/3	1/3	1/6
Set 10	1/6	1/3	1/6	1/3
Set 11	1/6	1/6	1/3	1/3
Set 12	2/7	2/7	2/7	1/7
Set 13	2/7	2/7	1/7	2/7
Set 14	2/7	1/7	2/7	2/7
Set 15	1/7	2/7	2/7	2/7

rank presented below in Tables 11 and 12 (Table 11, the closer to one the better).

Table 11 is the main result of this article, and its meaning is clear: regardless of the set of weights, the more compact layouts, Transect, Compact Theory and TOD, come out on top of the quantitative analysis, followed by the two less committal planned layouts, the Garden City and Ville Radieuse. The Infill proves to be overall an improved version of the real layout, but still considerably far from planned layouts. The real layout comes last, except against its infill version when the focus is on pleasantness, proving it has clear problems of inefficiency.

The fact is that results favor the compact layouts can be traced back to them outscoring the other one in three out of four criteria. Compact urbanism has been criticized on several fronts (Bajracharya et al., 2020; Fujii et al., 2017; Nelson, 2017; Neuman, 2005; Stevens, 2017; Yang et al., 2015), but the actual quantitative calculations do not support those views. Considering efficiency and physical pleasantness as dimensions of reality, the compact layouts offer tangible advantages over both the real layout and other layouts that try and compromise between those two dimensions.

5. Discussion

The analysis ultimately lead to a well-defined conclusion: the more compact layouts have a sizeable advantage, mainly due to better transport and land-use efficiency. In terms of the indicator values, the alternative layouts tend to form three clusters: Infill, pleasantness-oriented (Garden City, Ville Radieuse), and the more compact layouts (Compact City Theory, Transect, TOD).

The Infill layout mitigates much of Coimbra's sprawl, but that was not enough to make that layout competitive with the other ones. Nevertheless, Infill Coimbra proves that improvement is possible within municipal master plans, i.e., without structural changes to the urban fabric.

The pleasant-oriented group, Garden City and Ville Radieuse, also the two oldest classic models in the analysis, emerged in a time where cities were far away from environmentally friendly, or even people oriented. By the beginning of the XXth century most urban dwellers had no access to public green spaces and adequate sanitation, living in polluted neighborhoods that later became brownfields. More than urban planning models, both were socioeconomic stands towards equity and more humane living conditions (Fishman, 1982; Gillette, 2010; Howard, 2010; Le Corbusier, 1972; Le Corbusier and Boesinger, 1955). Their large number of parks, green areas, and wide streets led to higher pleasantness scores. However, mix land use did not play such an important role as it does in the top three models, leading to lower scores for this criterion and accessibility, limiting layout performance from that side. That said, these two models should not be discarded, as both are important sources of planning motifs towards pleasantness and equity.

The more compact layouts, Compact City Theory, Transect Planning and TOD, have in common high compactification and densification. These layouts, especially Compact City Theory, have been widely debated in the past decades and the present research provides quantitative evidence that vindicates claims on efficiency, which arguably leads to a better chance at achieving much-needed urban sustainability. The Transect and TOD layouts are slightly different, in that they consider different housing types and city areas while taking advantage of all the available space, making them slightly more balanced and with a more diversified built environment. Within the three compact layouts, Transect Planning comes out marginally above the others so, if a "winner" is to be called, this would be the most natural candidate. In a sense, the Transect layout can be seen as a compromise solution within the more compact layouts.

Given that at least some planned layouts are arguably older than the massive inflow of people towards cities, it is fair to ask why only very few cities follow those layouts. Cities worldwide have put into practice the best knowledge, strategies and policies that were available at the time, aiming at not only to solve the problems at hand but also preparing the built environment for the future. While fine in theory, this intention usually fell short in practice. The solutions are neither universal nor always applicable on the field, and strategies may not yield the same outcomes. As such, politics influenced the solutions in the local context, playing a crucial role in adapting them to a specific urban area, often improvising to overcome the initial problem while responding to peoples' interests, aspirations, and needs. This reality, to which the rise of the private car contributed greatly, has led to urban features recognizable in most cities: sprawled residential neighborhoods with single-house families, industrialized city outskirts, classic city centers reminiscent of older times, large highways and viaducts connecting different city areas, and newer central areas with high-rise construction and a

Table 11
TOPSIS preference rank results ([0–1] scale).

