Politecnico di Torino

Master of science programme in building engineering
A.Y. 2020/2021
Graduation session November 2021

Innovative tools for urban regeneration planning.

The study of alternatives for accessibility to the city of Coimbra

Relator:
Professor Ostorero Carlo Luigi

Candidate:
Para Marvin

Co-Relator:
Professor Natividade de Jesus Eduardo
Doc. Medina Monteiro João Pedro

Abstract

This thesis project presents a comparative analysis of the city of Coimbra (Portugal), modelled according at its current and present physiognomy (2021) to a compact version of itself; aiming at identifying an urban planning tool able to emerge as one of the possible ways to achieve a sustainable development of the city.

The tool chosen for the interpretation and numerical comparison of the two models was identified in the accessibility index, a position-based indicator, calculated through a digitization of the built and inhabited areas in a GIS environment.

The results, summarized in indexed maps and tables with weighted average distances per inhabitants to facilities, show how the compact city reduces the average distances between inhabitants and facilities by 70%, with peaks (on maximum distances) of 81%. In addition to that, thanks to a pronounced reduction of the average distances between citizen and facilities we can find a higher possibility of moving around the city actively (walking and cycling) thus improving transport sustainability and accessibility equity. To quantify this variation, a different and widely validated tool was used: the modal share.

The case study analysis shows how this method can provide an evaluation tool to improve further planning for the expansion and development of current cities. When aiming at a solution for the sustainable development of a city, this study methodology could also be implemented to other urban planning tools and hypotheses for the physiognomy evolution of a city.

This analysis provides a useful numerical contribution to the debate about investigation methodologies of cities sustainability and on the effectiveness of their distributions.

Index

1 Introduction 4

1.1 Role of science in cities development 5

2 Literature review 8

3 Real cities and compact cities 11

3.1 Real cities 11

3.2 Compact cities 11

3.2.1 Key policy strategies for the compact city 12

3.2.2 Sustainability aspects: trade-offs 14

3.2.3 How dense is "dense enough"? 14

4 Methodology 16

4.1 Accessibility 18

4.1.1 The role of weights in defining facilities attractiveness 20

4.1.2 What defines accessibility as a cost and why 22

4.1.3 Refining accessibility 23

4.2 Modal share 26

4.2.1 Role of modal share in the research 27

4.2.2 Methodology simplifications for the research 27

4.2.3 Results explanation 28

5 Study case, the city of Coimbra 30

5.1 Present day Coimbra 30

5.1.1 Origins 32

5.1.2 Destinations: facilities 33

5.1.3 Road network (streets) 34

6 Redrafting the city as a dense version of itself: compacted Coimbra 36

6.1 Initial assumptions on planned densification 36

6.1.1 Geo-morphological considerations 37

6.1.2 Legal and administrative considerations 38

6.1.3 Demographic considerations 40

6.2 Description of the city's transformation process 42

6.2.1 Redrafting the city maintaining its actors 42

6.2.2 Selection of land parcels and use of constructability percentiles 43

6.2.3 Modelling buildings on selected areas, the 3 factors 49

6.2.3.1 Impermeabilization index, max surface area 50

6.2.3.2 Building dimensions and housing determination 50

6.2.4 Drawing buildings and preparing densification 53

6.2.5 Moving origins into new locations 54

6.2.6 Re-shaping the city 55

6.2.7 Moving facilities 56

6.3 GIS evaluation of accessibility 57

7 Results 59

7.1 Compact Coimbra has higher accessibility scores 61

7.2 Walkability in the compact city 62

7.2.1 Comparison about the actual situation in the real city of Coimbra 63

7.3 Accessibility equity 64

7.4 Impact on sustainability 65

7.4.1 Transport-related aspects 66
7.4.2 Modal share analysis 67
7.5 Possible impact in future city planning 68
7.5.1 Cities expansion programmes 69
7.6 Uncountable aspects of compacting a city and final thoughts 70
8 Summary and future works 77
8.1 Critique 78
8.2 Future development 79
9 Bibliography 80
10 SITOGRAFIA 86
11 Attachments 88

1 INTRODUCTION

Generating over 80% of the world's wealth and devouring more than 78% of all energy produced on the planet, cities are and remain the driving forces of our economy, with more than half of the world's population currently residing in urban areas (UN, 2021) and with steadily increasing growth forecasts.

Inspecting what has led to this trend, we can look back 12,000 years ago, when Earth was fitting 10 million inhabitants: the birth and advancement of agriculture and even more the growing specialization of well-defined skill-based societies, together with the tendency to unite and form cities, and then proceed to expand them, have resulted in a rapid proliferation of mankind.

If, at the advent of the industrial revolution, the terrestrial census counted 1 million inhabitants, by the end of the 1930s the count had already doubled, and now we reach the figure of 7.9 billion (UN, 2021). It should be noted that the single specific percentage-increasing item with the steepest growth curve is cities, where if in 1950 only 29% of the world population lived in urban areas, by the year 1965 that percentage had risen to 36% and again to a staggering 50% in 1990. To date, forecasts estimate that by 2050, 70% of the world population will live in cities, with a peak relative to OECD* countries equal to 86% (OECD Green Growth Studies, 2012). It can be observed that the growth rate of urban population rose from 2.6% between the 1960s and 1980s, and to 4.5% between the 1980s and 1990s: a pace that, if it had continued to date, in terms of economic and natural resources, it could not have been supported by our planet.

The continuous growth of the urban population requires, with an urgency that cannot be ignored, a new policy for the optimization of territorial resources. With a good approximation, in 30 of the 34 OECD countries, land use, due to urban expansion and subsequent construction of structures and infrastructures for the inhabited area, will exceed the rate of population growth.

As of today, we can observe a slow decrease in world urban population growth which, however, has been steadily (over the last two decades) between 2.2% and 1.8%, in line with the current urban growth forecasts and with the estimated achievement of a percentage of population pertaining to urban areas around 60% by 2025 (Rogers, 1997).

**Organisation for Economic Co-operation and Development*

1.1 ROLE OF SCIENCE IN CITIES DEVELOPMENT

Demographics have changed, cities are attracting people as they are able to offer better overall housing standards, to provide multiple job opportunities, better education, and higher health standards (Tsui et al., 2015). Given their great importance in modern society and their complexity, modelling cities to achieve reliable quantitative predictions has become one of the main challenges of the modern world, working on examining their evolutionary behaviour and assessing their sustainability (Barthelemy, 2019; Phillis et al., 2017).

Since the dawn of cities, going back to as far as Vitruvius, the spatial layout of the city has been a highly debated issue, not only for scholars and researchers, but also for entities concerned with evolution and sustainability of urban areas, and in general for those who aim to improve the living conditions of citizens (Hall, 2014; Kristjansdottir, 2019; Tellier, 2019). Even though studies have been carried out for decades, cities, as intended in the modern concept, have gone through dozens of possible solutions and urban design models, but in the end, most cities have eventually evolved based on different ideas and models, incorporating multiple influences over the course of time (Adolphe, 2001; Cataldi et al., 2002; Conzen, 1969; Gauthiez, 2004; Li, 2020).

Although numerous, these discussions have rarely reached the field of quantitative observation: they were (and often still are) limited to the field of qualitative observation of solutions and alternatives; mainly because they lacked an adequate analytical tool that could bring to light the numerical advantages that one urban layout could have over another, thus providing a numerical comparison between the models or between the model and the city.

As highlighted by Hernandez (et al., 2014) and Rodwin (1981), most cities have evolved and expanded in response to practical questions related to the need for new housing, aimed at solving short-term problems, without considering future consequences or sustainability issues.

Today's computing capabilities, provided by modern computers, and the possibilities of data organisation, provided by new software (as GIS), have added a large range of new options in the field of city-planning, making it possible to test cities and models in a way that was almost impossible to think of before. These programmes are allowing new evaluations of the most important strategic aspect of the city, its urban layout, whose profound mark affects several and hugely important characteristics. The possibility of obtaining, as in the case of accessibility, indicators on these aspects provides evidence and directions on how to plan and develop the urban fabric.

This research, along with the others from which it has budded, represents one of the first steps towards quantitative comparative analyses between real cities and alternative and future development models, based on indicators dependent on urban layout.

Taking accessibility as an indicator, defined as a central index for physical planning and spatial modelling (Geurs et al., 2015; Handy, 2020), this paper proposes a benchmark methodology applied to the real city of Coimbra (Portugal) and its compact version.

This study could open many avenues regarding the future conception of urban planning and certainly brings a contribution to the debate on how cities should evolve considering the current concerns regarding their general non-sustainability and their continuous and uncontrolled trend of expansion.

2 LITERATURE REVIEW

Scientific literature on city design focuses on different models and layouts, as does this research, but the difference with respect to other types of analysis lies in the amalgamation of research type (comparative) and the quantitative output it presents.

From the proposals of classic or contemporary city models, most research addresses the virtues and shortcomings of layouts, generally focusing on one model in particular (Cervero et al., 2004, Correa, 2006; Neuman, 2005). At a quantitative level, these studies are usually limited to the evaluation of the impact of the single idea, without intervening in any change in the structure of the city (Ling and Yang, 2006; Lyu et al., 2016; Ratner and Goets, 2014).

This research moves on a different axis from other comparative studies where comparative analyses of different city structures and urban layouts are only treated from a qualitative aspect. This research instead proposes a quantitative type of analysis. Classic debates, in terms of comparative studies, on the spatial layout of cities include Fishman (1982), Frey (1999) or Lynch (1960) which have impacted and influenced trends in spatial planning to date.

The multi-comparison carried out by Frey stands out because it compares in parallel the performance of six city models: satellite city, galaxy of settlements (or TOD, transit-oriented development, nowadays), polycentric city, core city, star city and linear city. The evaluation and comparison were carried out in terms of sustainability indicators and involve different assumptions. However, the results showed that all theoretical models had similar scores, which assumes that there may have been some inaccuracies that led to incorrect assumptions, a criticism to his research that Frey himself acknowledges.

Quantitative comparison of urban models and layouts in the field of scientific research is rather scarce: as of today, there is only one published research, cited above, concerning a comparative analysis between the real city of Zhujiajio in China and its urban reproduction based on the garden city (Yuan et al., 2014). This analysis, however, considers accessibility to the green areas of the city, finding that in the new garden city the results present a better accessibility score towards the aforementioned areas.

Parallel to this research project, other studies are being analysed in the laboratory of the University of Coimbra, focusing on the analytical and quantitative comparison of spatial alternatives (in terms of layout) for the city of Coimbra. This project is therefore part of a broader, multi-faceted analysis involving several proposals: from historical utopian models to innovative, modern solutions. The groundwork of this research is to be found in an initial modelling, in a GIS environment, of the city of Coimbra and then in the choice of some main factors, within the evaluation indices of pleasantness and sustainability of a city, for the assessment of the built environment. It is thanks to this solid base that it was possible to carry out, cascading, all the subsequent comparative analyses.

It should also be remembered that, like previous works, this research is just one tessera of a larger mosaic that allows us to understand, in a more technical and technological way, how the city has evolved and what directions it is taking. The work derived from this analysis can serve as a basis for other types of research, since, as will be said later, the choice of evaluation factors was made within a broad spectrum of indices. Nothing deflects from the reliability of the results to be presented, but this also means that from these computer models it is, and will be, possible to derive other results: complementary to those obtained (such as the appendix relating to the modal share in this analysis) or in complete opposition.

3 REAL CITIES AND COMPACT CITIES

3.1 REAL CITIES

A city can be seen as a complex organism, the result of layered processes over time that help shape the physical landscape (Williams, 2015).

Real cities have self-evolved, leading to layouts that reflect the trends of the population that has lived in them as well as the interest they carry. If years ago, cities were designed and built to give priority and space to motorised transport, with wide driveways (a choice applied to the Italian city of Turin), now the same driveways are being transformed, increasingly limiting space to cars and giving way to cycle paths and pavements, stimuli to a different, active, sustainable mobility. The city of Coimbra is one of the cases, not to say examples, of a long-term evolution during which it has accumulated change after change over the course of a whole millennium, thus providing the perfect real-world case study for this research.

In particular, in recent decades we have witnessed rapid urban transformations, due to technological and economic changes, that have led to urban dispersion (Alonso, 2018), a trend that Coimbra has also followed (Silva, 2008).

3.2 COMPACT CITIES

The compact city is a concept of urban design or, as in this case, urban planning, which basically promotes a few simple and essential concepts: high density residential character and mixed land use. The advantages of applying these axioms are numerous, as are the disadvantages. Although it is not included among the planning concepts, the basis of this theory is the transport system: this concept, in order to work, must be supported by an efficient public transport network and an urban planning system that promotes and allows the use of active mobility (walking or biking) to move within the city.

The advantages of this type of urban solution are manifold, ranging from a greater sense of security for the inhabitants, to lower per capita expenditure on transport and infrastructure and a lower impact on the environment of the entire community. Compact city model would ideally create benefits on a scale that would appeal to modern urbanites as it encompasses everything a resident seeks in a single community.

3.2.1 Key policy strategies for the compact city

Talking about compact cities is not enough, it is necessary to support it with a series of additional guidelines that refine its aspects.

The implementation of a densification policy requires the performance of several steps.

- Minimization of the negative aspects arising from an extremely dense city. It is necessary to encourage the expansion of green areas within the city, not only by conventional methods, i.e. integrating with parks, but also with the new frontier of vertical greenery, which greatly impacts the city.
- Promoting the quality of urban design, an element closely related to the previous one. It is necessary to conceal the perception of density with a careful study of the built environment and to encourage the provision of affordable housing. This last point is not obvious, since the

increase in quality of life within the city, potentially brought about by compaction, goes hand in hand with a cascading series of events: an upsurge in the cost of living within the city, which would lead to a prohibitive cost for those in lower income brackets, which would lead them, again, to move away from the city. Back to the initial condition then, where the generated urban sprawl would increase commute times and produce more pollution. To control this effect, the introduction a no-building greenbelt into the planning of compact cities could be used to physically and administratively prevent its expansion.

- Another package of strategies related to the promotion of the compact city relates to the retrofit of existing built-up areas, branching out into steps such as: regenerating existing residential areas, promoting the development and rehabilitation of brownfield sites, encouraging intensification in existing portions of the urban fabric and promoting transit-oriented development (TOD) in built-up areas.
- A further step is to improve the quality of life and to promote diversity, i.e. the promotion of mixed-land use together with a boost towards active travel methods, such as cycling and walking, and tasking the administration to give the community a narrow focus, generating a sense of belonging.
- When involving governance and city officials, it is absolutely vital for the city to set explicit compact city goals while encouraging densification and neighbourhood development. Some key elements of this plan of action may be to increase the efficiency of regulatory tools, to encourage strategic planning at the metropolitan level, to improve the

relationship and connection between city and countryside, to set some density minimums for new areas being developed and to avoid possible pickles by implementing a mechanism able to reconcile conflicts of interest.

3.2.2 Sustainability aspects: trade-offs

A strength, not to say THE strength, of compact cities is that of sustainable development, yet recent studies show that these developments do not always tip the scales.

By extension of its own concept, a compact city turns out to have an even more visible limit than that of today's uncontrolled and sprawled cities. The fact that the city can densify, and thus reduce in size so much, means that there is a limit to the people who can use a space: this limit being the constraints of design and of course the resources associated with it. Another criticism moves to the environmental impact of these cities: having many people in a single place means, by syllogism, a large concentration of pollution and waste.

This exponentially concentrated impact requires more effective control than is necessary in a normal city. These disadvantages highlight how some aspects of compact cities still need further analysis and better design, and show how, rightly, each element placed in the positive column represents a counterpart in the negative one.

3.2.3 How dense is "dense enough"?

The best and optimal level of urban density for compact cities turns out to be one that keeps residents close enough to community amenities, but also that allows residents to have access to the green areas of the city, a reasonable level of privacy and an acceptable view (Yue et al., 2016).

To better understand the discussion regarding compact cities, it is necessary to define some key points, certainly the most important one is that of urban density. This value, intuitively referring to the number of inhabitants per km^2 of city, is generally used as an indicator of how livable a city is. However, as of now, there is no single number that can categorise a normal city from a compact one: there is no single factor that describes this characteristic, depending on density, and there must also be a suitable proximity value.

Generally, two main sets of indicators are used to measure the results of compact city policies: the first are the indices representing compactness, i.e. proximity, accessibility to local services, density, closeness to public transport systems; while the second are indices that develop a comparison, i.e. those that compare the city with other cities or with other models of the same city.

4 METHODOLOGY

The pivotal concept on which the chosen method of investigation hinges is that of comparison, i.e. the indexed comparison of the city of Coimbra, modelled according to its current characteristics (geographic-location type) and its compact counterpart.

The comparison is proposed to obtain a benchmark that can serve the population, as well as the legal-administrative competences, to better understand the possibilities of future development of the city's fabric; aware, however, of the use of only accessibility as the benchmark indicator of the research.

It should be specified, before going into detail on the implementation of the indicator within the research, how this type of instrument turns out to be one of the possible indices suitable for this type of comparison; not only, this research methodology can be implemented with the insertion of various other complementary evaluative typologies, obviously on condition that they can be positively implemented in a GIS environment.

The implementation of the tool considers an indicator related to accessibility, strictly numerical-quantitative, linked to the geographical position of the elements of interest (inhabitants and facilities), is therefore exclusively based on demographic and geographical data for its evaluation.

The concept behind the operation was simple: collect and organise all the data needed to generate the indicator for the real city, digitise in a GIS environment, then generate a copy of the city and reallocate geographically its physical elements to obtain a compact version of it.

Starting from moving infrastructural and recreational apparatus (facilities), then digitally building new estates in the city's inner territory (new buildings), proceeding in a concentric way with respect to the weighted city centre, based on inhabitant's density. The last step of this reallocation was redistributing population (Inhabitants) from the peripheral areas of the city in the new residential complexes designed. It should also be remembered that while urbanizing new areas of the city was also necessary to draw new infrastructural lines to be able to access the housing (streets). Once the new layout (Compact Coimbra) was obtained, containing the same number of inhabitants, infrastructures and facilities, the accessibility index was recalculated and compared with the one from the real city.

The entire process of compacting the city, with the technical and legal references, as well as the logical-spatial implications, is detailed in chapter 5 (Study case, the city of Coimbra and its compacted version). In the same chapter are also included some considerations on the relocation of the population carried out during the operational phase of the compacted digital twin of the city, with its ethical and social implications.

The choice of using accessibility as a tool to demonstrate the validity of the method seems to be a natural choice as it is a concept that is being continuously and increasingly incorporated into metropolitan transport plans and national planning guidelines (Debooosere et al., 2018; Kompil et al., 2019). Also, looking at the city within a broader concept, this index is recognised as one of the possible paths to achieve sustainable development (Bertolini et al., 2005; Shen et al., 2020; Verma et al., 2019).

The technique used to define this concept and the expression (mathematical formulas) used to define and evaluate it are outlined below.

4.1 ACCESSIBILITY

The definition of accessibility turns out to be a non-trivial task. Despite the fact that over the course of time, many have managed to find, in various ways, a semantic solution of a qualitative type, its analytical and measurement circumscription is difficult to implement. Specifically, we refer to the difficulty in finding a workable definition of it (Handy. 2002). We are faced with a concept related to urban spatial layout (Banister, 1995; Papa and Bertolini, 2015) and inextricably linked to transport and land use within the conurbation, interlacing with the city's economic systems and with the increasingly rigid and pressing environmental needs (Bertolini et al., 2005).

Although the concept may still have a fluid meaning, it is now widely accepted that accessibility can be seen as the ease of reaching a destination (Boisjoly and El-Geneidy, 2017).

In this research it was therefore decided to use the latter definition as the cornerstone for calculating the index, using impedance as the calculation variable, a factor (described in detail below) that quantifies the difficulty of a user in moving from one place to another, generally referring to quantifiable data such as distance (physical distance from the subject to the point of interest) and duration of the journey between them. Accessibility is then defined as the cost (Aparicio et al., 2008, Ryan and Pereira, 2021, Shen et al., 2020 Gutiérrez and Urbano, 1996) necessary for the user to reach the destination; this instance is often used (as anticipated above) in research, in the fields of transport planning and urban and geographic studies (Vale et al., 2016, Miller, 2018, Brunisma and Rietveld, 1998, Geurs and van Wee, 2004).

Once the definition of accessibility has been theoretically defined, it is possible to write the index in mathematical characters, remembering the position-based nature of the survey tool. Some of the components of the equation will be explained later in the multiple breakdowns of the formula.

In its most immediate sense, the equation is presented as:

$$A_i = \sum_j w_j f(I_{ij})$$

Equation 1

With:

i : 1, ... , I number of origins	w_j : weight, based on attractiveness of the destination j
j : 1, ... ,J number of destinations	f : function of impedance
A_i : Accessibility score of origin i	I_{ij} : impedance separating origin i and destination j

In this application we have defined the origins (i, inhabitants) as residential buildings, i.e. the geographical location of the inhabitants, representing the demand for interaction with the destinations (j, facilities). The destinations, differentiated according to typology, are associated with a weight that defines their attractiveness, further details about criteria for assigning weights to categories of destinations will follow in the next paragraph. To make this calculation possible, it is necessary to clarify, even before evaluating the other elements in the equation, how it was possible to apply *Equation 1* within the calculation environment: a georeferenced system of the road network of the entire study area was inserted into the project environment, connected to the i-j system (inhabitants-facilities/destinations) by means of a proximity lock system. It is thanks to and through the connection between the road network and the i-j point system that f was calculated, translating the changing distance between origins (i) and destinations (j) into a utility and uselessness score.

If accessibility is defined as a utility or benefit, f is generally a decay function (like atmospheric pressure), a function that we will also cite later during the calculation of the modal share (log-logistic curve). Thus, these two curves are found to be inversely proportional: if accessibility is defined as a disutility or a cost, then f should be directly proportional to impedance.

4.1.1 The role of weights in defining facilities attractiveness

The assignment of weights for the different types of facilities was attributed, in this research, based on past studies carried out within the same laboratory where this investigation was conceived; the weight related to attractiveness, summarised in the table below was therefore identified by the researching body in a series of previous studies (Sousa et al., 2018, 2019). This metric was also used for comparative research (currently under review and not yet published) on the city of Coimbra and its digital counterparts, differentiating according to urban-spatial layouts derived from theoretical solutions (e.g. Coimbra garden city).

Below is a summary table of the destinations with relative attractiveness weights:

Group 1 facilities $\boldsymbol{w_j = 1}$	Group 2 facilities $\boldsymbol{w_j = 2}$	Group 3 facilities $\boldsymbol{w_j = 3}$
Churches	Entertainment sites	Bakeries and pastries
Cultural organizations	High schools (ISCED 4-5)*	Grocery stores
Elderly care centres	Parks and green areas	Middle schools (ISCED 2-3)*
Post offices	Pharmacies	Primary schools (ISCED 1)*
Sports facilities	Primary healthcare services	Kindergartens (ISCED 0)*
Universities and Institutes (ISCED 6-8)	Restaurants	Supermarkets
	Shopping centres	

Table 1: Facility groups and weights
(ISCED): International Standard Classification of Education, Eurostat 2018*

The explanation regarding linkages between weight and facility/destination is relatively straightforward: higher weight values correspond to greater frequency of visitation by residents, large weights relative to facilities correspond to places that are enjoyed more frequently. The values of the weights are consistent with travel frequencies by facility type (GOV.UK, 2018).

It should be stressed that the list of destinations selected in this research does not represent a complete list of facilities, and that other types of destinations could be considered. Also, the distribution of weights could be done differently, since cultural, historical and even regional factors can greatly influence the distribution. By further adding that the size of the destination and its peculiar territorial location can vary, it becomes clear that in these particular situations, it would be more appropriate to make a selection on a case-by-case basis. Sticking to the array of chosen destinations, it is possible to observe how some facilities may be of extreme interest to a particular, narrow portion of the population, but of almost absolute disinterest to the most significant portion of the inhabitants. Some examples of destinations of great interest to relatively small peaks of the population, which were excluded in the selection of the most influential facilities, are: banks, newsagents, tobacconists, sporting goods shops, estate agents, undertakers and many others.