Weight sets	Compact Theory	Transect Planning	TOD	Ville Radieuse	Infill Coimbra	Garden City	Coimbra
Set 1	0.7418	0.7607	0.7056	0.3694	0.1819	0.3791	0.1422
Set 2	0.8257	0.8086	0.7925	0.3364	0.1770	0.2945	0.0922
Set 3	0.7489	0.7590	0.7248	0.4215	0.1692	0.4274	0.2204
Set 4	0.5905	0.6674	0.5767	0.3866	0.1629	0.5013	0.1786
Set 5	0.8091	0.7836	0.7135	0.3654	0.2055	0.3353	0.1018
Set 6	0.8265	0.8053	0.7981	0.3638	0.1718	0.3281	0.1485
Set 7	0.7039	0.7467	0.6939	0.3487	0.1687	0.3857	0.1228
Set 8	0.8501	0.8090	0.7730	0.3437	0.1925	0.2899	0.0784
Set 9	0.6019	0.6732	0.5993	0.4255	0.1543	0.5218	0.2324
Set 10	0.8107	0.7813	0.7242	0.3947	0.1978	0.3695	0.1628
Set 11	0.6801	0.7193	0.6255	0.3758	0.1927	0.4280	0.1343
Set 12	0.7072	0.7467	0.7011	0.3720	0.1643	0.4035	0.1638
Set 13	0.8501	0.8066	0.7777	0.3631	0.1883	0.3159	0.1275
Set 14	0.7399	0.7612	0.7000	0.3520	0.1855	0.3636	0.1058
Set 15	0.6846	0.7205	0.6377	0.4005	0.1865	0.4459	0.1782

Table 12
TOPSIS ranking positions.

Weight sets	Compact Theory	Transect Planning	TOD	Ville Radieuse	Infill Coimbra	Garden City	Coimbra
Set 1	2	1	3	5	6	4	7
Set 2	1	2	3	4	6	5	7
Set 3	2	1	3	5	7	4	6
Set 4	2	1	3	5	7	4	6
Set 5	1	2	3	4	6	5	7
Set 6	1	2	3	4	6	5	7
Set 7	2	1	3	5	6	4	7
Set 8	1	2	3	4	6	5	7
Set 9	2	1	3	5	7	4	6
Set 10	1	2	3	4	6	5	7
Set 11	2	1	3	5	6	4	7
Set 12	2	1	3	5	6	4	7
Set 13	1	2	3	4	6	5	7
Set 14	2	1	3	5	6	4	7
Set 15	2	1	3	5	6	4	7
Average rank	1,60	1,40	3,00	4,60	6,20	4,40	6,80
Final rank	2	1	3	5	6	4	7

high concentration of city dwellers. Coimbra's inefficiency testifies that urban planning should follow well-grounded long-term strategies that can define a clear path for city development, improving their sustainability and resiliency while preventing the creation of a city patchwork that is outperformed by all the alternative layouts evaluated.

What the present research shows is that, long term, planned urbanism can provide better urban solutions in comparison to unrestricted urbanism, which does not encompasses long term strategies and policies with definite goals and tends to disregard efficiency.

5.1. Impact in city planning

Realizing in practice the classic layouts, or any other highly planned solution the future may bring, will be difficult, especially given that cities are already built, and it is not conceivable to reconstruct them for the sake of efficiency. Nevertheless, practical applications of the results found in this research may come in two ways: cities expansion programs, and development of new cities. Many cities around the world are growing and this trend is expected to continue in the next decades (United Nations, 2018), requiring the creation of new neighborhoods and urban areas. The urban layouts studied in this research were proposed for mid-size and large cities, but their ideas are general and can be applied at smaller scales. Also, city expansions could go potentially reach large dimensions, in which case the models can be applied in their full extent (Blundell, 2019; Duxbury, 2019; GOV.UK., 2019). New cities are also being built developing countries (Khanna et al., 2014; Lynch, 2019) and these are the prime candidates to apply one of the planned layouts.

In practice, when city expansions (or new cities) are planned, municipal decision makers often consider layouts other than the classic models discussed in this research. In this case the methodology can be applied to evaluate the different planning proposals. Individual criteria values can be derived for each proposal and put to discussion among the stakeholders (see, e.g., Mosso et al., 2021; Natividade-Jesus et al., 2019; Shen et al., 2019; Slemp et al., 2012; Yang, 2014 for a list of these). Different views of the stakeholders can then be reflected in the multicriteria analysis as weights. The results derived for the layouts explored in this research can also act as benchmarks for comparing those proposals, so that everyone can examine what trade-offs the multiple possibilities entrail.

Urban regeneration actions are yet another possible application of the methodology. Often these actions involve tearing down and rebuilding, assigning new uses to derelict land plots, and modifying the road network (Monteiro, Para, Sousa, et al., 2023), a prime context for using the methodology to evaluate the various projects that might be under consideration.

5.2. Research limitations

On the technical side, studying more city models and real cities could strengthen the conclusions. More quantitative benchmarking indicators could also be added (e.g., an explicit equity indicator), as well as improvements on the current ones. Mobility in particular was represented only by one proxy indicator that does not consider traffic congestion. Considering congestion is likely to degrade the transport energy scores, especially for sprawled cities with dense centers, as the inflow of cars and busses towards the center during rush hours would increase fuel consumption due to slower speeds, stop-and-go traffic, and drive-bys looking for parking spots. Space syntax indicators can also be added to the methodology. These help measuring how urban form impacts social and accessibility aspects, reinforcing that dimension of the analysis. For instance, the more connected the urban space is, the greater chances are that it conveys a sense of belonging (social aspect) and that active chained trips occur (accessibility aspect, with impact on transport energy). Chained trips are round trips which include stopovers at multiple facilities (not considered in the transport indicators – another limitation).

Finally, concerning practical implementation of the results, these are mostly limited to new construction, as real cities evolve slowly, and are subject driving forces that may be stronger than planned urbanism. Furthermore, factors such as orography, floodplains, and other geographic issues are non-trivial determinants of city growth and may constrain constructive solutions. Full cycling may also prove difficult achieve. Factors such as lack of road safety, hilliness, harsh climate, or absence of parking facilities are known deterrents to cycling (Codina et al., 2022; Fowler et al., 2017; Monteiro, Sousa, Natividade-Jesus, & Coutinho-Rodrigues, 2023d; Packman, 2022; Pearson et al., 2023; Sousa et al., 2017) and could take a toll on the active modal share and transport energy indicator values.

5.3. Conclusions: towards an ideal city form

This research set out to contribute to the debate on what is the ideal city form. The quantitative evidence raised from the methodology and multicriteria analysis makes it possible to draw some conclusions for the debate that also carry policy implications and recommendations. These conclusion need not be restricted to the classic models; they also apply to any other proposals the future may bring.

First and foremost, the consistent performance of compact layouts throughout all sets of weights shows that the ideal city form is likely to be a relatively dense environment. Compactness brings efficiency and, together with mix land use, contributes to the social aspect of proximity life.

Second, the transect planning example shows that it is possible to combine compactness with pleasantness to some degree. Transect Coimbra is competitive with the pleasantness-oriented layouts while keeping distances short and this is the main reason why it scores so well in the ranks. Having wide streets and mix land use are possible ways to achieve this compromise.

Third, the pleasantness-oriented layouts have the caveat of longer distances. However, it may be possible to mitigate distance by implementing high-frequency, low carbon public transport (e.g., electric shuttles). Both the Ville Radieuse and the Garden City have natural avenues for implementing public transport lines. Cities and people evolve and change with time, so if in the future physical pleasantness of the built environment becomes a dominant factor requiring more open spaces, the ideal design must cater for pathways that connect those spaces in good time and restore any sense of belonging that might otherwise be lost from distance.

6. Summary

In this article a quantitative multicriteria methodology for the analysis and benchmarking real and classic city layouts was presented. The debate around urban form and its impact on quality of urban life has been ongoing for centuries and the results presented add to that debate, providing a common ground of comparison between city layouts, based on multiple indicators that evaluate different dimensions of reality, thus providing tools for municipal authorities to evaluate past, present, and future urban forms. Furthermore, the methodology gives clear figures on urban layout performance concerning each dimension separately and combinedly, in a multicriteria way. Herein lies the main novelty of the approach.

The methodology was applied to a case study of a real city and its redraft as five classic city models and an infill version of itself. Results showed that densification, compactification, and mix land use are important to urban sustainability and resiliency, as they can shorten distances and lead to better accessibility, higher active modal share, shorter public transit lines and travel time, reduction in transport energy consumption and associated greenhouse gas emissions. Sprawl has developed for over half a century in many cities, making it commonly present in urban environments. As there is now a clear understanding of its negatives, municipal authorities are well-advised to acknowledge this and revert trends, although it seems likely it will take another half a century of planning strategies and policies to correct it.

Classic city models can have an important role on cities future development by providing guidelines and concepts that can create more sustainable and resilient urban environments. These denser, more compact urbanism paradigms also have higher mix land use and retain acceptable levels of physical pleasantness, making them competitive in comparison to the patchwork or sprawled urbanism present in many of nowadays' cities.

The quantitative benchmarking of cities, made possible by advances in computer science, enables putting to the test real cities and classic and contemporary city models. We hope the ideas proposed in this article can open new research avenues and stir the debate on the ideal form of cities, as well as shaping the view of urbanists on how to plan upcoming city expansions.

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CRediT authorship contribution statement

João Monteiro: Writing – original draft, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Nuno Sousa:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João Coutinho-Rodrigues:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Eduardo Natividade-Jesus:** Writing – review & editing, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2024.105040.

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