4.1.2 What defines accessibility as a cost and why

The pivotal pair impedance and f governs, in this research, the definition of distance (determined through the referenced road network) measured as impedance and the identity function of f ($f(x) = x$).

It is precisely this choice that leads accessibility to be defined, in this study, as a cost, specifically as a (weighted) distance to a system of fixed destinations (facilities); this set of choices leads to a flexible and easily interpreted definition of accessibility.

The reasons why accessibility is used in a definition that is easy to understand are many: in the superpartes vision of the research environment framed as a practical tool and not only as a means of technical information by researchers and professionals, it is intended for policymakers. It is precisely on this point that the development of this portion of the research wants to focus and on which Straatmeier and Bertolini (2008) have particularly insisted, namely: the measure of accessibility must be easily readable and comprehensible by those who, in practice, make political decisions. Regardless of the type of research user, quantitative accessibility assessments derived from location-based measures are useful for exploring the shape of urban space, as stated by Horner (2013). A large part of this research project is indeed based on this dual concept, namely accessibility as a tool for investigating form and as a device for easy interpretation.

Regardless of the type of origin (inhabitants) and thus the traveller profile, distance is a measure of the cost of (location-based) accessibility, which means that its value and the respective consequences deducible from it can be easily understood even if extrapolated from the context.

In addition to that, distance, compared to time-dependent measures, does not appear to be affected by variables that are difficult to calculate or of changing complexity such as traffic (Lee et al., 2019). This does not deflect from the fact that, as mentioned above, other formulations of the accessibility index can be used with the same results and conditions of generality (such as independence from time and advantages related to distance-based calculation) as long as it is possible to calculate them using massive georeferenced data processing tools such as GIS. Other research has been carried out in this regard (see Vale and Pereira, 2016).

To conclude, taking up the input from the beginning of the paragraph concerning the correlation I_{ij}- f-A_i: the relationship between distance and impedance does not require a parameterization related to f, as it is indispensable in the determination of the modal share index, making this measure (unlike other location-based measures) less arbitrary.

4.1.3 Refining accessibility

We have therefore established that accessibility will be a parameter assimilated to a cost, and this means that when a high number of destinations are considered, high A_i accessibility values are induced. This leads to a tendency for the indicator to degrade when multiple facilities of the same type are analysed.

The degradation of the index goes against to the concept it embodies: accessibility is designed to have better values when multiple facilities (of the same type) are considered. This behaviour can be successfully reproduced by considering only the closest facilities for each typology, in this way there will be a "natural" spatial selection of destinations, where the closest ones will take precedence over the most distant ones, always considering the starting condition: they must be destinations of the same typology.

In this way, rather than considering every possible destination (j), in ***Equation 1***, the impedance calculated between the origins (i) and the destinations (j) is calculated for the facilities of each type that are closest to 'i', at which point they are aggregated into A_i, according to ***Equation 2***, that follows;

$$A_i = \frac{\sum_{jk} w_j L_k(j) I_{ij}^k}{\sum_j \ w_j \sum_k \ L_k(j)}$$

Equation 2

Where:

- A_i : Accessibility score of origin i
- w_j : weight of facility type j
- L_k : Freedom of choice factor for the k-th closest facility type j
- I_{ij}^k : Impedance separating origin i and the k-th closest facility of type j

- I : 1, … , I number of origins
- j : 1, … , J number of destinations
- k : 1, … , number of closest facilities, in this research we used K=3

In ***Equation 2***, a normalisation factor is placed in the denominator to ensure that the values of A_i are independent of the scales used for the weights and the factors given by the freedom of choice of the facility.

L_k (j) factor indicates the importance of having freedom of choice between k facilities (k=3).

These factors are monotonically decreasing in k since the further away a facility is, the less likely a person is to visit it. This is one of the possible ways to model the demand for multiple facilities in mathematics (Brimberg et al., 2019), among its advantages we find how it manages to preserve the interpretation of accessibility as a distance.

These factors depend on j, since in some types of destinations (j_1-type) proximity turns out to be the only relevant factor in the choice process, which is then reduced to a selection by proximity. Among these we can for example note schools (not of every kind and degree, but only up to compulsory education), pharmacies, hospitals and post offices. On the other hand, we find destinations such as supermarkets, restaurants, cultural organisations, where it makes sense to allow freedom of choice. In the following table we can look at the complete list of facilities and their categorisation according to L_k-freedom of choice.

Closest facility j_1-type	Closest three facilities j_3-type
Kindergartens	Bakeries and pastry shops
Primary schools	Churches
Middle schools	Cultural organizations
Primary healthcare services	Elderly care centres
Pharmacies	Entertainment sites
Parks and green areas	Grocery stores
Post offices	High schools
	Restaurants
	Shopping centres
	Sports facilities
	Supermarkets

Table 2 : Facilities categorized in "freedom of choice" levels

For j_1-type destinations the factors are $L_k(j_1)= \{100,0,0\}$. For j_3-type facilities a tern of values for $L_k$was used, in ascending order by value of k, specifically: $L_k(j_3)= \{70,20,30\}$ and $L_k(j_3)= \{50,35,15\}$. The factor $\boldsymbol{L_k}$ can be interpreted as, using the last asset as an example, a 50% preference to go to the nearest supermarket, followed by a 35% chance of going to the second nearest supermarket and a 15% chance of going to the third nearest supermarket. The greater the value of $L_1(j_3)$, the better the accessibility score A_i will be, since I_{ij}^k increases as k increases.

4.2 MODAL SHARE

Also called Modal Split, it refers to the percentage of trips combined with a certain type of transport.

This concept, linked in the scientific literature to compact cities, but more often related to analyses of metropolitan cities, is of particular importance in the assessment of the sustainability of urban mobility. The use of this evaluation index (usually expressed as a percentage value) is to assess the approach of a more sustainable modal split for interurban trips. This trend is generally referred to as a modal shift, i.e. a change in the methodologies used for travel: doubly linked to sustainability policies.

4.2.1 Role of modal share in the research

Generally, modal share data, i.e. percentages from surveys and travel data, are obtained through sampling, interviews and geographical extensions. In this comparative analysis it was of course not possible to carry out survey research for the compact city of Coimbra: we proceeded in a different way, extrapolating percentages for different modal split afferents through graphs.

In addition, this research does not refer to all categories generally observed within the share (walking, cycling, public transport, private vehicle) as only the portion of the share related to active trips is considered, so the index used becomes the active modal share. This indicator contains data on active mobility by biking and walking. Specifically, a double analysis was carried out on the modal share related to the choice of moving through the city: only by walking and the summed combination of walking or cycling.

4.2.2 Methodology simplifications for the research

The calculation methodology is slightly more complicated than the one introduced for accessibility. For this reason and in order to allow fluidity and less overabundance of data, this research paper does not carry out a detailed analysis of the modal split calculation method.

However, it is important to mention the method of data identification: the system consists in identifying, for each facility, the probability that the average user reaches the said destination with the selected transport method (walking or in a non-exclusive walking/cycling combination). This probability is obtained by crossing the distance of the destination (placed on the ordinates) with a logarithmic curve (log-logistic curve) of non-linear correlation, adequately adjusted with parameters related to the type of destination, since not all facilities are equally attractive, and an independent parameter manages the two types of movement selected.

The data collection and its treatment took place, as for the accessibility, within the ArcGIS software, while the synthesis of the results was transposed on Excel spreadsheets.

The inclusion and treatment of the data in a more comprehensive manner is postponed to another more extensive research, always including the city of Coimbra and its implications in the compact version, which correlates several indices between them to verify other aspects related to sustainability of the city in its densification.

4.2.3 Results explanation

Results presented in chapter 7 deal, as anticipated, with the comparison of modal shares for only two fields. These two results are not meant to be complementary but symbiotic: the first one will refer to the possibilities of the city to be travelled by walking only; the second figure is instead related to the percentage related to the whole active modal share, i.e. the determined possibility according to which the population would move within the city in a combination of the travel methodologies of cycling and walking. It should be mentioned that this figure is not complementary to the modal share of walking alone, as subtracting the data does not give the figure for the probability of moving around the city by bicycle alone. The result is in fact related to all active mobility, cycling and walking.

5 STUDY CASE, THE CITY OF COIMBRA

This chapter explains in detail all the practical methodology that has been used for implementing the analysis of the city of Coimbra, in its real and compact version.

Most of the operations that will be described have been carried out on the ESRI ArcGIS 10.7 GIS environment, in addition to which Excel spreadsheets have been used for the detailed treatment of the results obtained through the software, and all the codes and algorithms necessary for the massive treatment of the data have been developed in Phyton and subsequently inserted into the GIS environment.

Regarding the policy-wise treatment underlying the compaction of the city, reference was made to the current legislation (2021) in force in the municipality of Coimbra. All the administrative-legislative instruments used will be mentioned as their use is explained.

5.1 PRESENT DAY COIMBRA

Coimbra, with its 104,643 inhabitants (143,396 considering its metropolitan belt), is the seventh most populous city in Portugal, located its central region. Founded in the Roman era, the city has developed to this day in an unrestricted way, owing to its long history of occupation by many different cultures. Characterized by narrow cobbled streets in the city centre and large boulevards, in antithesis, in its newer parts, Coimbra represents an example of urban design influenced by different urban trends and pressures over the centuries (Silva, 2008).

As mentioned above, most of the work was done on ArcGIS software and to understand what and how it was done, it is necessary to briefly explain what digitising a city consists of. The amount of work necessary to generate a digital twin of a city is almost incalculable but, as is well known, every problem lends itself to different solutions: in this case it was resolved by simplifying, as much as possible, the datafication of the city, highlighting and modelling only what was strictly useful for the research. Furthermore, a type of modelling was chosen that does not involve the generation of three-dimensional shapes or figures, but rather a system of data points and lines.

First it was necessary to establish a perimeter within which to extend the field of research: part of the population belonging to the metropolitan basin of the city was therefore cut out. In this way it is possible to represent more truthfully the portion of the population that makes daily trips to the city. The city is of medium size, developed mainly along the east and west banks of the Mondego River.

Once the search area had been defined, a scalable base map of variable resolution (upscaling at closeness) was loaded into the software: a flat satellite image of the city. The toponyms of the road network, modelled in the form of lines, were then added, or rather inserted, to this background. Each line is catalogued within the programme and a multitude of information is included, such as: length, geographical location, sequential identification code and much more.

The base map and the road network form the backbone of the model, on top of which the "destinations" and "origins" (in the form of points) were placed, whose relative distances will be calculated following the course of the road network. Each point belonging to the facilities or inhabitants is in fact magnetically associated (snapped) with the nearest road to bind it to a position. In this way a (non-unique) route is formed linking the two elements: destination and origin, making it possible to calculate reciprocal distances.

The premise on which the calculation possibility of this research is based hinges on this collaboration between the layer containing the road network and the various sequential planes where destinations and origins are inserted. The role of the magnetic snaps is fundamental as it makes it unnecessary to associate each point with a precise position not only in space (in this case the base map) but also within the road network.

The various modelling phases of the elements will now be examined in detail.

5.1.1 Origins

To define routes, it is necessary to establish the origin of each journey to a particular destination (facilities). However, this task is particularly difficult as it is necessary to determine the precise origin of each inhabitant of the city. While the absolute position of the facilities within the city is easy to identify, the determination of each origin represents a significant challenge. The solution to this problem is possible thanks to the coexistence of two factors: the first relates to the definition of an accepted level of precision (within the orders of magnitude of this research) regarding the location of the origins, the second is attributable to the INE, the National Institute of Statistics of Portugal.

In 2011, the INE made available the release of the statistical subsections of the distribution of the Portuguese demography, which made possible to distribute the population, with a sufficient level of precision (the size of a subsection is approximately one block), according to the centroids of the residential buildings. This solution, i.e. having the building centroids as origins, would have generated too much visual interference when trying to display graphically on the map the score related to accessibility (which is always associated with the origins), as the symbology would have overlapped.

This system also ensures that a single centroid of non-zero origin turns out to be uniquely associated not only with one inhabitant but with a multiplicity. Indeed, we expect to find multiple origin centroids in cities and unitary or null elements in more rural areas.

This problem was solved by defining a square mesh of 25 metres per side over the study area and deriving the respective centroids. This means that the origins, previously fixed (snapped) to the centroids of the buildings, are redistributed over the mesh in such a way as to be more orderly and visually comprehensible. The small size of the grid means that no changes are made to the population density between model and reality.

After the grid was laid out, the number of inhabitants in each square was added to the centroids-associated table using the join tool, after which the squares and centroids with zero inhabitants were removed. At the end of the process the non-zero centroids are 41.253. All the maps that will be presented later show a totality of points, representing the origins or inhabitants of the city, equal to the number of non-zero centroids; these 40,000+ points represent the totality of the city's population: 104,643 inhabitants.

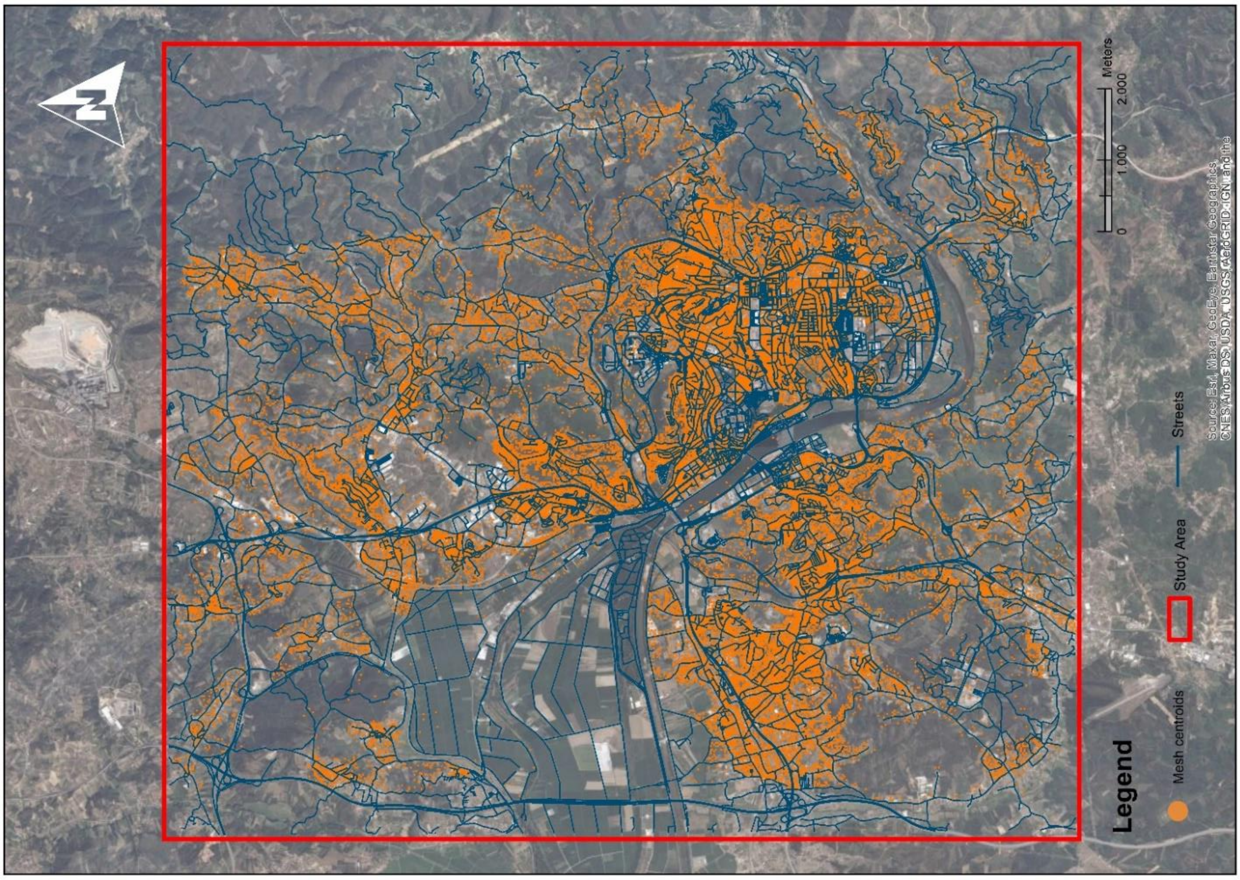
5.1.2 Destinations: facilities

The facilities were positioned differently from the way population was distributed. Given the numerically smaller size of the facilities and their strategic importance, it was decided to position them manually with a correlation relative to their current position on the base map. The same automatic magnetic fastening previously mentioned was used to associate the facilities to the road network.

5.1.3 Road network (streets)

The entire road network of the city of Coimbra was obtained through OSM (OpenStreetMap), a collaborative open-source project aimed at producing a complete content map of the world. The data contained in the OSM is freely available and distributed under a open licence, so it is also possible to use it for commercial purposes, as long as the source is mentioned.

The mapping of the road network extends to the limits of the study area and has been drawn for a total of 1,334,879 metres. Among the data included we can find information such as: name of the road, class of travel and typological classification.



Comparison 1: Size analogy between Coimbra (down) and its redraft as a compact city (Figure 1 and 2)

6 REDRAFTING THE CITY AS A DENSE VERSION OF ITSELF: COMPACTED COIMBRA

Compacting a built reality may seem, at first glance, an extremely difficult process. We are used to thinking of the urban environment as a historically self-defined unitary mass and we rarely manage to see the potential possibilities still hidden within it.

Initially, therefore, it might seem that compacting an existing system is an impossible challenge. However, by analysing the territory with the right tools, it is possible to read the hidden potential of each area. Cities, and Coimbra in particular, are far from being cities without compacting prospects.

6.1 INITIAL ASSUMPTIONS ON PLANNED DENSIFICATION

Before starting the process of digital compaction of the city, it was necessary to analyse the existing system of constraints around the urban fabric to better organise the densification process and to understand how far this process could be carried out.

Considering the present conformation of the city, the size of the historic centre and the weighted position of the facilities, a threshold of 35/40% was hypothesised, i.e. the digital delocalisation of a quantity representing about 40% of population. The densification towards the city centre, as seen as the barycentre of the facilities, of about 40,000 inhabitants would have led to a significant improvement in the results of the accessibility index, which would have sufficiently justified the research work. As previously stated, the aim of the study is to move the centroids towards the city centre or facilities centre of gravity, taking for granted that, as can be observed in *Figure 3*, most facilities are concentrated in the immediate vicinity of the city centre, where therefore the accessibility score also tends to be higher on average. (The comparison between the accessibility score of the two cities will be detailed more specifically in chapter 7 "Results".)

6.1.1 Geo-morphological considerations

As previously mentioned, Coimbra has evolved and expanded over the centuries, following a physiological rhythm of expansion, spreading out over the surrounding territory without excessive limitations. In addition, in line with a national trend that is now well established, the city has developed considerably on two interdependent epicentres of the city, on either side of the Mondego River, which cuts the city in two. This binomial development straddling a river is typical of many Portuguese cities, for example Porto, which overlooks the Douro River and splits its identity with Villanova da Gaia.

One of the constraints that had to be set, during the embryonic phase of the study on how to compact the city, was to preserve the identity of the city as two parts of a whole. One of the compacting hypotheses envisaged the isolation of a large part of the city compacted in a single riverside, a proposition that was immediately discarded in view of the historical and cultural considerations about the city.

Another constraint, of geo-morphological nature, was of great help in the initial planning for densification: the presence of the Mondego River. If earlier we talked about how the identity of the city resides in the two halves split by the river, now we must consider the directions that these two halves face. In the process of densification, we kept the two city components residing in the river valley, but at the same time, we have used the bends of the river to the south and to the north as a natural delimitation for the development of the city. As it is possible to see in Figure 1, the two main sides of the city face the river with an east-west orientation, due almost entirely to the morphological conformation of the territory. For that reason, the main means of connection (road, pedestrian, and railway bridges) between the two city halves are located precisely at the interface of the two portions of the city. The remaining part of the river, on the other hand, lacks major links or arteries between the two banks. The reason for this is surely to be found in the topography of the area: in the south-eastern part of the city, nature becomes more rugged, and the already extremely hilly fabric of the metropolitan area is exacerbated, making connections difficult.

We wanted to take advantage of this natural and historical predisposition of the city to insist even more on the river-themed development, trying to limit as much as possible the expansion outside the bends.

As far as the system of constraints related to the geo-morphological conditions of the city is concerned, we did not find other significant limits that could influence the planning of the city's compaction process.

6.1.2 Legal and administrative considerations

This research, seeking to be an easy-to-understand and helpful tool for policymakers, sets out to comply with all the existing constructability and urban planning regulations currently in force within the municipality of Coimbra. The details of how this set of laws and regulations have been implemented, in the practical act of modelling, will be explained later, when describing the practical implementations on the model. In this short normative incipit, we will only mention the tools used (without explaining their functioning in detail) and how these rules have profoundly influenced the topography of the densified city.

The fundamental assumption from which it is necessary to start to disentangle the various concepts that follow is only one: **to compact a city means (in the practical act of this research) to densify as much as possible the built-up area** (residential and not), using all the land made available by the city and recovering those lands that now are not optimised**. This densification involves the construction, on the land identified, of residential buildings that maximise the percentiles of constructiveness given by the master plan (Plano Direitor)**. To do so, it is therefore necessary to identify the most suitable areas, with the most potential, within city bounds and look for land, of central relevance, that is currently decaying or unused. The specific search for a multi-potentiality of urban spaces in a compact city could not be dealt with in this research, but it could be a valuable addition in prospective follow-ups.

With a glance to the densification process, it was essential to identify the parcels of land with the greatest constructive attractiveness. This process is not trivial as it is permeated by a multitude of factors, not only economic but also (and above all) social. In this regard, a discussion was held within the research workshop that also involved the Coimbra town planning office (for some sections), about which areas of the city had undergone the greatest expansion in recent decades. In addition to fruitful discussions, an attempt was made to identify the areas subject to recent urbanisation by analysing satellite maps of past years.

The results of these discussions and research were cross-referenced with the study of the Classification and Qualification of Land in the Municipality of Coimbra (Classificação e qualificação solo, Divisão de Planeamento, Plano direitor municipal) *Figure 16*, together with the Piano Diretor Municipal (PDM, articles 49 to 136) and the Regulamento Municipal de Urbanização e Edificação (RMUE, Regulation number 381/2017 and revision 08/2018) *Figure 17*, in order to identify urban development areas with the greatest construction potential and where expansions of the urban fabric were currently occurring.

In addition to identifying the most desirable areas, through the administrative tools mentioned above, it was necessary to quantify the possibility of constructability on the given land and verify whether, respecting all the constraints mentioned above, the densification project of the city was possible.

6.1.3 Demographic considerations

A final consideration concerns a quantitative observation of the distribution of the population within the urban area of the city. To establish how to move operationally, as seen, several analytical steps were necessary to understand how to organise the process of densification and these include the study of the distribution of the population on the territory. It was possible to observe, thanks to the drawing up of Figure 1 with the distribution of the quadriculas, how the population density of the city decreases proportionally as it moves away from the city centre. It is also recognizable how the frequency of centroids tends to decrease in the peripheral areas but, remembering that a centroid generally contains a number of inhabitants greater than one, it is also possible to make a second collateral observation: by moving our gaze to the periphery, not only does the number of centroids generally decrease, but also their value in terms of inhabitants changes. In fact, for the centroids pertaining to the centre, the average value, which reflects the number of inhabitants synthesised within it, is decidedly higher than the values relating to the periphery. It is precisely in the peripheral areas that we find almost all the centres with a value equal to unity, where the population density collapses. There are in fact some medium-low density areas that reach 40 inhabitants per km^2 (almost 10 times lower than the average population density of the city, which stands at 418.7 inhabitants per km^2).

This observation, correlated with a score relative to accessibility with the worst values of the entire peripheral belt, has indicated which parts of the city would be better to move first. Touching many centroids but a low number of inhabitants (we would have potentially wanted to carry out, strictly speaking, the opposite) led the compacting process to be time-consuming but it was the way chosen for the densification. The method was prospecting an instantaneous leap forward, therefore an improvement, of the score relative to accessibility: moving first the origins from which the worst results derived.

Another hypothesis of displacement would have been to start compacting from the exact centre of the city (concentrically with respect to the weighted barycentre of the population) filling in the possible spaces as they formed. This second solution would have perhaps produced, in the course of time, results with greater efficiency than the previous technique, but with a not indifferent expenditure of time and resources. Furthermore, with a similar methodology, it would not have been possible to determine intermediate results to understand if the process was bringing appreciable improvements in terms of results: for most of the process, centroids with high accessibility scores would have been dismantled, making it difficult to estimate *in itinere* the improvements brought by densification.

This was the last preliminary consideration for the implementation of the densification process, which will be explained in detail in the following paragraph.

6.2 DESCRIPTION OF THE CITY'S TRANSFORMATION PROCESS

So far, this paper has described the theoretical implications and considerations on which the practical work of compacting the city has been based on. In this chapter the practical processes that have been applied will be examined: modifications made to a copy of the real city's model to make it a compact one.

To better understand certain passages, some notions already mentioned in paragraph 5.1 will be reported, in order to understand the transformative processes, it is good to be clear about how the starting model of the city was obtained, what its limits and its potential implications were.

6.2.1 Redrafting the city maintaining its actors

One of the fundamental concepts of the research deals with the fact that the transformation of the city must not take place by distorting the actors in play (interpreted by the destinations). It is precisely to follow this axiom that to re-model the city by compacting it, the best choice is not to start from scratch, using a new base and rearranging the interpreters, but rather using a copy of the current city.

Having accepted this concept, it is possible to start explaining the densification process from the beginning. We proceeded by generating a copy of the entire existing model of the current city of Coimbra, including every aspect within it: facilities, inhabitants and the street network. We ended up with a representation of the city identical to the one shown in Figure 1. We have chosen to use this technique in order to preserve all the data related to the facilities and origins already inserted, since the densification of the city must maintain all the main characteristics of the real one: the number of facilities must not change since the amount of people who will live in the city will be the same, this means that the catchment area for the origins will remain unchanged, a logical reasoning that leads us to preserve each facility and simply relocating it on the territory.

6.2.2 Selection of land parcels and use of constructability percentiles

The next step was to search for and mark on the base map areas that had been identified as suitable (during the preliminary study phase), verifying that, at the time the modelling began, no buildings were being constructed on them. At this stage of the work, in fact, buildings were constructed, or rather modelled, in the digital copy of the real city, designed in full compliance with the current regulations in force in the municipality of Coimbra, and which will act as a catchment area for the centroids housing populations with low accessibility values.

This construction, generating new living spaces and the subsequent relocation of the population, was by far the most time-consuming operation, as it was decided to simulate a related-to-reality possible future course of events.

Once it had been verified that the areas were clear, it was possible to move on to measuring and cataloguing them: for each marked territory the identification of net area (m^2), the assignation of the alphanumeric categorisation relative to the PDM (C1, C2, C3 and subcategory R1, R2, R3, R4), the calculation of the relative building indices (primary and secondary), together with the index of impermeable surface, the maximum number of executable floors, the maximum constructability per lot. All factors were measured and each of them was assigned a sequential code indicating its belonging.

According to the PDM (Plano Diretor Municipal), each plot of land has two building indexes, the first of which has a limiter on reaching the 1000 m^2 of constructible surface area. For this reason, in most cases it has been decided to sub-lot the plots of land to maximise the buildable area of each plot (where possible), with the proviso that in this research, plot is defined as a parcel of land on which it is possible to construct one single building, regardless of its size.

The inclusion of this large amount of data for each individual parcel of land was decisive in the success of the modelling as it reduced the time needed for calculations to determine the size of the individual buildings that could be erected, and therefore their maximum capacity in terms of inhabitants within them, but it could also be useful in a possible future calculation of the various elements included in this research.

As mentioned above, each suitable area was catalogued and inserted into a database (Excel spreadsheet and table of contents on ArcGis) containing multiple factors. These elements are not particularly challenging to understand, but it is necessary to explain them fully and then cite them in the respective official documents.

Each plot, falling within the metropolitan area of the city of Coimbra, belongs to a specific land use classification area, established by the PDM which sets out the constraints on its constructability and use. In the preliminary area selection phase, the Land Use Classification Map, in support of the PDM, was used to establish the plots with the best building values. The map presents an incredible multitude of types of area subdivisions, as it is possible to see in Figure 16; to avoid confusion we will refer only to the areas of interest in this paragraph: area classification of "Urban Soil", with specific interest in the class of "Central Spaces" (central area C1, C2 and C3) and the sub-classes "Residential Spaces" (R1, R2, R3, R4). Each classification subtends a set of data and limits related to the buildability of the land under consideration, following an extract of the PDM (Figure 17) related to the central area C2.

Artigo 88.°

Usos

Na área central C2 deve-se:

a) Acentuar a função habitacional, garantindo que em cada nova edificação esta função ou outras que fixem pessoas ao longo do dia deverão ocupar, salvo justificação fundamentada, 50% da área total;

b) Reequacionar a circulação, privilegiando o transporte público e os modos suaves de transporte;

c) Promover a ligação ao Rio, eliminando a barreira constituída pela linha de caminho-de-ferro;

d) Recuperar, com eventual reutilização, os edifícios existentes que apresentem valor patrimonial.

Figure 17: Close up on an extract from PMD

Each area and sub-area hold its own indices and limits. In the following table the main data of the classifications involved in the areas selected in the research was collected.

	R1	R2	R3	R4	C2	C3
Primary Buildability index	0.7	0.9	1.3	1.8	1.8	1.8
Secondary Buildability index	0.45	0.45	0.65	0.9	0.9	0.9
Impermeabilization index	0.55	0.6	0.65	0.7	n.a.	0.65
Maximum number of floors	2	3	5	7	n.a.	4

Table 3 : Indices linked to soil classification

Ultimately, an array of data similar to that presented in table 4 was collected for each area, ready to be used in the subsequent deployment.

ID	Area (m^2)	PEI	SEI	II	Floors	Lots nº	ApL (m^2)	BApL (m^2)
185	1306	R3	0.65	0.65	5	1	1306	1348
…	…	…	…	…	…	…	…	…
160	8499	R4	1.8	0.9	7	3	2833	3055

Table 4 : Example of land parcel classification

Where PEI stands for primary buildability (edificabilidade, from Portuguese) index, SEI as secondary buildability index, II as impermeabilization index, Apl as area per lot and BApl as buildable area per lot.

The most interesting piece of information is the buildable area for each parcel: this information, which can be obtained theoretically in a simple and direct way, is of particular interest because it was manually calculated for each lot due to the interdependence between the PEI and SEI indices and the ever-changing position of the marked areas.

To obtain the total buildable area, knowing the indices and the area of the lot, it is sufficient to multiply these two data between them, acquiring the maximum buildable area. The value, given in square metres, of BApL summarises the use of the two indices PEI and SEI to determine the buildable area for the entire lot. Unfortunately, however, it was not possible to identify an unambiguous equation linking these indices as they are dependent on the spatial location of the lot in relation to the road. In fact, the PEI value can only be used in ***Equation 3*** for the portions of the area, with a depth of 25 metres, that border the road network.

$$BApL = PEI * Area$$

Equation 3

It is therefore necessary to break down the lot area into two different portions, the first one bordering the road, the second one pertaining to the remaining portion of the lot. But that is not yet enough: ***Equation 3*** can only be used up to a maximum result of BApL equal to 1000 (m^2), forcing us to use instead SEI for the remaining portions of the area, even if capable of satisfying the condition for use of PEI (adherence to the road, calculated with the tangent length and with a maximum depth of 25 metres). For simplicity, in the following formulas, we will break down the total area into area tangent to the road surface and residual area, in the form of:

$$A_{tot} = A_{tg} + A_{res}$$

Equation 4

The formula for calculating BApl therefore turns out to be such a system:

$$BApL = \begin{cases} A_{tg} * PEI + A_{res} * SEI \ \ per \ A_{tg} * PEI \leq 1000(m^2) \\ 1000 + (A_{tot} - A_{tgu}) * SEI \ per \ A_{tg} * PEI \geq 1000(m^2) \end{cases}$$

Equation 5

with:

$$- A_{tgu} = \frac{1000}{PEI}$$

Equation 6

with:

- A_{tgu} : useful tangent area, i.e., the area of land bordering the road required to produce, if associated with PEI, a buildable area of 1000 m^2

As can be seen from ***Equation 5***, in the case of large plots with important portions bordering the road network, there are immense losses of building area, due to the difference between the values of PEI and SEI. In order to avoid these losses, we have tried, where possible, to maximise the use of PEI up to the maximum value of $A_{tg} * PEI$ (=1000m^2), subdividing the various plots of land (Lots) into sub-areas, each of which has the possibility of exploiting the PEI index up to its maximum. The choice of opting for the subdivision of the plots of land was convenient in terms of the quantity of square metres that could be built on and allowed for a considerable optimisation.

The drawback of this method lies in the fact that, as already mentioned, it was not possible to snap the various areas to the road network, therefore, the calculation of the A_{tg} areas was carried out according to a semi-manual method assisted by Excel spreadsheets. Terrain data was loaded in the software, which evaluated the convenience (or otherwise) of subdividing the plot into several sub-areas, using the appropriately modified ***Equation 5***.

The equation has been varied and adapted: once the size of A_{tgu} has been determined, deriving from the knowledge of the lot relevance to the respective residential space (R1, R2, etc.), the division between A_{tg} of the whole lot and A_{tgu} is carried out, obtaining the number of sub-lots by default approximation:

$$\text{Lots number} = \frac{A_{tg}}{A_{tgu}}$$

Equation 7

Then the value of the residual area was obtained as:

$$A_{res\_tot} = A_{tot} - (\text{ Lots number}{*}A_{tgu})$$

Equation 8

This must then be divided again by the number of lots to determine the individual A_{res} of the lots, from which:

$$A_{tot_{single}lot} = (\frac{A_{res_{tot}}}{\text{Lots number}} + A_{tgu})$$

Equation 9

As mentioned above, this procedure is not fully automated because, as well as the determination of the portion of the plot bordering the road, the possibility of the plots to have street frontage (with a maximum depth of 25 metres) was also determined by the operator.

6.2.3 Modelling buildings on selected areas, the 3 factors

Once the selection of areas identified as profitable had been completed and their details entered in the spreadsheet, it was necessary to determine the size of the building that could be constructed on each lot and sub-lot, depending on the building area obtained.

Three main decision factors come into play in this choice: the index of impermeability, II, the maximum number of floors that can be built and the choice of the size of the flats on each floor.

6.2.3.1 Impermeabilization index, max surface area

As far as the index of impermeability is concerned, the limit derived from it is expressed in an equation of rare simplicity: the maximum impermeable surface (S_{max}) is obtained from the product between the total surface of the lot ($Area$) and the index of impermeability (II):

$$S_{max} = Area * II$$

Equation 10

The effective sealed area S_{imp_eff} was made to coincide with the building footprint, i.e. the gross size of the single floor. This simplification was made because in the vast majority of cases, the value of S_{max} turned out to have a numerical value comparable to BApl, i.e. the total buildable area for a single lot, and it was possible to avoid reaching the threshold value S_{max} by choosing to build two floors above ground, making the footprint, and therefore the impermeable surface, at least half of BApL.

6.2.3.2 Building dimensions and housing determination

The second and third factors are the maximum number of storeys that can be built and the sizing of flats, and they both can be said to have come into the design in a symbiotic manner. Once it had been established, almost a priori, that to overcome the obstacle given by the maximum impermeable surface area it was sufficient to provide buildings with at least two floors, the design focus shifted to the choice of the average size of the built-up area and the estimate of the occupants of each building.

This is perhaps the most delicate phase of the study, as it considers many factors, not only statistical, but also related to the quality of life of the occupants. In this regard, many simulations were carried out regarding the minimum and average size of the dwellings normalised on the number of inhabitants. This series of trials led to the determination of a reference table, *Table 5*, which summarises the weighted choices for this phase of the study.

Portuguese apartment classification	Gross square meters average	Assumed inhabitants
T_1	55	2
T_2	72	3
T_3	91	4
T_4	105	5

Table 5 : Dwellings averages and range of inhabitants

In Portuguese real estate industry, flats are classified with a letter T followed by a number indicating the number of separate bedrooms, for example a T1 refers to a studio with no separate bedrooms, a T3 will have three bedrooms.

The size chosen for the different classes complies with all the current regulations in Portugal concerning the minimum size of flats and the minimum size per person; similarly to what happens in Italy, the minimum size for a flat with six people is 80 m^2.

The estimated number of inhabitants per flat is always linked to the classification of the flats by choosing, when possible, the most restrictive number of inhabitants: in the “T3” class of flats, it is possible to include in the calculation 5 inhabitants, we have chosen to adopt a default estimate.

Using *Table 5*, knowing the maximum surface area available and maximum number of floors, it was possible to define, for each building unit, a layout of flats per floor that maximises the available surface area with the number of inhabitants accommodated. Clearly, the surface area of a dwelling is not defined solely by the sum of the gross surfaces of the flats that compose it. To this end, a surface area called buffer, was considered, which includes the average dimensions of some elements generally found in condominium buildings, such as: stairwell surface area, lift space, entrance hallway, technical room; the average size of these elements was included in the a priori evaluation of the choice of occupancy solutions for the building.

To this set of indications and rules, two other constraints concerning good construction practice and adherence to the current Portuguese trend were added. Firstly, to limit the variability of flat types within a single building, it was decided to follow a good construction practice establishing a standard plan and repeating it throughout the vertical development of the building, so that once the composition (in terms of classes of flats) of a floor had been chosen, it was sufficient to multiply this result by the total number of floors in the building.

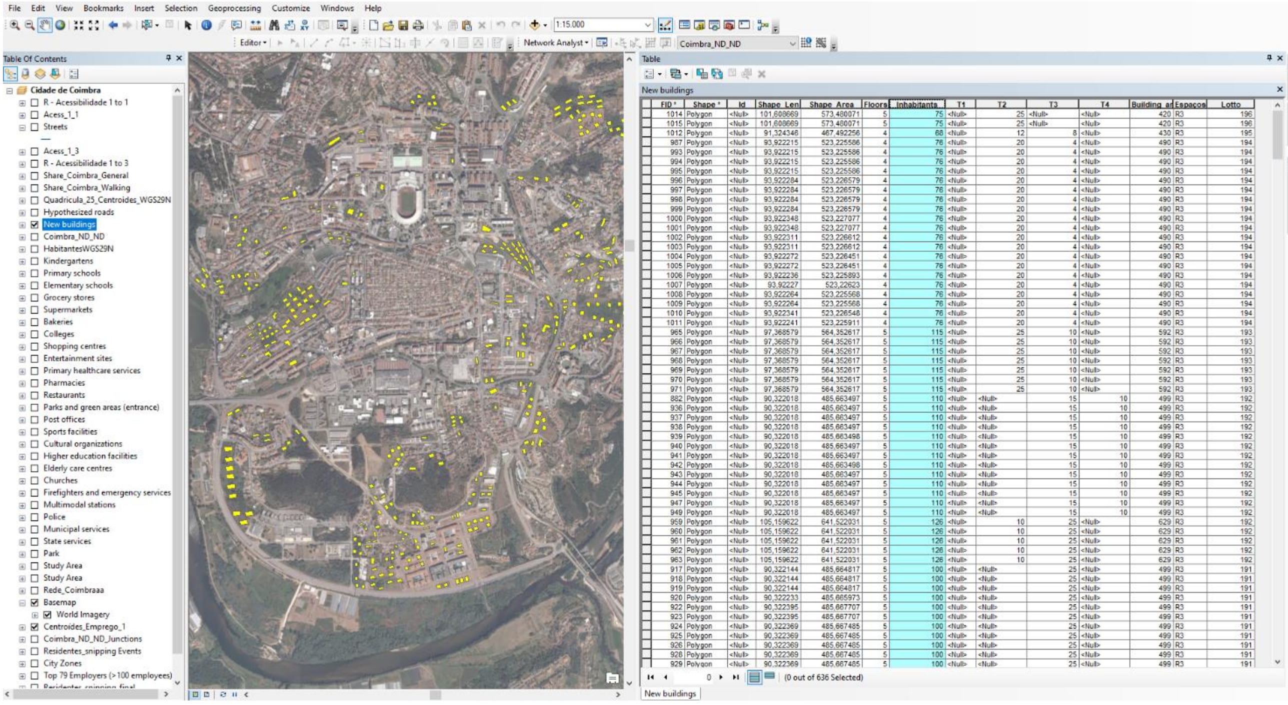
Secondly, the other constraint also works as a design aid: we developed the choice of flat classes, over the total number of flats generated, following the current Portuguese real estate statistical composition, i.e. the percentage of flats T1, T2, T3 and T4 over the total number of flats. The numbers generated in the model follow the distribution percentages of these classes in the real estate reality of the country. Unfortunately, it was not possible to obtain the same percentage values in Coimbra as we did not have data on the city. Not having included two types of classes (T0 and T5) the percentages obtained tend to be slightly different, but still largely in line with the national distribution in the country: for example, the percentage for the T4 flats is 8% of the total, while in our case it is 7%.

6.2.4 Drawing buildings and preparing densification

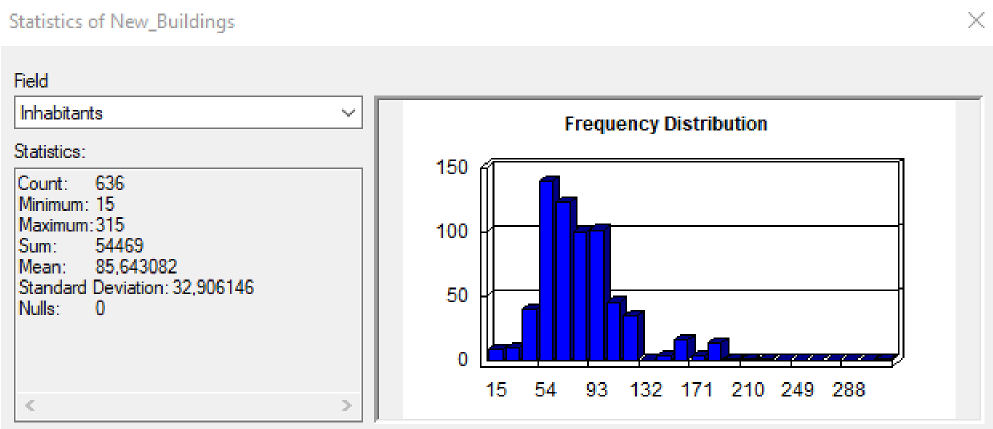
Once all the preliminary calculation and estimation operations were completed, the only thing left to do was to insert the buildings into the model. For each selected area, depending on the number of sub-lots calculated, a quadrilateral was drawn, having a mostly regular shape, representing the single building. All the data defining its qualities were inserted into this simple geometric form: footprint area, number of floors, ID, lot number, classification in residential space, number of flats per class and capacity in terms of inhabitants.

The total number of Lots considered was 196, representing an amount of modelled building of 636. In Screenshot 1, a capture of a building modelling phase, we can see on the left, the table of contents of the modelled elements with all their details. In Screenshot 2 we can see a small summary table of the item "Inhabitants", belonging to the table of contents of the newly modelled "New buildings". This snapshot was taken when the availability of new areas suitable for construction within the centre of Coimbra was fully saturated. This small table shows the statistics of the distribution of inhabitants in all the buildings and shows the total capacity of population that these buildings can accommodate: 54.469, which is well above the planned threshold of generating buildings for 40% of the population.

In *Figure 8*, it is possible to see the totality of the modelled buildings (as geometric quadrilaterals) where it can be observed that some of the plots selected for construction have generated entire small neighbourhoods.



Screenshot 1 : an ArcGIS working window



Screenshot 2 : Statistics of the "Inhabitants" column, from "New Buildings" layer

6.2.5 Moving origins into new locations

Once the preparation phase, i.e. the construction of buildings to accommodate part of the population with low accessibility scores, was completed, it was necessary to move the centroids.

Even though the research concept envisages the shifting of origins from the lowest positions in the accessibility ranking to new buildings, the practical process in which this concept was realised was not exactly that of a shift. The centroids in fact turn out to be the sum of the bystander inhabitants on an imaginary square lying on the base map, not null, of about 25-metre-long sides; this means that, given the decreasing density as one moves away, the centroids of the peripheral area will have an extremely low average value. Moving thousands of centroids with a unit value or slightly higher would generate a great symbological interference on the map, making it difficult to read. The solution was therefore to eliminate the centroids, starting from those with the lowest score, and then generate new ones by placing them directly in the areas of the new buildings and giving them the exact value (of inhabitants) of the intersected dwelling (as in each building the capacity of residents is given).

Contrary to what happened for the arrangement of centroids in the model of the real city of Coimbra, for its compact version it was decided to place the origins directly within the space occupied by the buildings modelled to house them. In this way, the number of total points (centroids) was reduced, generating less graphic interference. As shown in Screenshot 2, which summarises and schematises the distribution of the capacity of inhabitants in new modelled dwellings, it can be seen that in the new residences the average number of inhabitants per building is 85, with a minimum of 15 and a maximum of 315.

6.2.6 Re-shaping the city

Given the hypotheses and the limits imposed at the beginning of the research concerning the characteristics to be satisfied in order to obtain a compact city, it was not possible to proceed with the elimination of all the low scoring centroids until the total generated flow rate of 54.469 inhabitants was reached. In fact, when about the half was reached, the centroids were identified and eliminated manually, thus defining the new layout of the city. Of great help in this selection work were the natural limits of the city (Coimbra's characteristic is precisely that of being built on and between hills) and the state road network, which made it possible to delimit a further perimeter when the natural limits did not guarantee one. Another selection criterion, again keeping an eye on accessibility scores, was to eliminate points where the density of facilities was lowest.

Once enough points had been eliminated it was possible to fill, with new ones, the blanks generated by new facilities. We moved on to the generation of new points, again data points, inserted in the barycentre's of various buildings modelled previously.

6.2.7 Moving facilities

As a final step in the densification of the city, it was necessary to move the facilities that had remained outside the living perimeter of the city after the densification. In fact, the new shape excluded a substantial portion of facilities that had been established outside the city centre over time. At first glance the density of destinations outside the city centre has dropped considerably but the catchment area remains the same and requires the same number of facilities to meet the city's needs.

The work carried out on the facilities is the same as the work done for the origins: it was necessary, for each type of destination needing relocation (colleges, bakeries, pharmacies, etc.) to determine an average footprint and to give the same space they previously occupied in the new version of

Coimbra. For example, if a supermarket, located in a part of the city that is uninhabited in its compact version, occupies an area of 1 square kilometre, then in the compact city it will be necessary to provide an area of the same size to accommodate it.

The redistribution of the facilities has been made by trying to distribute each type of facility as evenly as possible on the map, favouring the positioning of more facilities in denser areas.

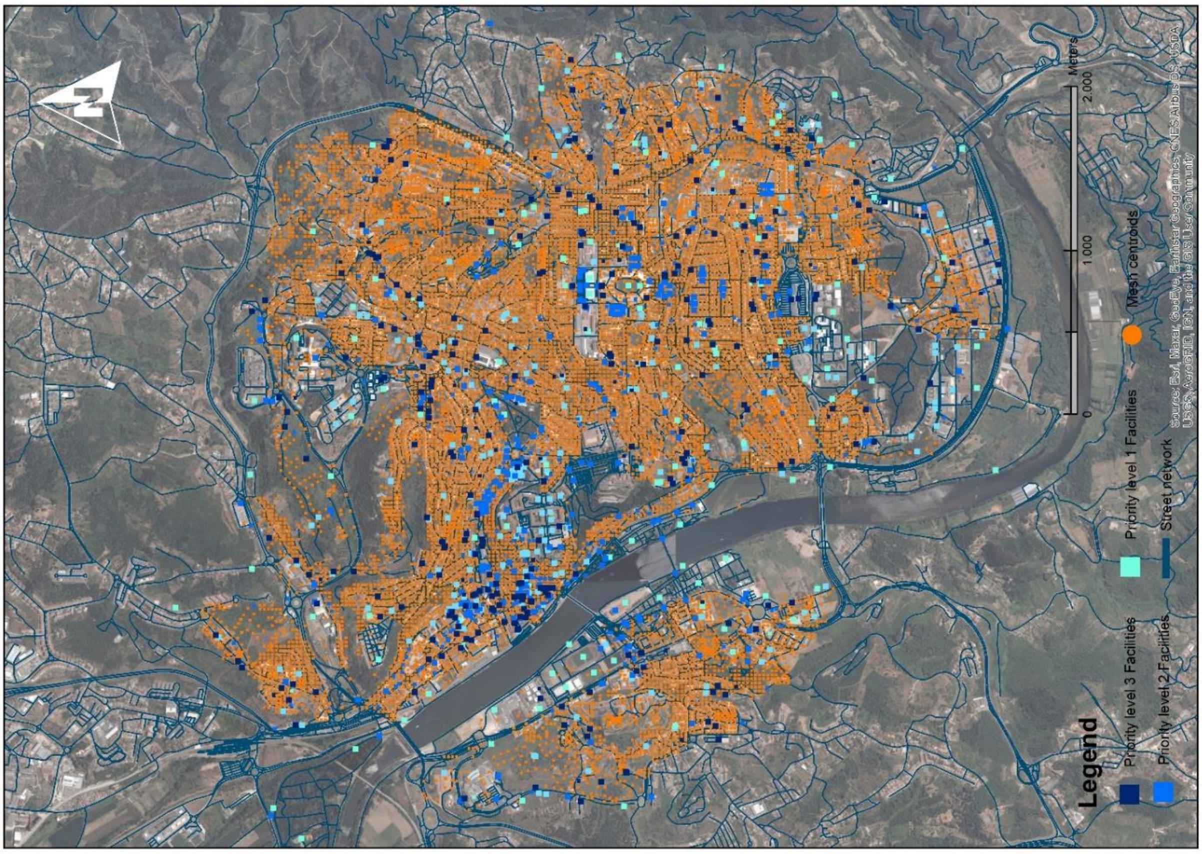
6.3 GIS EVALUATION OF ACCESSIBILITY

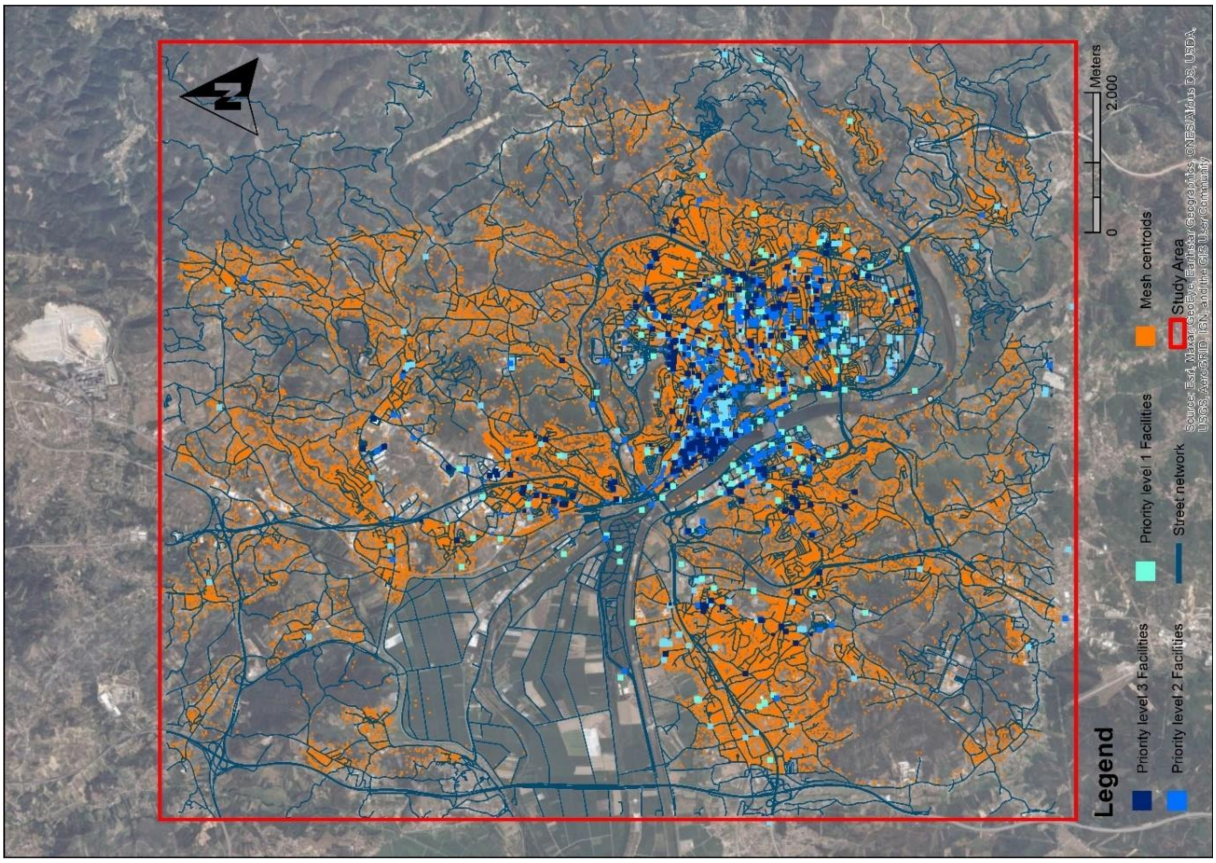
From the "feature" class of road network, datasets systems were created for the two city layouts, considering distance as an impedance.

Using the Closest Facility Routing tool in ArcGis, the distances to the nearest facilities were obtained, then added for each origin to the tables associated with the origin feature classes.

The snap tolerance for origins and destinations was set to 100 metres, checking for any location errors for points further away than the tolerance, and then taking a manual localization if necessary. The distance derived from the automatic snap is a direct line between the point and the network dataset, the latter is not added to the impedance.

The systematic error due to the snap distance deviation is small as origins and destinations usually have access points close to the road network.





Comparison 2: Contrast between Coimbra (down) and its redraft as a compact city in terms of facilities arrangement (Figure 3 and 4)

7 RESULTS

The results are presented as maps showing the colour-coded accessibility scores for each source and as summary statistics. We have established that the basic scenario was well summarised in the version of the accessibility calculation with a greater adherence to reality: the case where $Lk\ (j3)$ = {70,20,10}, the results for this scenario are shown in ***Figure 13*** and ***14*** and form together with the summary table of statistics ***Table 6*** to ***8*** the main results of this research.

At the end of the densification process, the total area of the city was reduced from 141,720,00 $\boldsymbol{m^2}$ to 16,732,000 $\boldsymbol{m^2}$, a reduction of about 88%. (The extension of the real city of Coimbra is attributed to the definition of the study area and refers to a rectangle including the 104,643 inhabitants related to the case study, the surface of the compact city instead is measured on a snapshot that uses a snap on the streets that include within them the entire population).

The following figures (*Comparison 3, 4* and *5; Figure 9* to *14*) show the complete comparative maps representing all result sets for the sensitivity analysis. The data are represented in the same colour scale (logarithmic) to facilitate direct comparison. The scale of the map, however, is different because of the sensible reduction of the size of the city: compact Coimbra is much smaller than the real one.

The set of maps shows how the urban sprawl of the city of Coimbra has a great impact on accessibility, in line with similar results found in the literature (Brueckner, 2000; Tannier et al., 2012).

Some of the observations we can make concern the city of Coimbra in its real version: accessibility scores with high results are present almost exclusively for origins in the most central areas of the city, where we find a higher density of destinations/facilities. We can also observe that the density of origins does not necessarily lead to an increase in the accessibility score, in fact some suburbs, despite having a very high population density, have much lower scores than the city centre. In the densified version of the Coimbra map, we find better and more homogeneous accessibility scores, with small variations due to a higher density of facilities that are not displaced, either because they were historically determined or because they did not require displacement.

The results for the other triads of Lk show similar results: for $Lk\ (j1)$ = {100,0,0} we can see a maximisation of the accessibility values for the compact city, exactly as it happened for real Coimbra, provided that in this case scores have extremely improved, but we are still in the most favourable condition (results-wise) where freedom of choice factor is inhibited.

Tables 6 and ***9*** summarise the main results obtained, which make clear the quantitative differences between the two city layouts: real and compact. Statistical measures are calculated on the set of values of A_i. The second column "Weighted", in ***Table 6***, collects data for a second type of evaluation, concerning the "average per inhabitant", defined as:

$$\frac{\sum_i h_i\, A_i}{h_i}$$

Equation 11

With:

- h_i population on the origin and the average value of accessibility per person.

7.1 COMPACT COIMBRA HAS HIGHER ACCESSIBILITY SCORES

Tables 6 and *9* reveal some important insights: the first and most obvious being that Coimbra in its compact version provides a better accessibility result, specifically, as mentioned in the abstract, we are faced with a reduction in the average travel distance between origins and destinations of 70% (594 metres against 1936). This result is not extremely surprising, given the order of magnitude of the compaction; however, it takes on a whole new value in that it could not be defined without explicitly performing the calculations made possible by the methodology applied.

The significant reduction in travel distance involves a chain of other considerations not only related to accessibility. The reduced commute distance can also be translated into less energy spent on travel, which reflects the result in lower GHG emissions (derived from the consumption of fossil fuels for active transport). The prospect of GHG reduction is not linearly related to the reduction of travel distances, but the immense advantage of this solution derives precisely from its non-linear correlation: as commute distances decrease, active mode trips become more likely, reminding us that this type of movement is emission-free, more energy-efficient and sustainable.

Active travel modes can also lead to a higher level of travel satisfaction, as they are arguably more pleasant (Mouratidis et al., 2019).

Compacting the city could mean transforming today's energy black holes into highly energy-efficient and highly pleasant places to live, as they are more suitable for active travel.

7.2 WALKABILITY IN THE COMPACT CITY

The average distance from origin (inhabitants) to destinations (facilities) ranges from 594 m to 687 m, depending on the choice of Lk and thus the definition used for accessibility. These values are slightly higher than the traditional guidelines of a quarter of a mile (402 m) as a walkable distance, however all average accessibility values, regardless of the choice of definition, fall within the range of distances proposed by recent research that moves the guidelines forward by about 100%, defining a new threshold value for acceptable walking distances. These new suggested sets report, respectively, a walkable distance of 805, 705 and 820 m Buehler et al. (2020), Hsu and Tsai (2014) Yang and DIex-Roux (2012), however these threshold values are defined not as limits, they imply different innuendos: the value of 805 m above refers to the average distance walked in a day while the values of 705 and 820 metres refer to the 50% percentile. This clarification means that not all pedestrians would be willing to walk such long distances.

A limitation related to the reading of results, which has not yet been taken into consideration, concerns the fact that the accessibility values summarised in the tables refer to a one-way stretch for the inhabitants: the fact that the majority of the trips belong to the category of round trips is not taken into consideration. This means that even a trip of 500 metres, largely within any walkability indicator, if understood as a roundtrip takes on a completely different connotation, going beyond the kilometre of travel distance.

In spite of these considerations, we can nevertheless affirm that Coimbra in its compact version turns out to be a largely walkable city, especially if we look at the average data. The most interesting feature on the other hand is perhaps related to the rediscovered cyclability of the city: as stated by Buehler et al. (2020), the average distance covered by bicycle (in the United States) is 3790 metres, while Larsen et al. (2010) report an average distance of 3890 metres for commuting trips, and those values are similar for Europe. Crossing these data with the renewed accessibility results we can see that, even for the worst-located inhabitants (worst Lk combination, accessibility score = 1786 m), the distance is extremely reachable within the limits of cycling, although they may be distances not suitable for walking.

With total trip distances (round trip) within the 5 km range, i.e. between the most distant points of the "social distance", the use of the bicycle becomes competitive with that of the private car (Dekoster and Schollaert, 1999), and thus making the bicycle a reliable option for the majority of trips within the social city (compact Coimbra) and a strong candidate for commuting trips.

7.2.1 Comparison about the actual situation in the real city of Coimbra

The situation in the real city of Coimbra turns out to be quite different: with an average distance per inhabitant to facilities of between 1352 and 1498 metres, the concept of the walkable city disappears completely. These distances (not conceived as commuting) are manageable for a very small proportion of the population: this single condition is sufficient for most of the population to select other means of transport.

Looking at the general results of accessibility, we observe that the average values oscillate around 1900 metres, with maximum distances of 8200 metres. While it is understandable that the bicycle can still be a valid means of transport for the average citizen, it is as much comprehensible that the most disadvantaged inhabitants are clearly outside a reasonable range of cycling. In addition to that, the inhabitants who reach these very high accessibility values generally live in low density areas, where there is not sufficient connection to the city's public transport network, forcing them to use the private car. Similarly, as mentioned before, we find high density city suburbs that have grown to a level where services and businesses are now appearing; however, it is shown in the research that this compensation is not sufficient to provide all the necessary services and the use of the private car is still heavily relied upon. These implications, which lead most of the population living in the outskirts of the city to use private vehicles for their movements, show how the use of the car is almost unavoidable for many inhabitants of Coimbra. This lack of choice affects the increase in GHG emissions, which jeopardises the sustainability of the city in the long term, as well as generates traffic jams at peak times, noise pollution and the need for parking space.

7.3 ACCESSIBILITY EQUITY

Based on result readable through tables and maps, the city of Coimbra in its compact version generates more accessibility equity than the real city. This social aspect, or rather, this social impact, can be quantified by observing the dispersion of the results: the difference between the minimum and maximum values, the standard deviation, the coefficient of variation, all these values report much lower results in the densified city than in the real city. As can be deduced from it for the actual city of Coimbra, there is a clear and distinct difference between those who live close to most of the facilities and those who simply live far away from everything. In its compact counterpart, this difference is less sharpened: the accessibility values between those who live in the centre and those who are at the greatest possible distance from everything differ minimally, by what is only a few hundred metres.

Regardless of the social levers which led to inequity in the current city, we can state that its compact version presents itself as a possible instrument to fight this status-quo and ensure a more equitable and fair development.

7.4 IMPACT ON SUSTAINABILITY

As argued by Bribri and Krogstie (2017), sustainable cities struggle to achieve specific outcomes. Some of these outcomes include elements that, in view of the global goals of the 2030 deadline but more generally for a better quality of life in cities, we would like to incorporate in every city. Those elements are, namely: reduction of the need for transport, with a consequent reduction of pollution, increase in energy efficiency, encouragement to move around the city by walking and cycling then spatial proximity, design scalability and finally equity and liveability.

As the results show, many of these aspects are achieved, or rather improved, in the compact city compared to the real city, with emphasis on equity-related measures, transport scores and its dependent variables, such as the environmental aspects. We can therefore say that the compact city of Coimbra is, arguably, a more liveable city than its real counterpart.

Moreover it was possible to quantify precisely what the difference is for most of these measurements, meaning that under the aspect of sustainability compact Coimbra is, perhaps, better than the real city.

We can not state, only through the evaluations made in this research, that it is but there are also other aspects that influence these kinds of city characteristics and further research is needed to understand how the compact city would behave in terms of sustainability compared to its real counterpart when subjected to different indices.

7.4.1 Transport-related aspects

The results indicate that, under the aspects considered, the city is more sustainable than its real counterpart but, scientifically, this reading is still flawed, or rather incomplete, as it is seen from the perspective of accessibility alone. This interpretation, however, gives us an important fact: since the characteristics of a city in relation to transport are extremely relevant and important, and those are the main subject where changes happened, a difference in that area (transportation) especially of this magnitude, can produce appreciable results. Every action aimed at reducing the energy consumption and emissions of the city has an immense impact on its sustainability.

The fact that this research yields a quantitative measure makes it possible to estimate the impact of these changes and, above all, can serve as a benchmark for other possible city layouts or for comparisons between real cities.

Keeping the focus on transport, the compact city also retains some advantages for long commutes, i.e. people who have to travel to work to the city despite living outside its limits. While this research does not deal with the relationship between the short distances of the compact city and the working commute, it must be said that in the densified city there is a high probability that the work destination (if within the city limits) is within easy walking or cycling distance of the main city terminals, be they train or bus stations. In this way, even commuting takes on a different aspect of attractiveness, without considering the relative differences (savings) in CO2 emissions compared to using personal transport.

7.4.2 Modal share analysis

Before talking about the multitude of conclusions that can be deduced from the analysis of the modal share results, it is worth saying that it would be extremely interesting and productive to translate the values obtained, the differences between Coimbra and its compact counterpart, into energy savings for the city. The quantitative analysis of this aspect is in fact already included in the research chain programme and will focus on the relationship between fuel consumption, GHG emissions and energy consumption. Modal share will be correlated and quantified, thus allowing another quantitative comparison with Coimbra's densified counterpart.

Table 8 is an easy-to-read chart, preaching active modal share alone, the "coefficient of variation", which indicates the statistical variability between two results, drops incredibly steeply; the divergence in this indicator fluctuates around 32.41-34% (between Coimbra and compact Coimbra) reaching values between 10 and 11% for the densified city. These values express the distribution of possibilities: in accessibility we had talked about equity, a discourse that if adjusted, can fit to this issue as well.

The game-changing differences, however, can be seen by looking at averages: for walking alone, the figures have roughly doubled (again at the discretion of the selected triad) from 14.05% to 33% (referring to accessibility/modal share 1 to 1, 100/0/0). It means that, on average, one person out or three (roughly 34,000 people in the whole city) can easily walk around the city to reach the vast majority of destinations; a result that, as of now, only 19,000 inhabitants can claim.

We can however say with certainty, that between the two elements in play, i.e. walking modal share and composite walking + cycling mode split, the great difference is made by the use of the bicycle. In fact, the average probability that an inhabitant of densified Coimbra chooses to cycle to reach one of the destinations jumps from 33% (walking only) to an incredible 87% (walking + cycling). This single comparison allows us to say that, **if the city can be considered walkable to a large extent, but not for the totality of the population, it is totally and completely bikeable** (data referring to the Modal 1 to 1 section).

7.5 POSSIBLE IMPACT IN FUTURE CITY PLANNING

It was possible to assess how, and crucially how much, aspects of the city such as accessibility and equity can be improved by densifying the city. These quantitative results can allow decision makers to make important inferences in the planning and design of urban areas, especially considering recent concerns regarding sustainability.

Despite this, it is not likely that real cities, in this case Coimbra, would be completely transformed, being rebuilt from scratch in a more efficient manner. The costs, resources, inconveniences, and human implications associated with this choice would be prohibitive, incalculable, and unimaginable. The purpose of this research is not to suggest radical transformations such as those carried out on the model, but to give policymakers a useful and alternative tool, as there are many practical aspects that can be gathered from this research.

7.5.1 Cities expansion programmes

Cities are constantly changing, while some are shrinking, most are tending to grow in both population numbers and economic activities (Greca and Martinico, 2016; Martin-Fernandez et al., 2012). The development of new areas of the city and rehabilitation of old ones is bound to increase and continue, as long as the social movement from the countryside to the city and within the city persists.

The results that this research brings to light show that it is possible to expand the city, in a completely new way, without a physical correlation between expansion and growth, with a marked tendency towards efficiency, sustainability and an active mode of movement within the city. It has not been mentioned so far, but by encouraging the development and use of an active mode of transport within the city, the lifestyle of the population shifts towards a healthier one.

The help that can be given to decision makers is to analyse past layouts of city expansion and compare them with new proposals and, at the same time, to make accurate predictions about the future of the cities.

Moreover, because of the way the development model of this research is done and therefore as for the way it is structured theoretically and practically, this densification does not require immense human, economic or social efforts. In fact, it does not present any huge upheaval in the urban layout and is proposed as an extremely feasible alternative, not only in spatial terms, since it has been done based on the real buildable areas of the city, but also on the administrative side, since the current legislation has been followed and respected. Clearly this is not a project that actually requires physically moving the population from the periphery to the centre, but, seen in terms of the expansion of the city, it is an absolutely logical and viable solution.

As acknowledged by Tgn and Tan (2012), the New Urban Era is a unique opportunity to remake and reinvent the city: the challenges faced decades ago are strikingly different from those we face today, but the priorities are still the same: economic growth, good quality of life, maintaining a clean environment while doing the best (and doing what is possible) with the available resources.

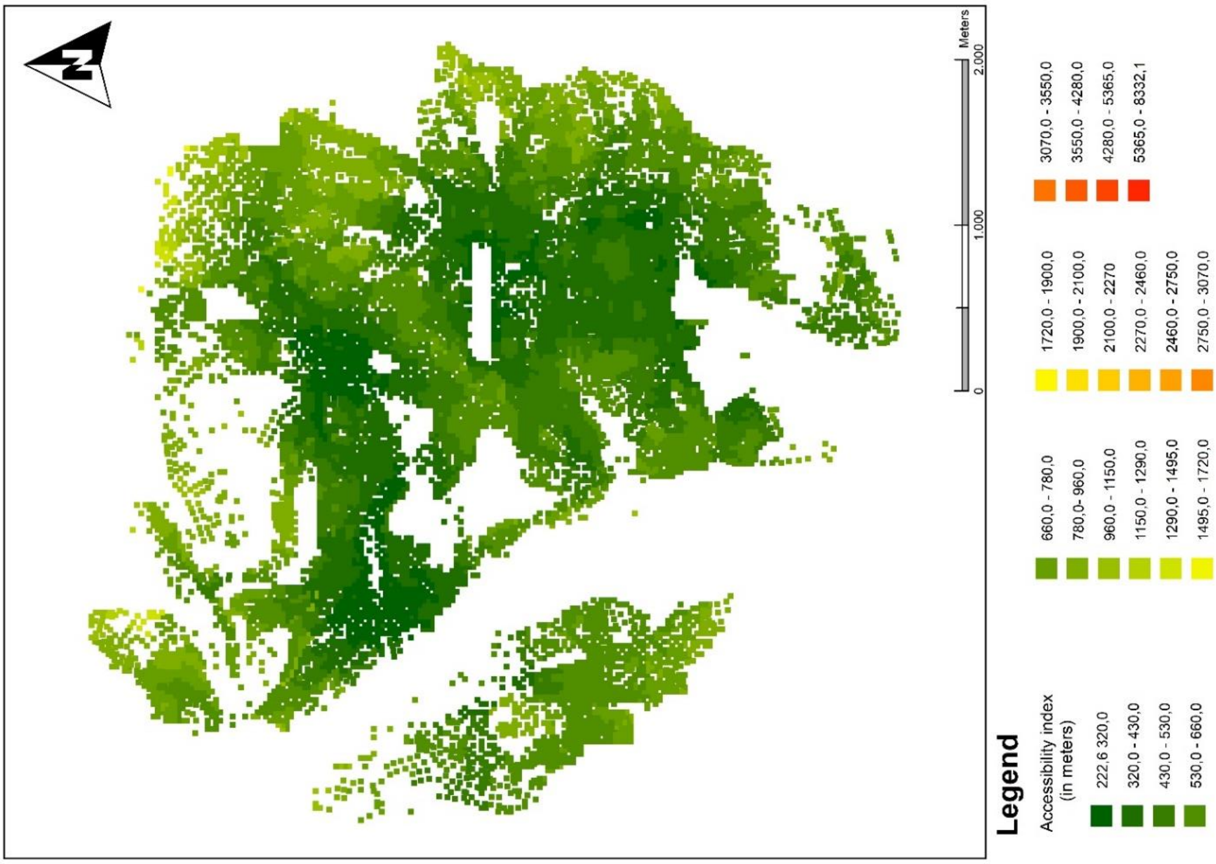
The growth and development of a city is unlikely to follow predefined theoretical patterns and expand exactly at our will, but this research provides quantitative elements, laid out so that everyone can understand, judge, predict, and then make decisions, regardless of what the future may bring.

7.6 UNCOUNTABLE ASPECTS OF COMPACTING A CITY AND FINAL THOUGHTS

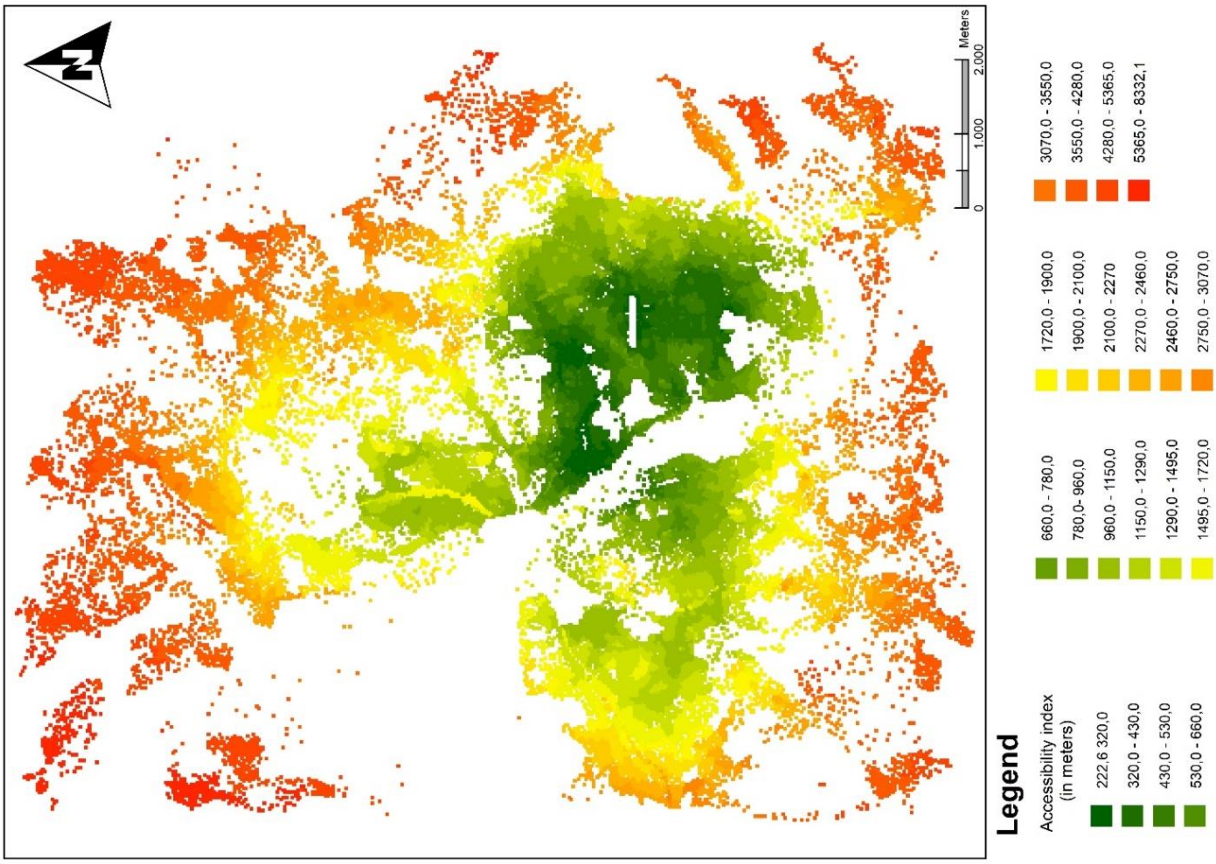
Ultimately, it is important to remember that the benefits of densifying the city are mainly connected to transport and movement within it, as well as all related aspects. As mentioned just above, urban development is influenced by many factors and especially, the possibility of densifying the city depends enormously on social issues: the equity discourse is only one indicative factor, but the forces that lead to the development of inequalities are multiple and extremely complex. Social factors are then inextricably linked to economic factors, on which they are interdependent, and, also to cultural issues. It is not possible to simply, and trivially, demonstrate how an urban layout can bring benefits, or to plan and construct new buildings to get people to relocate: multiple stimuli from multiple sources are needed to achieve this.

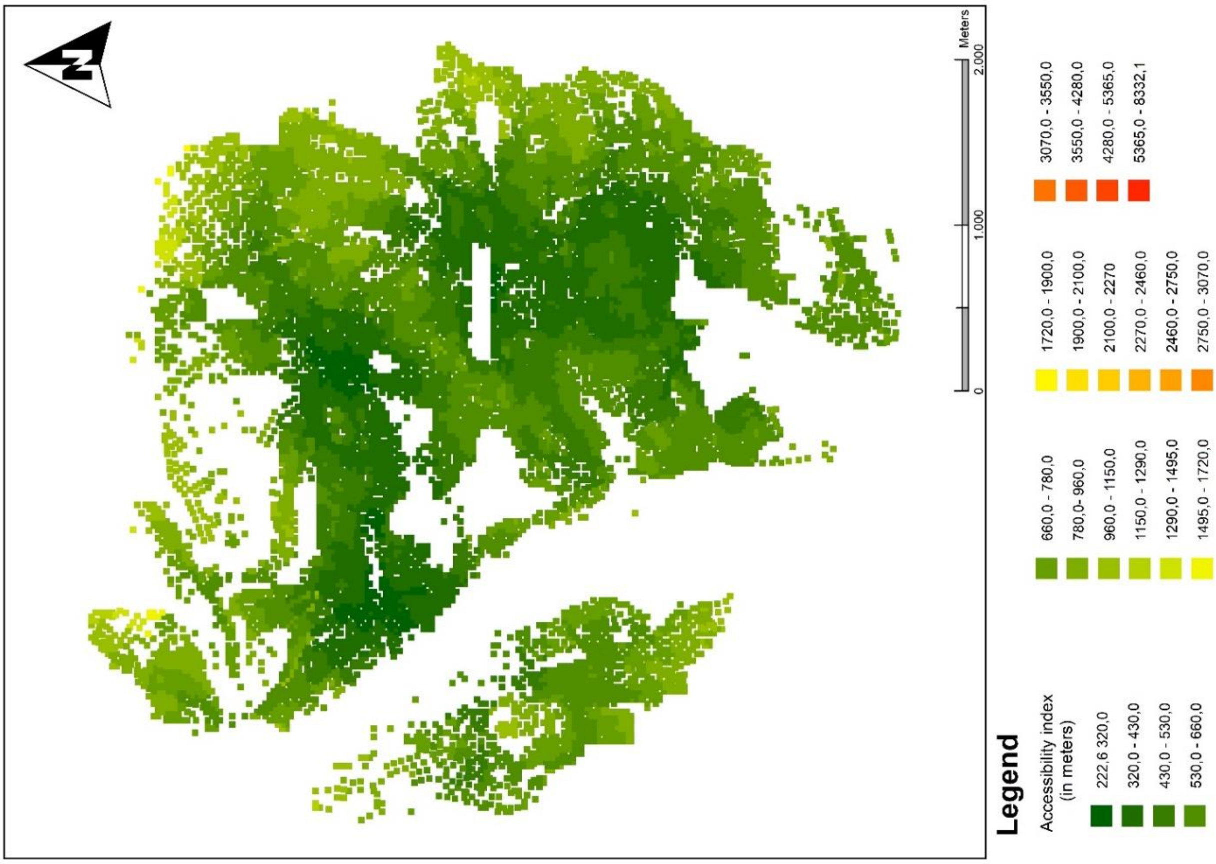
In the same way we can talk how sustainability, accessibility, distances, and therefore transport (to make an extreme simplification) are not the only aspect to be taken into consideration, it is true that compacting the city would make it easier to walk and cycle, but it is not certain that these positive results are reflected in the whole range of what is possible, for example in the economic or social spheres.

Densifying the urban fabric is therefore a step forward for the city in terms of its accessibility, with all the consequences that this entails, especially about emissions and energy efficiency, but it is not necessarily the best option, nor, above all, the only one.

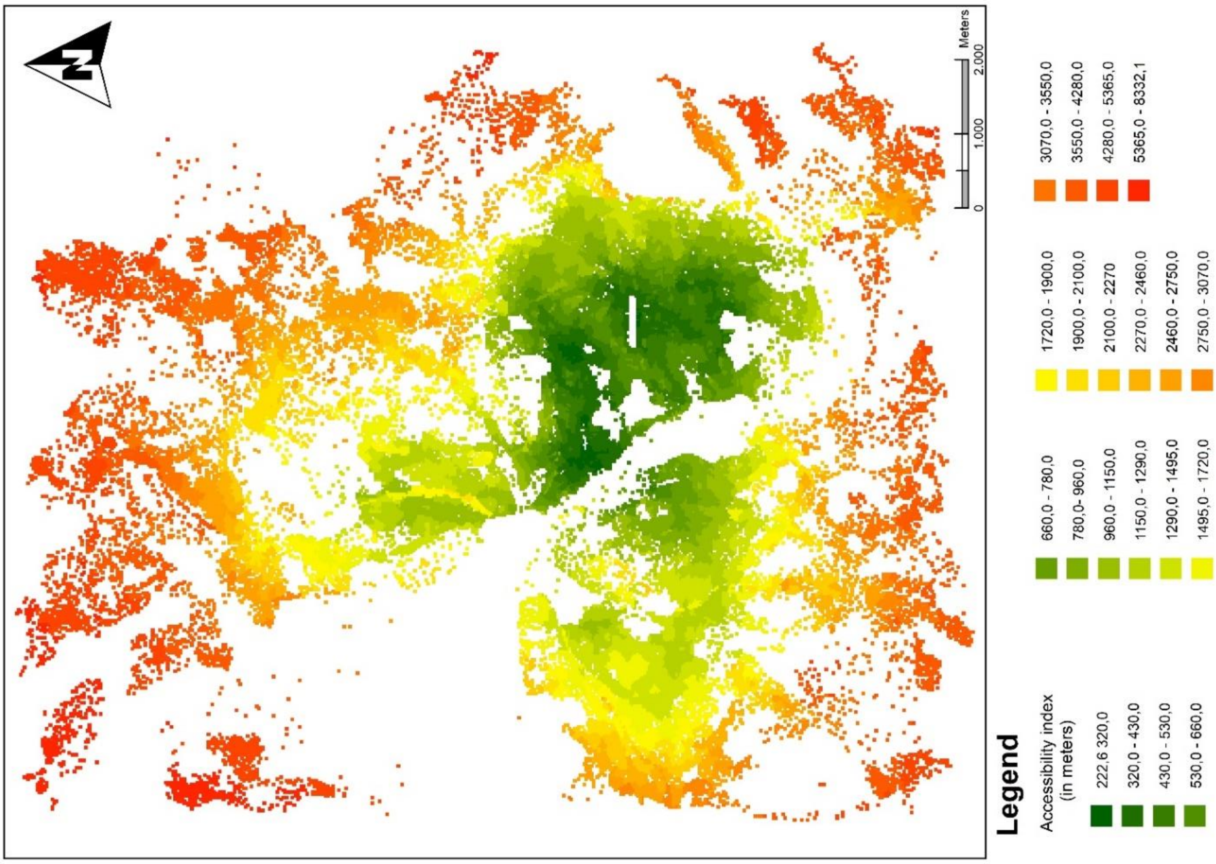


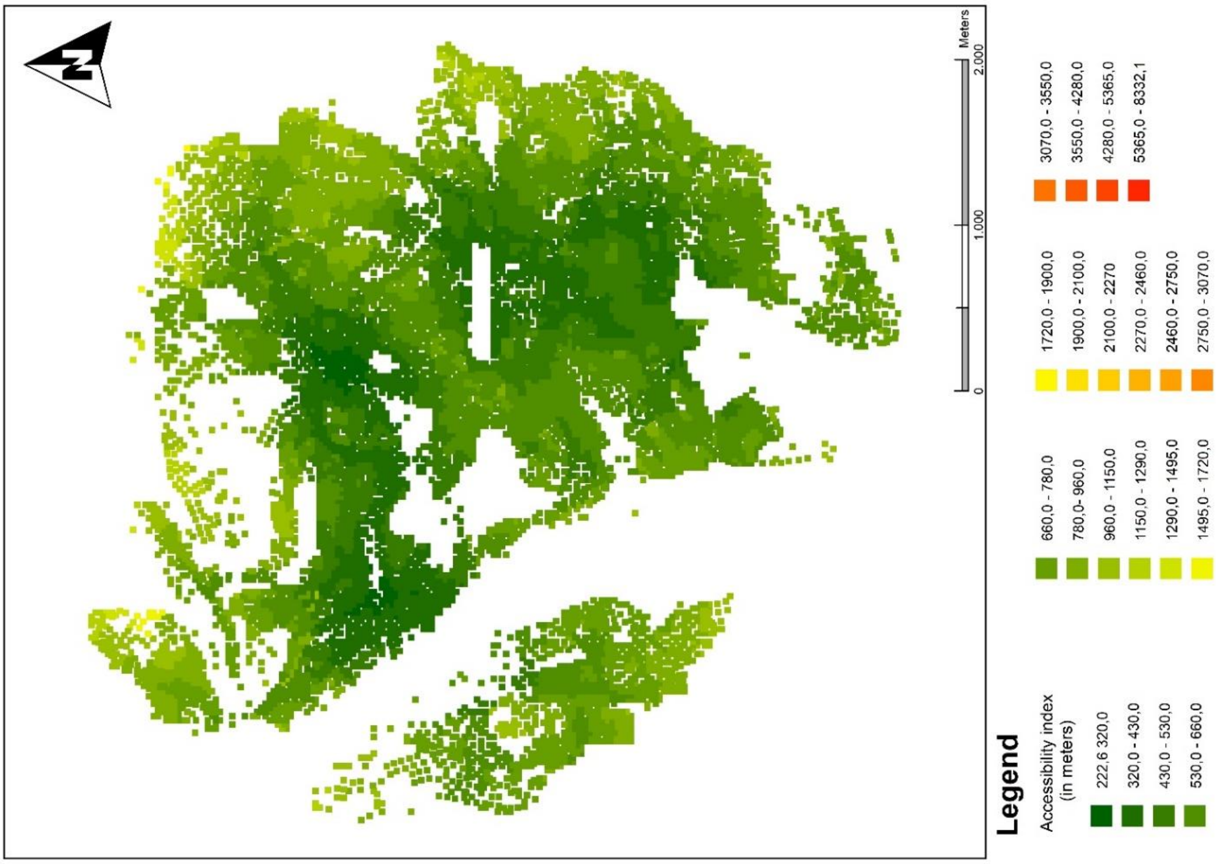
Comparison 3 : Accessibility to urban facilities for Lk ($j1$) = {100,0,0}, Figure 9 and 10



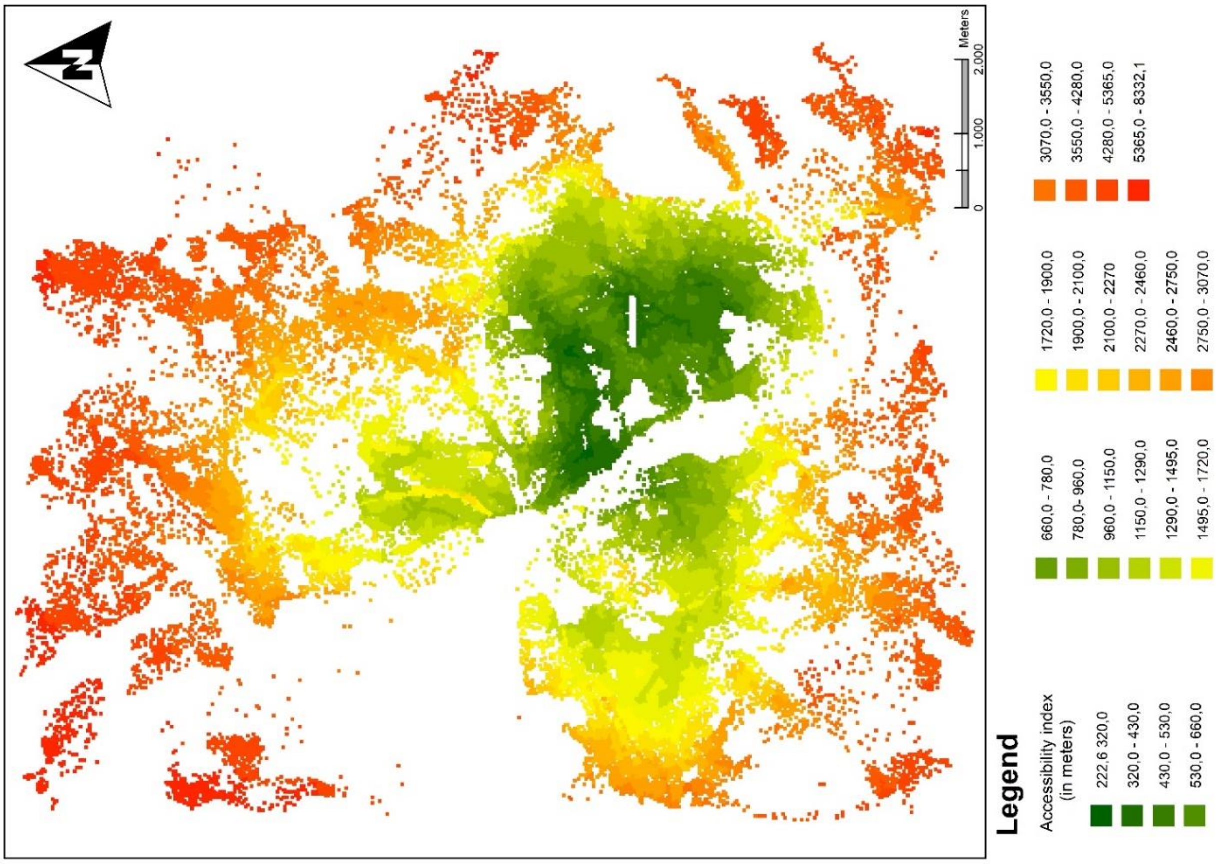


Comparison 4: Accessibility to urban facilities for Lk (j1) = {50,35,15}, Figure 11 and 12





Comparison 5: Accessibility to urban facilities for Lk (j1) = {70,20,10}, Figure 13 and 14



	Average Accessibility p/ Inhabitant		Coimbra (m)		Compacted Coimbra (m)	
			Equal	Weighted	Equal	Weighted
1 to 1	100/00/00	min	238	223	238	223
		MAX	7878	7908	1744	1685
		Weighted Mean	1381	1352	617	594
		Mean	1859	1833	566	546
		Standard Deviation	1322	1321	187	180
		Coefficient of Variation	0,71	0,72	0,33	0,33
1 to 3	70/20/10	min	281	268	n.r.	252
		MAX	8146	8099	n.r.	1746
		Weighted Mean	1492	1440	n.r.	651
		Mean	1991	1936	n.r.	594
		Standard Deviation	1365	1352	n.r.	187
		Coefficient of Variation	0,69	0,7	n.r.	0,32
	50/35/15	min	310	295	n.r.	271
		MAX	8332	8230	n.r.	1786
		Weighted Mean	1565	1498	n.r.	687
		Mean	2077	2003	n.r.	624
		Standard Deviation	1395	1374	n.r.	193
		Coefficient of Variation	0,67	0,69	n.r.	0,31

Table 6 : Accessibility summarised statistics

	1_1				1_3			
	Accesibility							
	A_NW_H	A_NW_NH	A_W_H	A_W_NH	A70_W_H	A70_W_NH	A50_W_H	A50_W_NH
Minimum	242,28	237,64	224,53	222,57	254,51	252,47	272,91	270,81
Maximum	205758,4	1744,42	205314,14	1684,57	214387,31	1746,25	220243,35	1785,76
Mean	4810,78	565,87	4632,69	546,39	5072,23	594,08	5351,73	624,34
tandard deviatio	13987,33	187,11	13482,64	180,29	14792,67	187,65	15622,84	193,21
Sum	63362867	7453122	61017289	7196633,96	66806356,93	7824740,82	70487645,58	8223276,34
Weighted mean	617,8609	72,67652	594,98878	70,17546181	651,4388499	76,30022642	687,33565	80,18640631
Coefficient of variation	n.r.	0,330659	n.r.	0,329965775	n.r.	0,31586655	n.r.	0,309462793

Table 7 : Accessibility summarised outputs from ArcGIS (compact Coimbra)

Table 7 is the direct summary deducted first from ArcGIS after an initial treatment of data, and it contains all the information needed for compiling the "Equal" column for Accessibility 1 to 1 and the full "Weighted" column.

	Modal share (%)		Coimbra (%)		Compacted Coimbra (%)	
			only walking	walking+ cycling	only walking	walking+ cycling
1 to 1	100/00/00	min	65,89%	97,09%	65,89%	97%
		MAX	0,21%	5,74%	3,89%	50%
		Average active share p/ inhal	19,30%	95,90%	31%	84,45%
		Average	14,05%	57,13%	33%	87%
		Standard Deviation	13,72%	24,80%	11%	5,90%
		Coefficient of Variation	97,65%	43,41%	4,20%	11,00%
1 to 3	70/20/10	min	62,23%	95,70%	62,23%	96%
		MAX	0,20%	5,54%	4%	49%
		Average active share p/ inhal	17,64%	64,15%	27,90%	83%
		Average	12,83%	55,42%	31%	86%
		Standard Deviation	12,70%	24,54%	10,60%	6,10%
		Coefficient of Variation	98,99%	44,28%	3,90%	10,90%
	50/35/15	min	59,96%	95,65%	60,00%	96%
		MAX	1,95%	5,45%	4%	48%
		Average active share p/ inhal	16,56%	63,47%	26,23%	82,62%
		Average	12,04%	54,69%	29%	85%
		Standard Deviation	12,06%	24,46%	10,20%	6,30%
		Coefficient of Variation	100,17	44,72%	3,70%	10,80%

Table 8 : Summarised statistics for Modal Share

	1_1				1_3							
	Modal Share											
	HV100	HV100_H	HV100W	HV100W_H	HV70	HV70_H	HV70W	HV70W_H	HV50	HV50_H	HV50W	HV50W_H
Minimum	0,503	0,503	0,0389	0,0389	0,49	0,49	0,036	0,036	0,48	0,48	0,035	0,035
Maximum	0,97	263,83	0,66	72,24	0,96	260,48	0,63	67,33	0,96	258,31	0,6	64,12
Mean	0,87	6,65	0,33	2,38	0,86	6,52	0,31	2,17	0,85	6,43	0,29	2,04
Standard deviation	0,059	15,85	0,111	5,391	0,061	15,471	0,106	4,885	0,063	15,227	0,102	4,56
Sum	11461,64	87635,93	4350,83	31320,4	11268,33	85858,57	4016,12	28641,66	11145,74	84728,09	3798,93	26899,36
Weighted mean	0,111764178	0,854551155	0,0424256	0,305409938	0,109879183	0,8372198	0,0391618	0,27928914	0,10868379	0,826196	0,037044	0,2623
Coefficient of variation	0,111764178	0,854551155	0,0424256	0,305409938	0,109879183	0,8372198	0,0391618	0,27928914	0,10868379	0,826196	0,037044	0,2623

Table 9 : Modal share summarised outputs from ArcGIS (compact Coimbra)

Table 9 is the direct summary deducted first from ArcGIS after an initial treatment of data, and it contains all the information needed for compiling the “only walking” and “walking +cycling” columns for “Compacted Coimbra”

8 SUMMARY AND FUTURE WORKS

In this research paper a quantitative comparison was made on the accessibility of the real city of Coimbra (Portugal) and its redraft as its compacted self. The method used involved generating a digital model of the city of Coimbra with its constituent elements and geographically repositioning them in a copy of the model modified to represent the version of the same city but densified as much as possible, all of which was done in a GIS environment. After defining a location-based accessibility index, the two city layouts were compared.

The results showed that the accessibility in the compact city, measured as the average distance per capita from residential buildings to a set of urban facilities, is much higher when compared to the actual city, with average distances dropping from 1500 metres down to 500 metres, i.e. a walkable distance.

The implications of these findings go beyond the decrease of travelling and commuting times or the reduction of energy spent on transport, made affordable by a densified city that is shown to be fully cyclable and largely walkable. These changes would lead to a healthier, more sustainable and efficient lifestyle, as well as being environmentally friendly.

The result of this research sets a qualitative benchmark on what can be expected from implementing new alternatives to city development, instead of relying on their natural evolution.

This study shows how it is possible to compare real cities with other possible layouts or even with different cities, thanks to the GIS environment and to the production of quantitative and comparable data. This analysis also helps to better understand how to plan future city layouts and expansions.

Receiving insights from an accessibility analysis can provide urban planners with information on the best ways to create or renovate city neighbourhoods, as well as open the way for many sustainability-related analyses.

As mentioned, accessibility measurement is not the only way or criterion of analysis to compare different cities or different urban layouts, other criteria need to be implemented, such as energy efficiency, but these elements need to be defined in a way that can be measured in a GIS environment, which is a fundamental and founding prerequisite of the methodology proposed in this research.

A city of the future, ideally, should be smart, sustainable, pleasant, and efficient, the comparative and quantitative analyses of the city are made in the hope that they will open possibilities that can achieve these goals in the long term.

8.1 CRITIQUE

Transport-oriented benchmarks such as accessibility tend to favour compactness, the use and implementation of other measures and indices are indispensable if a broader and more holistic view is to be taken.

For example, just as people do not like to have their work too close to home, they also tend not to favour excessive concentration. A benchmark that relates urban planning to the degree of satisfaction of citizens could be of great use if implemented in the continum of this research, that could take into account the appreciation shown by citizens with the city they are in.

8.2 FUTURE DEVELOPMENT

One of the possible future developments could be to quantify the potential impact of this change in energy efficiency and greenhouse gas emissions, given the double effect of reduced distances: less distance per se, but also more active transport.

How the real city, whose urban sprawl requires most inhabitants to use cars, could be organised to be walkable or bikeable is a non-trivial result and the calculation could be well supported by the GIS environment, suitable to support and perform calculations with large data sets.

Future developments to create a comprehensive methodology for benchmarking city models will involve the search for quantitative indicators that go beyond accessibility and that can then be tested using the two city models proposed in this research as prototypes.

9 BIBLIOGRAPHY

Adolphe, L. (2001). A simplified model of urban morphology: application to an analysis of the environmental performance of cities. *Environment and planning B: planning and design*, *28*(2), 183-200

Alonso, A., Monzón, A. & Cascajo, R. (2018). Measuring negative synergies of urban sprawl and economic crisis over public transport efficiency: The case of Spain, *International Regional Science Review*, 41(5) 540-576.

Apparicio, P., Abdelmajid, M., Riva, M. & Shearmur, R. (2008). Comparing alternative approaches to measuring the geographical accessibility of urban health services: Distance types and aggregation-error issues. *International Journal of Health Geographics*, article nr. 7.

Banister, D. (1995). *Transport and urban development*, Taylor & Francis: Routledge, London,1-294.

Barthelemy, M. (2019). Modelling cities, *Comptes Rendus Physique*, 20(4), 1-15.

Bertolini, L., Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: A conceptual frameworkto integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward, *Transport Policy*, 12, 207-220.

Bibri, S.E., Krogstie, J. (2017) Smart sustainable cities of the future: An extensive interdisciplinary literature review. *Sustainable Cities and Society*, 31, 183-212.

Boisjoly, G., & El-Geneidy, M. (2017). The Insider: A planners' perspective on accessibility, *Journal of Transportation Geography*, 64, 33-43.

Brimberg, J., Maier, A. & Schöbel, A. (2019). When closest is not always the best: The distributed p-median problem, *Journal of the Operational Research Society*, 1-17

Bruinsma, F. & Rietveld, P. (1998). The accessibility of European cities: theoretical frameworkand comparison of approaches, *Environment and Planning A*, 30, 499-521.

Buehler, R., Pucher, J. & Bauman, A. (2020). Physical activity from walking and cycling for daily travel in the United States, 2001–2017: Demographic, socioeconomic, and geographic variation, *Journal of Transport & Health*, 16, 100811.

Brueckner, J. (2000). Urban sprawl: diagnosis and remedies, *International Regional Science,Review*, 23(2), 160-171

Cataldi, G., Maffei, G.L., & Vaccaro P. (2002). Saverio Muratori and the Italian school of planning typology. *Urban Morphology*, 6(1), 3-14.

Cervero, R., Murphy, S., Ferrell, C., Goguts, N., Tsai, Y. H., Arrington, G. B., ... & Witenstein, N. (2004). TCRP Report 102: Transit Oriented Development in America: Experiences, Challenges, and Prospects. *Transportation Research Board of the National Academies, Washington, DC*.

Conzen, M.R.G. (1969). Alnwick, Northumberland: a study in town- plan analysis, *Transactions and Papers (Institute of British Geographers)*, 27(2).

Correa, J. (2006). Counterpoint: Transect transgressions, *Places* 18(1), 24-25,

Deboosere, R., El-Geneidy, A. M., & Levinson, D. (2018). Accessibility-oriented development. *Journal of Transport Geography*, 70, 11–20.

Dekoster, J. & Schollaert, U. (1999). *Cycling*: *the way ahead for towns and cities*, Office for Official Publications of the European Communities, Luxembourg.

Fishman, R. (1982). *Urban utopias in the twentieth century: Ebenezer Howard, Frank Lloyd Wright, Le Corbusier*, The MIT Press, Massachusetts.

Frey, H. (1999). *Designing the city: Towards a more sustainable urban form*. Taylor & Francis: Routledge, London and New York.

Geurs, K. & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions, *Journal of Transport Geography*, 12, 127-140.

Greca, P. & Martinico, F. (2016). Energy and spatial planning: A smart integrated approach, in: *Smart Energy in the Smart City: Urban Planning for a Sustainable Future*, edited by Papa, R. & Fistola, R., Springer, Switzerland, pp. 43-59.

Gutiérrez, J. & Urbano P. (1996). Accessibility in the European Union: the impact of the trans-European road network, *Journal of Transport Geography*, 4(1), 15-25.

Hall, P. (2014). *Cities of tomorrow: An intellectual history of urban planning and sdesign sincen1880* (4th edition), Wiley: Blackwell.

Handy, S. (2002). *Accessibility vs. mobility: Enhancing strategies for addressing automobile dependence in the U.S.* Report for the 2002 European Conference of Ministers of Transport.

Handy, S. (2020). Is accessibility an idea whose time has finally come? *Transportation Research Part D*, 83, 102319.

Hernández, F., Kellett, P. & Allen, L. (Eds.) (2010). *Rethinking the informal city: Critical perspectives from Latin America*, Berghahn Books.

Horner, M. (2013). Exploring metropolitan accessibility and urban structure, *Journal of Transport Geography*, 264-284.

Hsu, C. I. & Tsai, Y. C. (2014). An energy expenditure approach for estimating walking distance, *Environment and Planning B: Planning and Design*, 41, 289-306.

Kompil, M., Jacobs-Crisioni, C., Dijkstra, L. & Lavalle, C. (2019). Mapping accessibility to generic services in Europe: A market-potential based approach, *Sustainable Cities and Society*, 47, 101372.

Kristjánsdóttir, S. (2019). Roots of urban morphology, *International Journal of Architecture and Planning*, 7, 15-36.

Lee, K., Park, J.S., Goh, S. & Choi, M. (2019). Accessibility Measurement in Transportation Networks and Application to the Seoul Bus System. *Geographic Analysis*, 51, 339-353.

Li, Y. (2020). Towards concentration and decentralization: The evolution of urban spatial structure of Chinese cities, 2001–2016. *Computers, Environment and Urban Systems*, 80, 101425.

Lin, J.-J., & Yang, A.-T. (2006). Does the Compact-city paradigm foster sustainability? An empirical study in Taiwan, *Environment and Planning B: Planning and Design*, 33(3), 365–380.

Lynch, K. (1960). *The Image of the City.* MIT Press, Massachusetts.

Lyu, G., Bertolini, L. & Pfeffer, K. (2016). Developing a TOD typology for Beijing metro station areas, *Journal of Transport Geography*, 55, 40-50.

Martinez-Fernandez, C., Audirac, I., Fol, S. & Cunningham-Sabot, E. (2012). Shrinking cities: Urban challenges of globalization, *International Journal of Urban and Regional Research*, 36, 213-225.

Mouratidis, K., Ettema, D. & Næss, P. (2019). Urban form, travel behavior, and travel satisfaction. *Transportation Research Part A*: *Policy and Practice*, 129, 306-320.

Neuman, M. (2005). The Compact city fallacy, *Journal of Planning Education and Research*,25(1), 11–26.

Organisation for Economic Co-operation and Development. (2012). *Compact city policies*: *A comparative assessment*. OECD.

Papa, E. & Bertolini, L. (2015). Accessibility and transit-oriented development in european metropolitan areas, *Journal of Transport Geography*, 47, 70-83.

Phillis, Y.A., Kouikoglou, V.S. & Verdugo, C. (2017). Urban sustainability assessment and ranking of cities. *Computers, Environment and Urban Systems*, 64, 254-265.

Ratner, K. & Goetz, A. (2013). The reshaping of land use and urban form in Denver through transit-oriented development, *Cities*, 30, 31-46.

Rodwin, L. (1981). Training City Planners in Third World Countries. In *Cities and City Planning* (pp. 210-226). Springer, Boston, MA.

Rogers, R., (1997). *Cities for a small planet*. London, Westview Press

Ryan, J. & Pereira, R.H.M. (2021). What are we missing when we measure accessibility? Comparing calculated and self-reported accounts among older people. *Journal of Transport Geography*, 93, 103086.

Lee, S., An, Y., & Kim, K. (2017). Relationship between transit modal split and intra-city trip ratio by car for compact city planning of municipalities in the Seoul Metropolitan Area. *Cities*, *70*, 11-21.

Shen, G., Wang, Z., Zhou, L., Liu, Y. & Yan, X. (2020). Home-based locational accessibility to essential urban services: The case of Wake County, North Carolina, USA, *Sustainability*, 12, 1-21.

Silva, C.N. (2008). Urban planning in Portugal in the twentieth century, *The International Journal of Regional and Local Studies*, 4(2), 23-39.

Sousa, N., Natividade-Jesus, E. & Coutinho-Rodrigues, J. (2018). Bike-Index – Um índice de acessibilidade velocípede recorrendo a programação em ambiente SIG, *Revista de Ciências da Computação*, 13, 67-88.

Sousa, N., Pais, F., Natividade-Jesus, E. & Coutinho-Rodrigues, J. (2019). Design of pedestrian network friendliness maps, *Proceedings of the Institution of Civil Engineers – Municipal Engineer*, 172(4), 224-232.

Straatmeier, T. & Bertolini, L. (2008). Joint Accessibility Design Framework Developed with Practitioners to Integrate Land Use and Transport Planning in the Netherlands. *Transportation Research Record*, 2077, 1-8.

Tannier, C., Vuidel, G., Houot, H., & Frankhauser, P. (2012). Spatial accessibility to amenities in fractal and nonfractal urban patterns, *Environment and Planning B: Planning and Design*, 39(5), 801–819.

Tgn, S. & Tan, S. (2012). *Designing our city: Planning for a sustainable Singapore*, Urban Redevelopment Authority, Singapore, 1-17.

Tsui, R., Wu, S. W., & Siu, A. (2015). Holistic approach to shape future cities. In *Future City Architecture for Optimal Living* (pp. 117-140). Springer, Cham.

Vale, D. & Pereira, M. (2016). The influence of the impedance function on gravity-based pedestrian accessibility measures: A comparative analysis, *Environment and Planning B: Urban Analytics and City Science*, 44(4), 740-763.

Verma, A., Verma, M., Rahul, T.M., Khurana, S. & Rai, A. (2019). Measuring accessibility of various facilities by walking in world's largest mass religious gathering – Kumbh Mela, *Sustainable Cities and Society*, 45, 79-86.

Williams, T. (2015). Archaeology: Reading the City through Time, in: *Reconnecting the city: The historic urban landscape, Approach and the Future of Urban Heritage*, Wiley: Blackwell, UK, pp. 19-44.

Yang, Y. & Diez-Roux, A. (2012). Walking distance by trip purpose and population subgroups, *American Journal of Preventive Medicine*, 43(1), 11-19.

Yuan, Z., Zheng, X., Lv, L. & Xue, C. (2014). From design to digital model: A quantitative analysis approach to garden cities theory, *Ecological Modelling*, 289, 26-35.

10 SITOGRAPHY

GOV.UK (2018) www.gov.uk/government/statistical-data-sets/tsgb01-modalcomparisons

INE – Instituto Nacional de Estatística (2011b) https://censos.ine.pt/xportal/xmain?xpid=CENSOS&xpgid=censos2011_apresentacao

UN – United Nations (2021) https://www.un.org/en/climatechange/climate-solutions/citiespollution

UN – United Nations (2018) https://www.un.org/development/desa/en/news/population/2018-revision-of-worldurbanization-prospects.html

11 Attachments

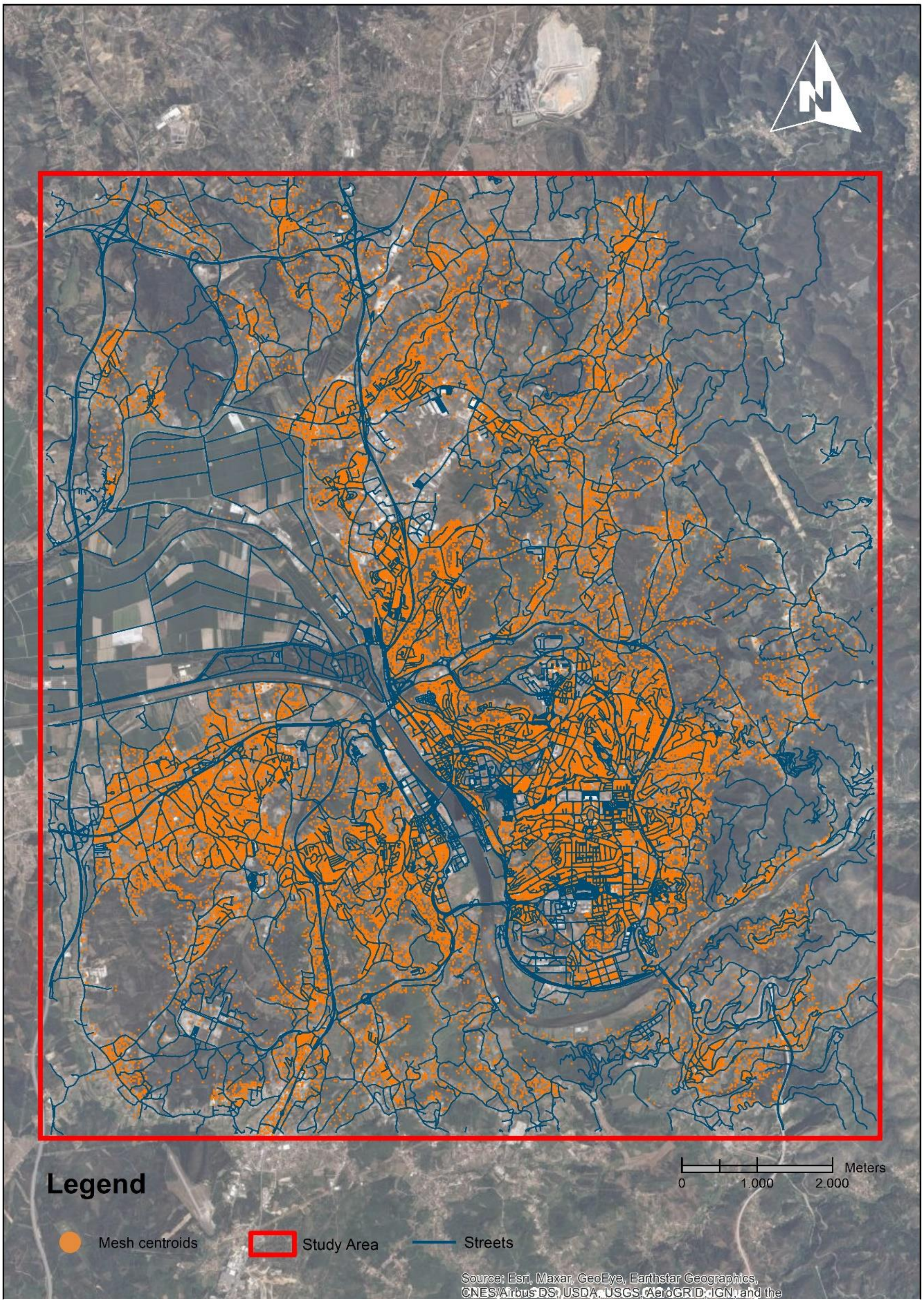


Figure 1: DIstribution of Coimbra's population

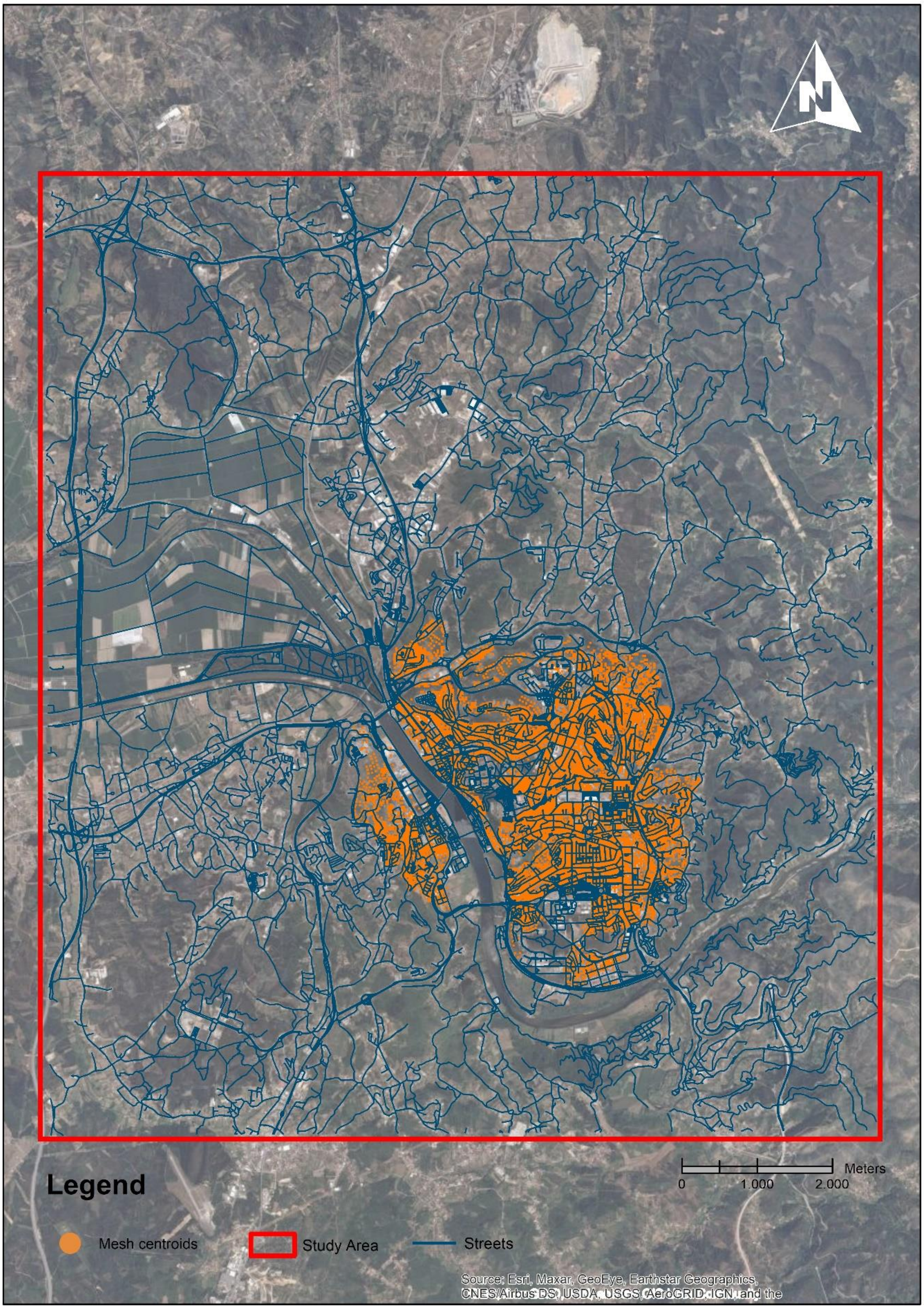


Figure 2 : Distribuition of population in the compact version of Coimbra

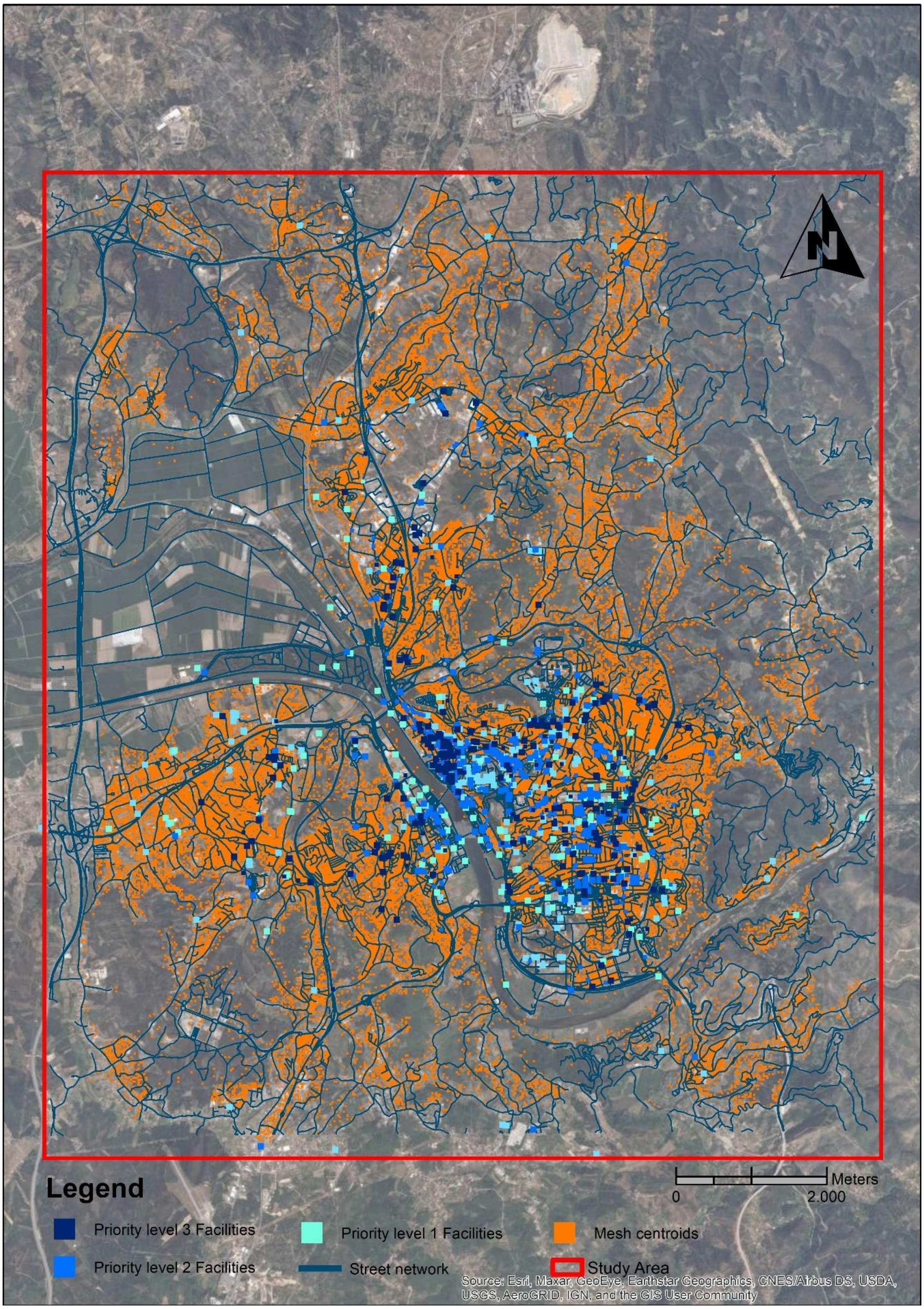


Figure 3 : Distribution of facilities in the actual city of Coimbra

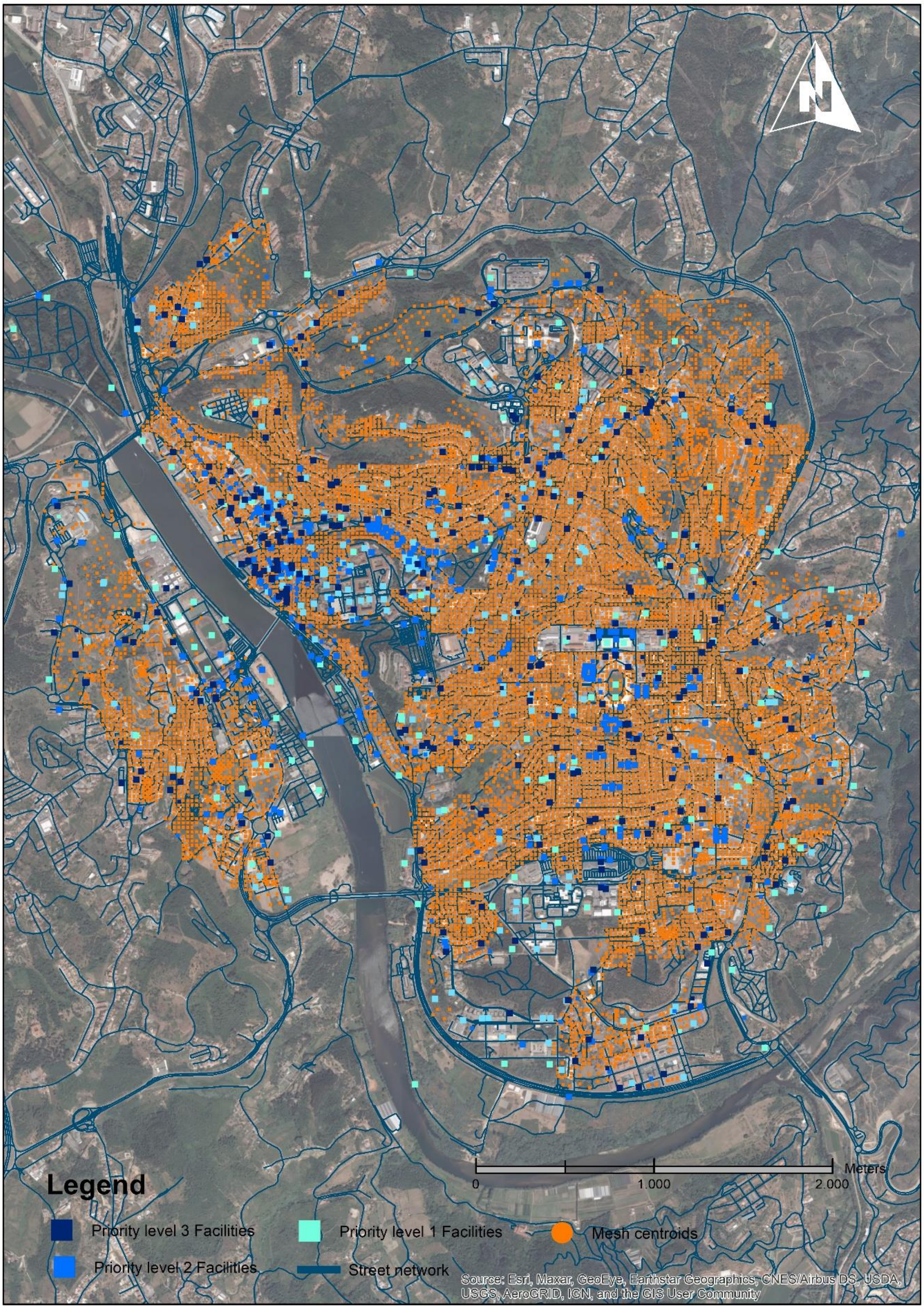


Figure 4 : Distribution of facilities in the compact version of Coimbra

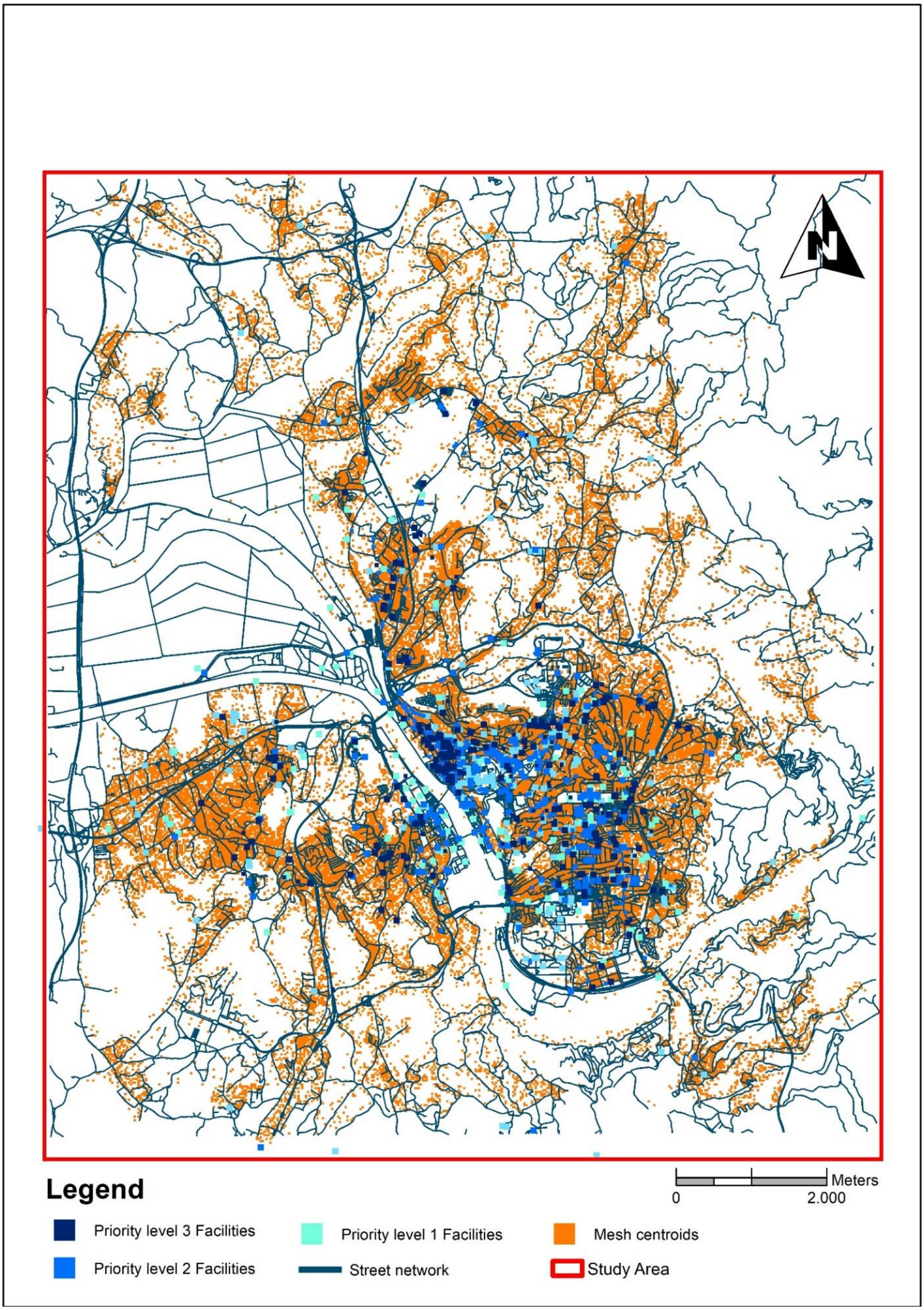


Figure 5 : Distribution of facilities in the actual city of Coimbra without base map

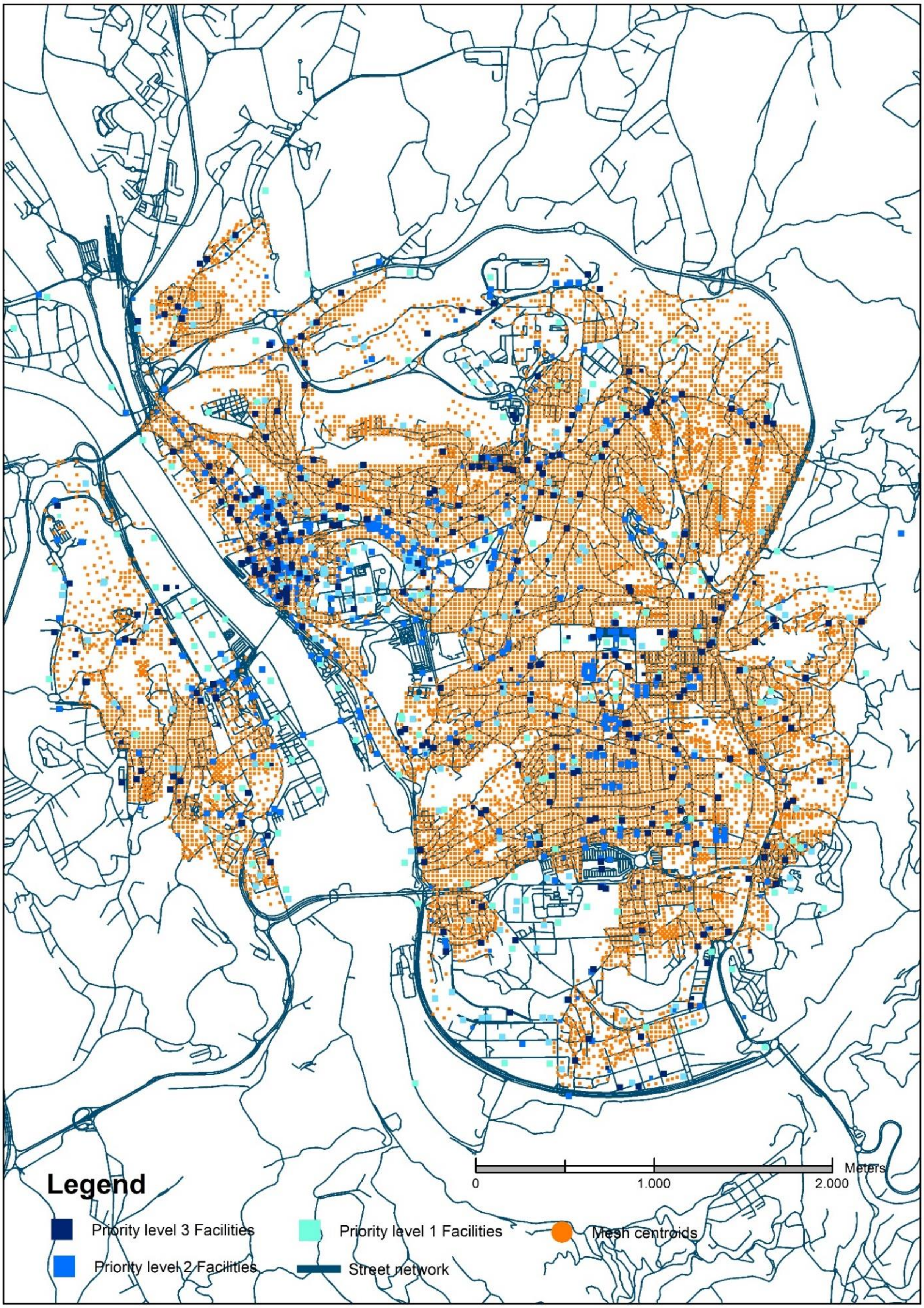


Figure 6 : Distribution of facilities in the compact version of Coimbra without base map

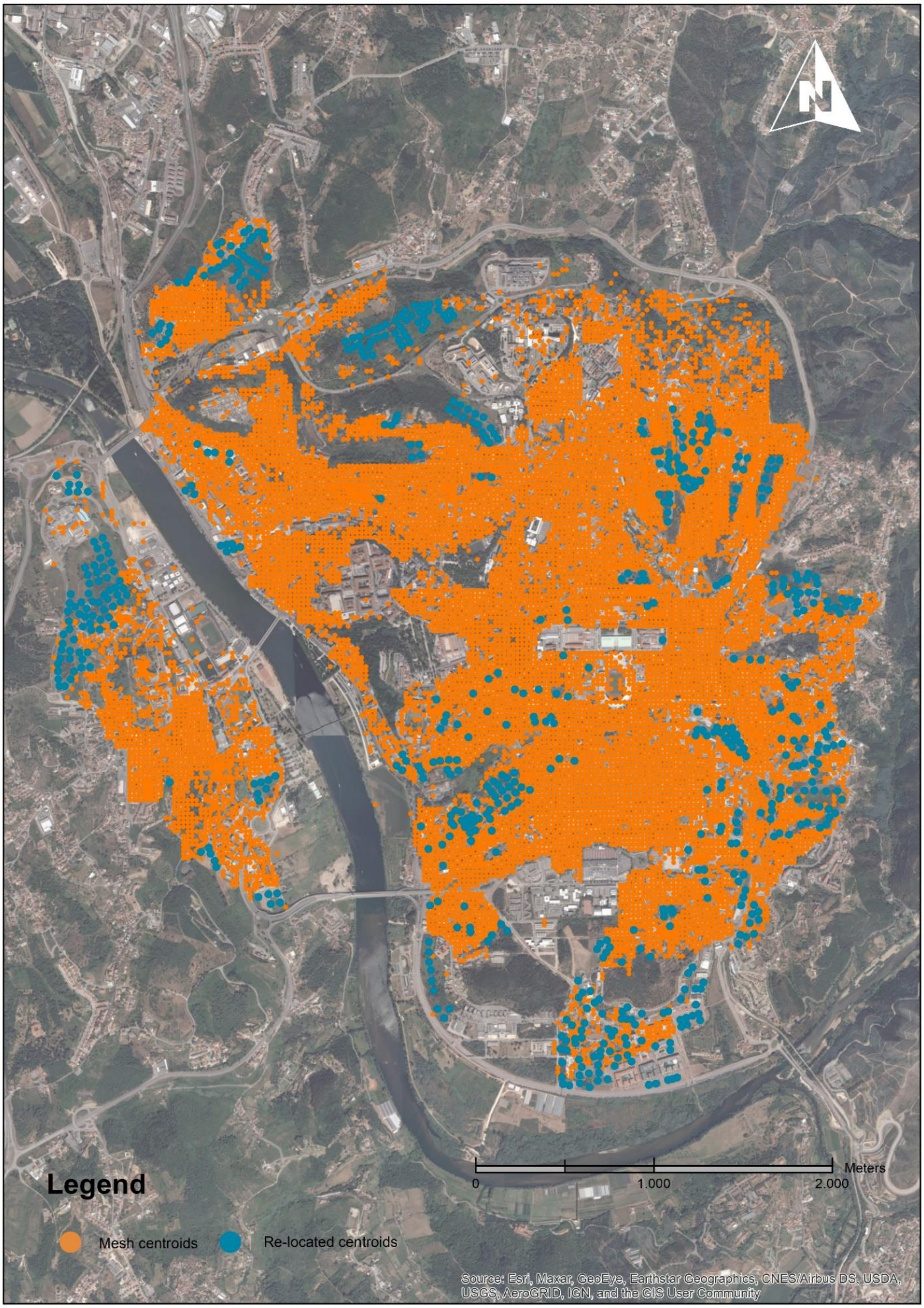


Figure 7 : Redistribution of centroids in Compact coimbra

Figure 8 : Hypothetical buildings modelled in compact Coimbra

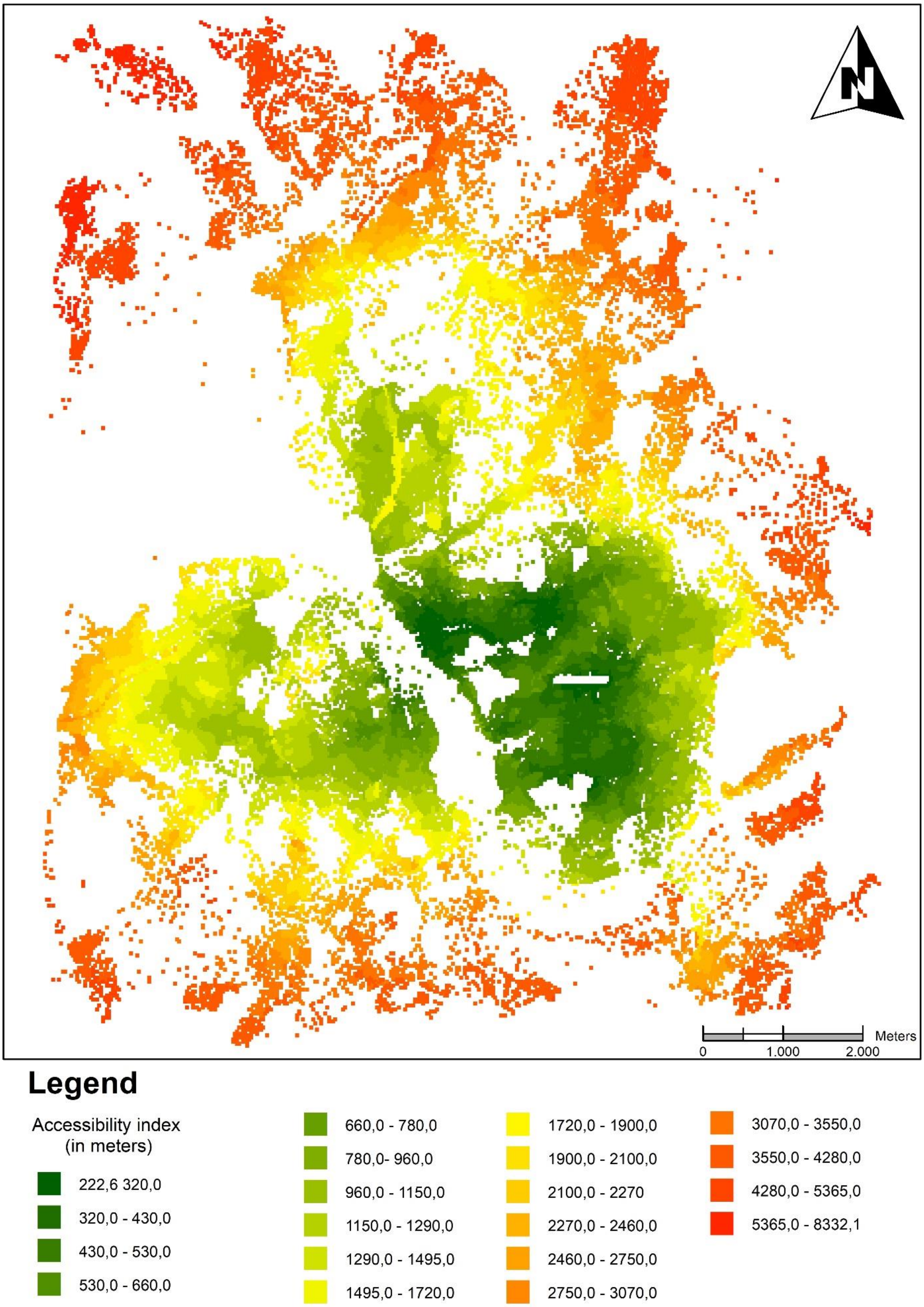


Figure 9 : Accessibility to urban facilities for Lk (j1) = {100,0,0}, real city

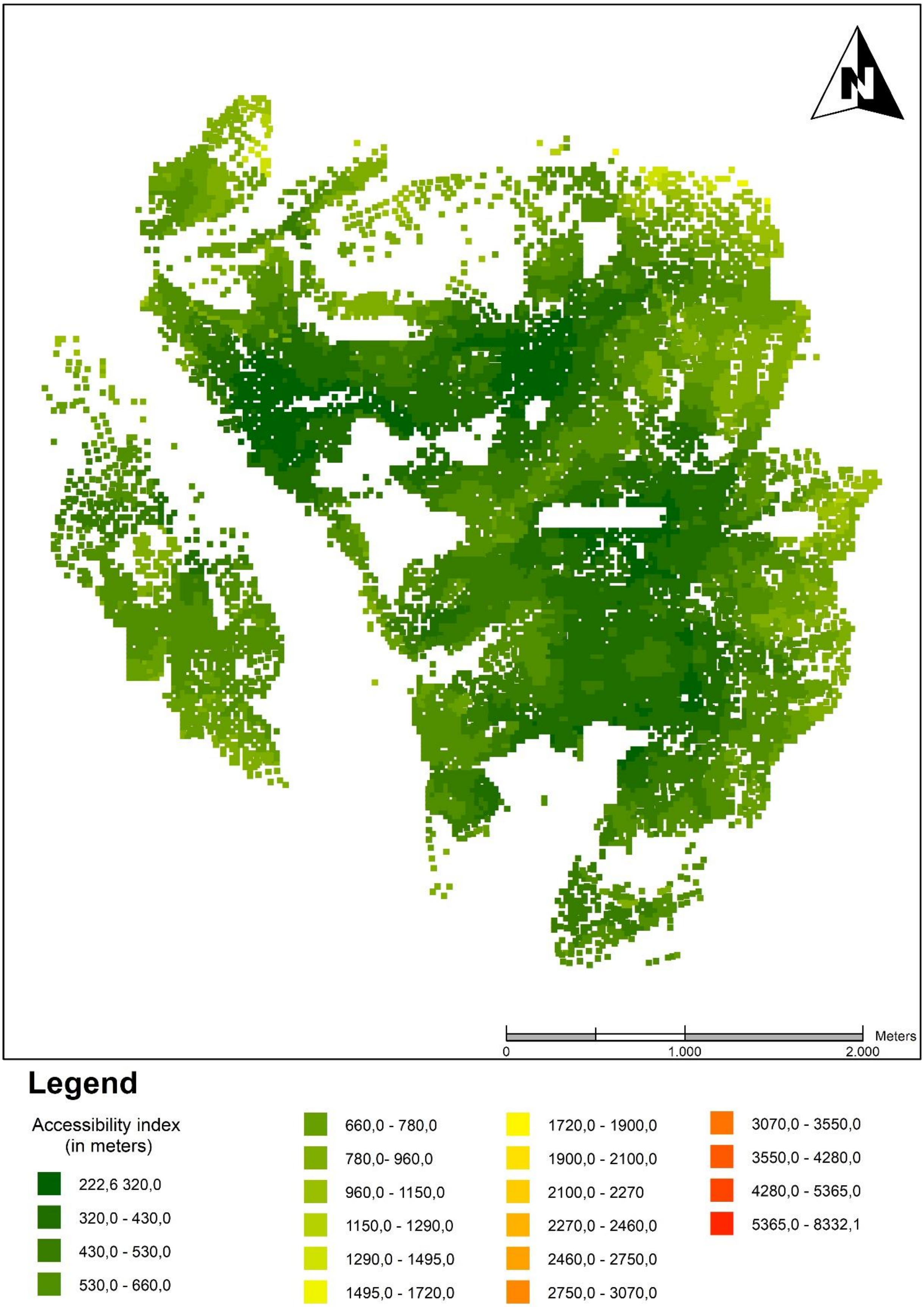


Figure 10 : Accessibility to urban facilities for Lk (j1) = {100,0,0}, compact Coimbra

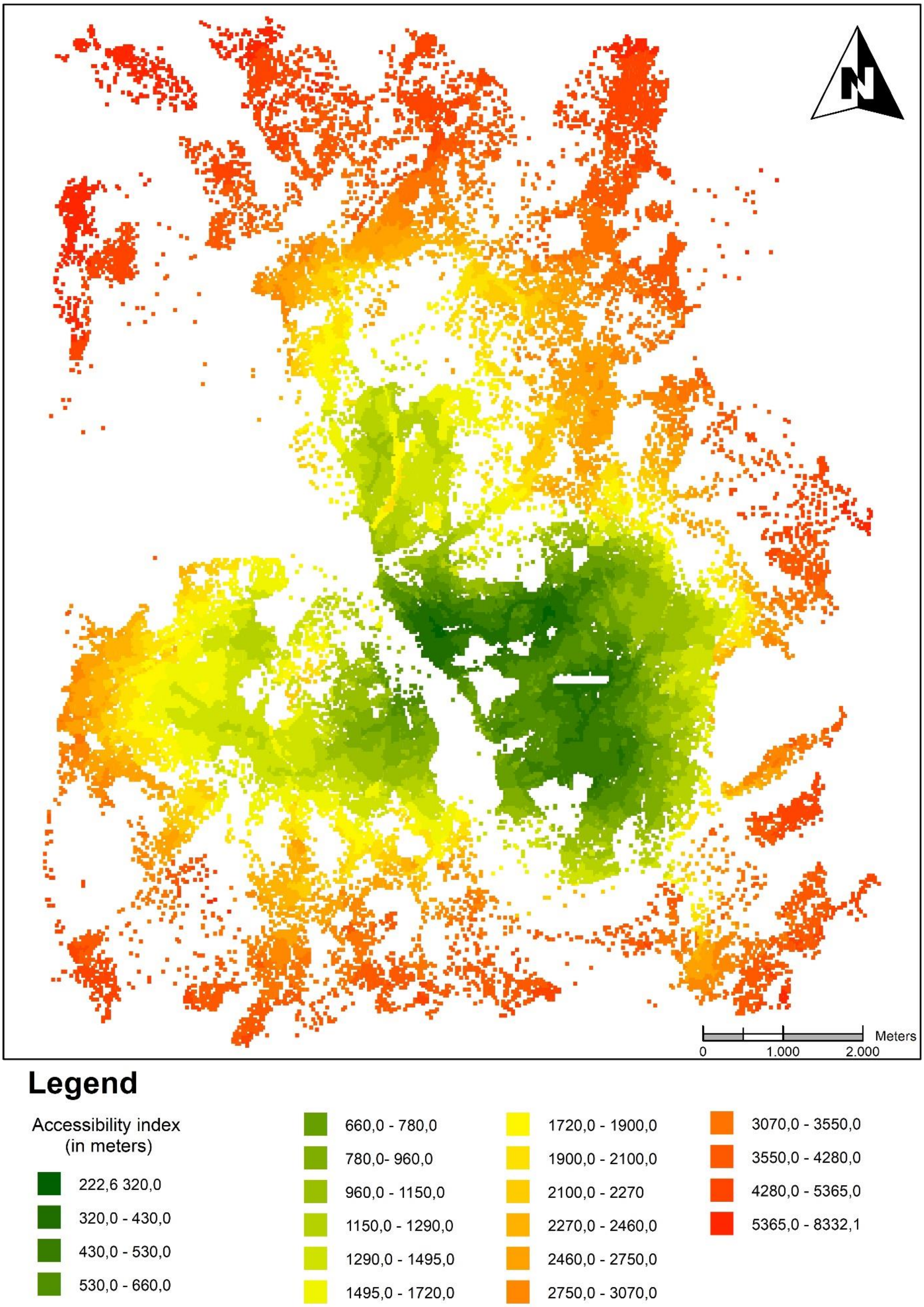


Figure 11 : Accessibility to urban facilities for Lk ($j3$) = {50,35,15}, real city

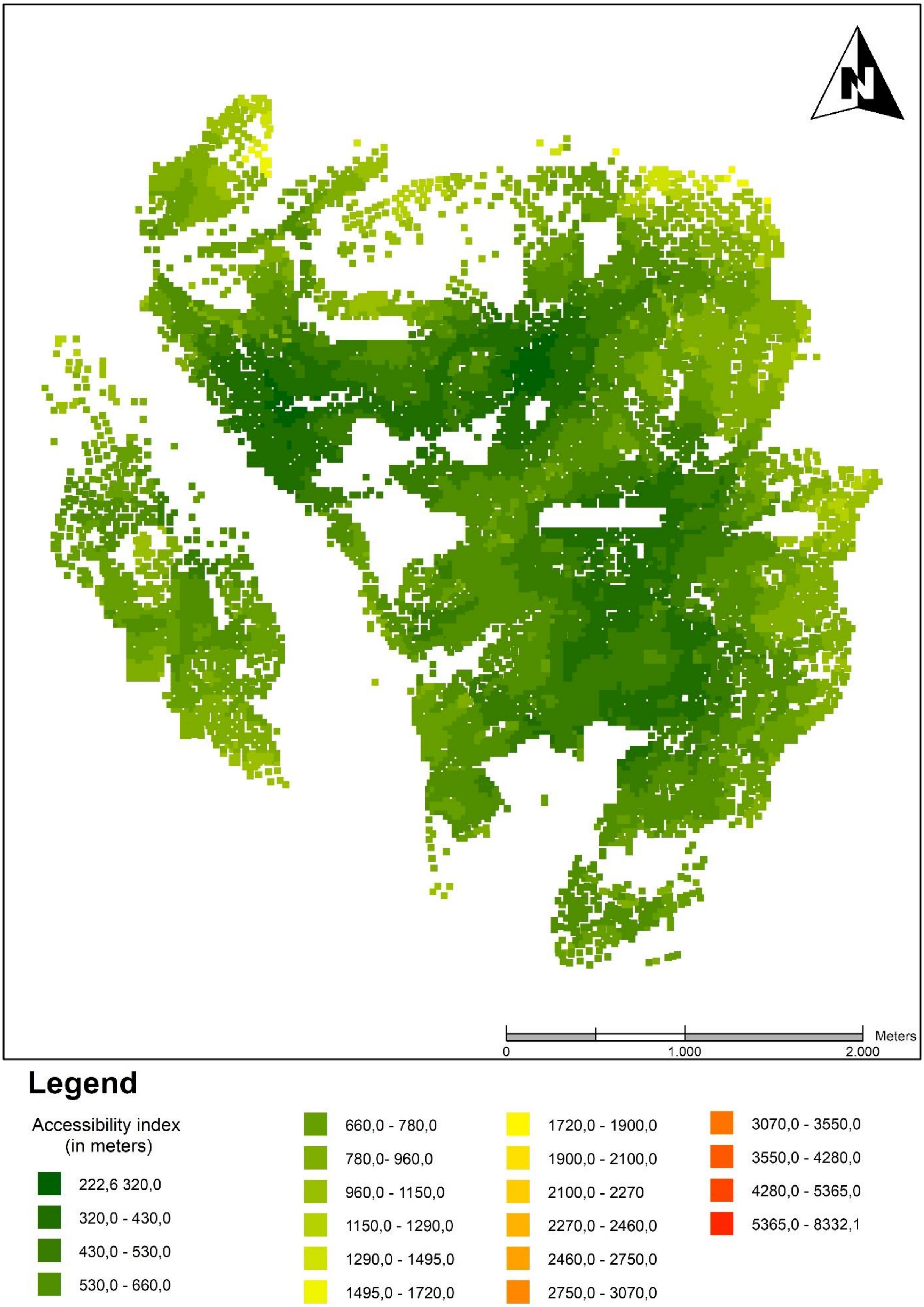


Figure 12 Accessibility to urban facilities for Lk $(j3)$ = {50,35,15}, compact Coimbra

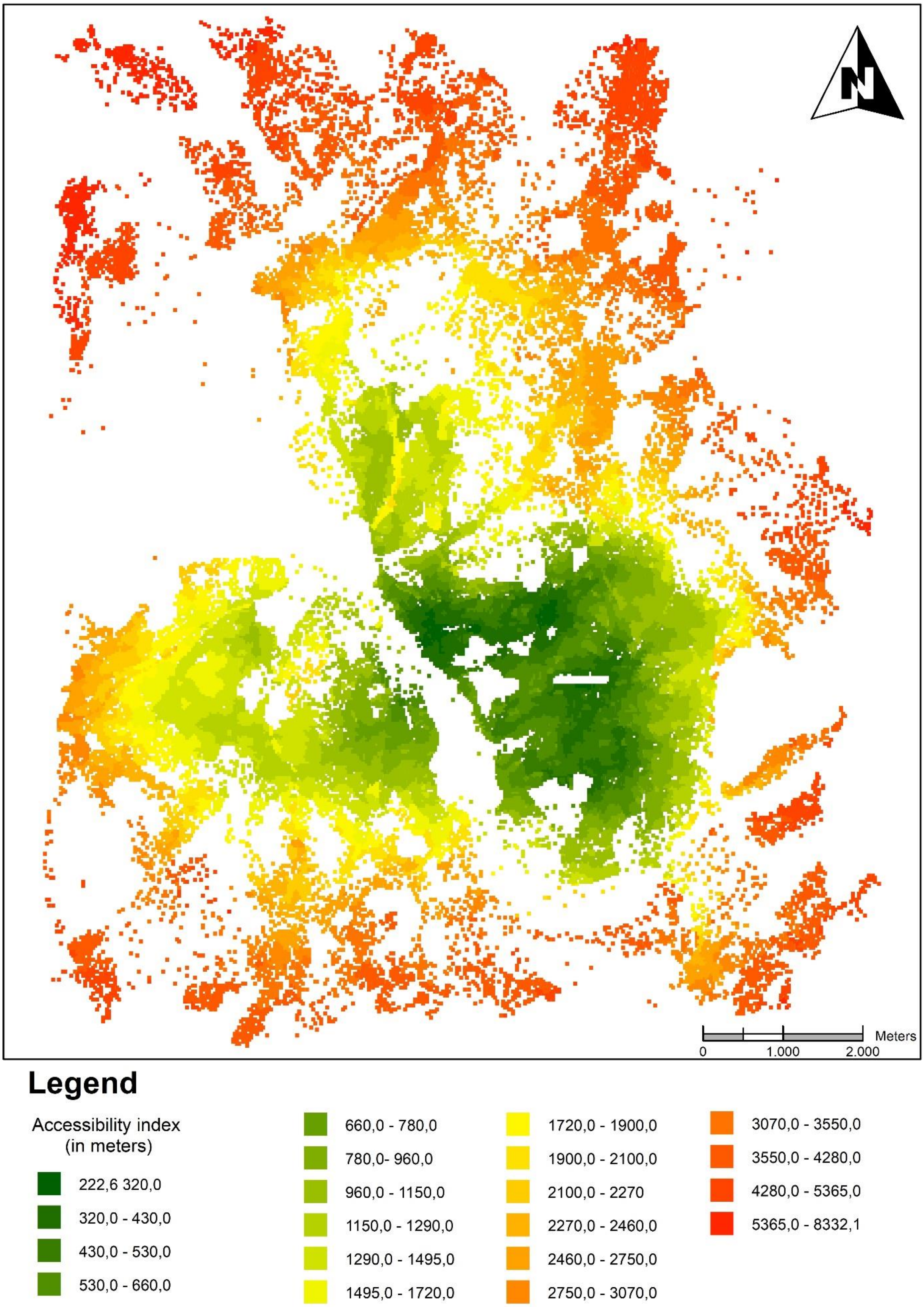


Figure 13 : Accessibility to urban facilities for Lk (β3) = {70,20,10}, real city

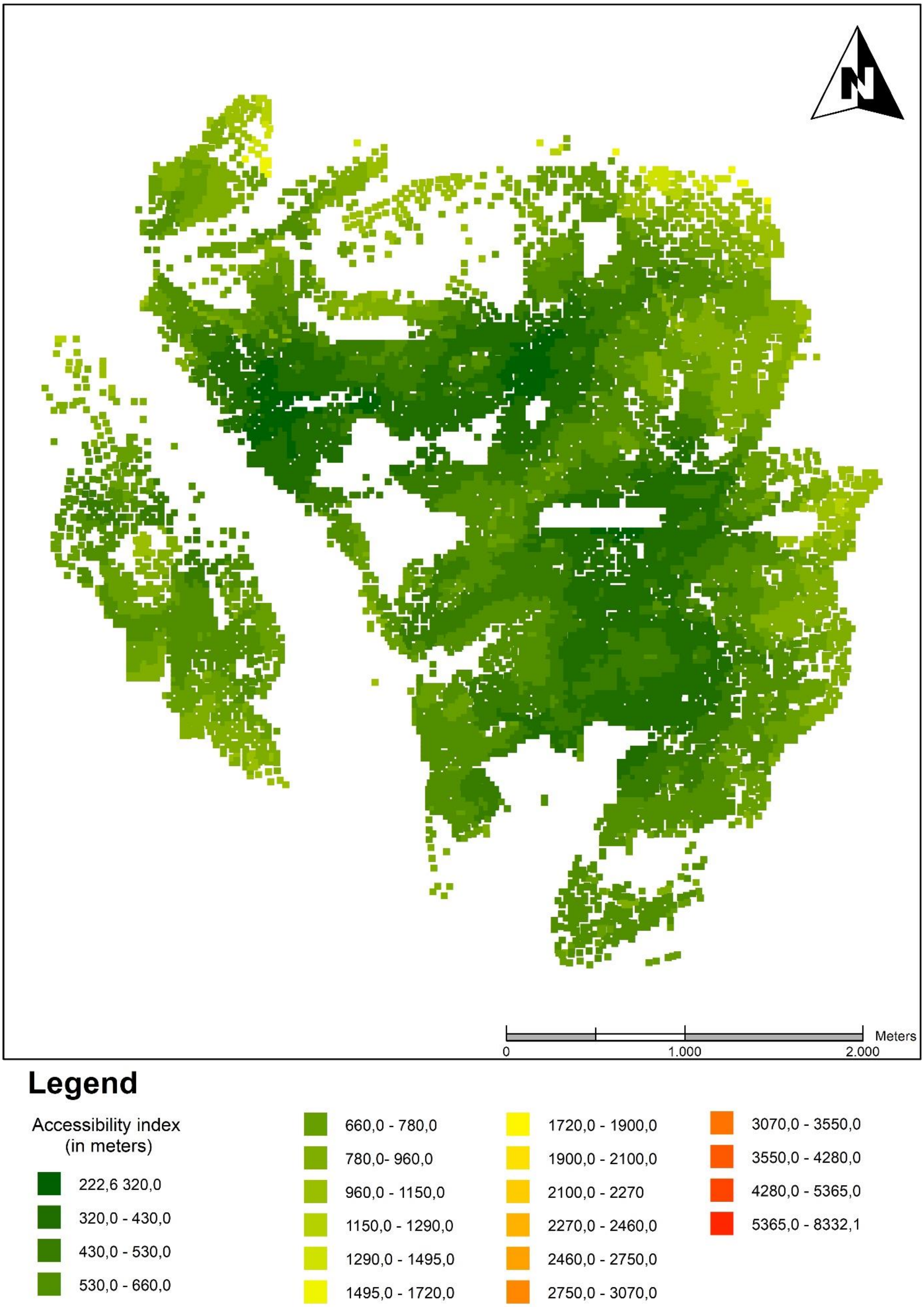


Figure 14 : Accessibility to urban facilities for Lk (f3) = {70,20,10}, compact Coimbra

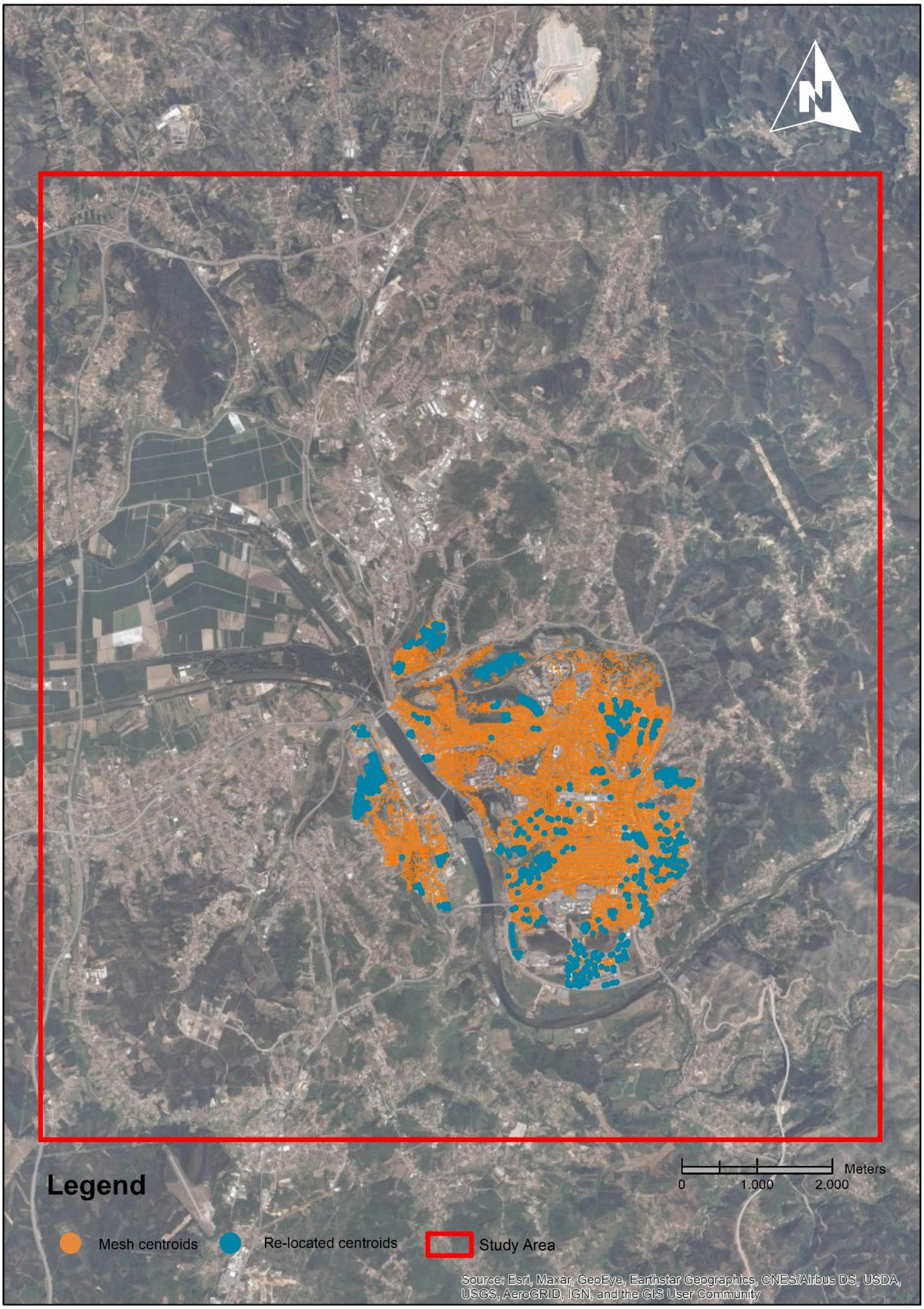


Figure 15 Redistribution of centroids in Compact coimbra, city overlook

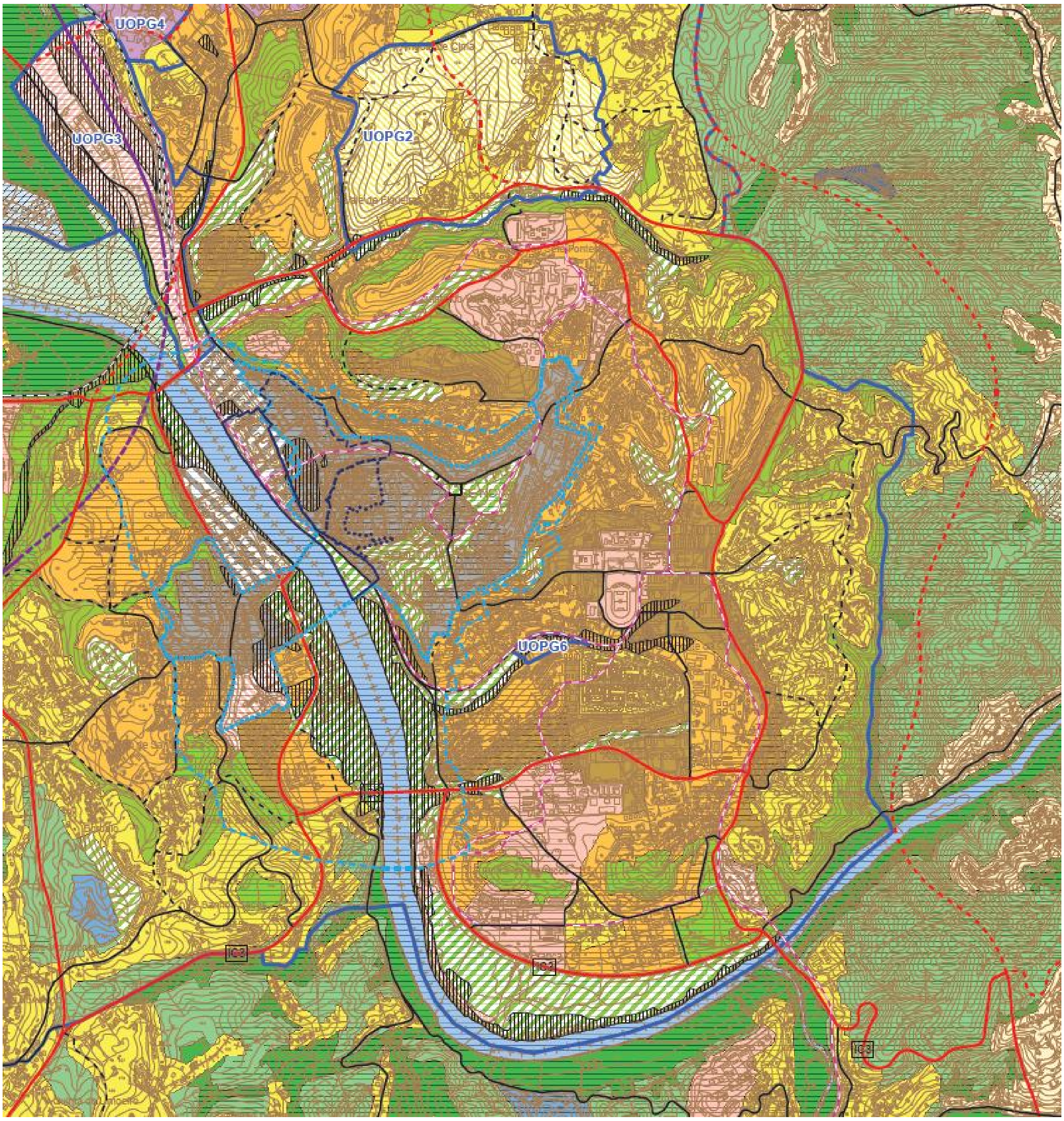
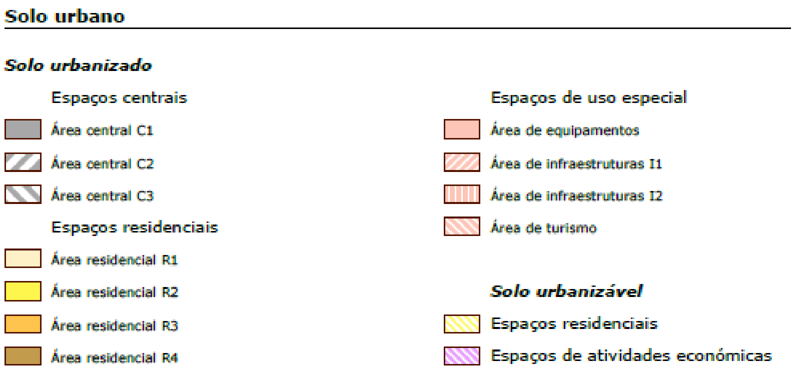


Figure 16 : Classificação e qualificação solo, close up on the city centre and its Legend



CÂMARA MUNICIPAL COIMBRA

Subsecção II

Área central C2

Artigo 87.º

Caracterização

A área central C2 corresponde à margem direita do Rio Mondego, compreendida entre a Ponte Açude e a Ponte de Santa Clara.

Artigo 88.º

Usos

Na área central C2 deve-se:

a) Acentuar a função habitacional, garantindo que em cada nova edificação esta função ou outras que fixem pessoas ao longo do dia deverão ocupar, salvo justificação fundamentada, 50% da área total;

b) Reequacionar a circulação, privilegiando o transporte público e os modos suaves de transporte;

c) Promover a ligação ao Rio, eliminando a barreira constituída pela linha de caminho-de-ferro;

d) Recuperar, com eventual reutilização, os edifícios existentes que apresentem valor patrimonial.

Artigo 89.º

Regime de edificabilidade

1. A superfície de pavimento máxima a autorizar será a resultante da aplicação dos índices de edificabilidade de 1,80 à faixa de terreno com profundidade de 25 metros, confinante a via pública, e de 0,90 à área restante do terreno.

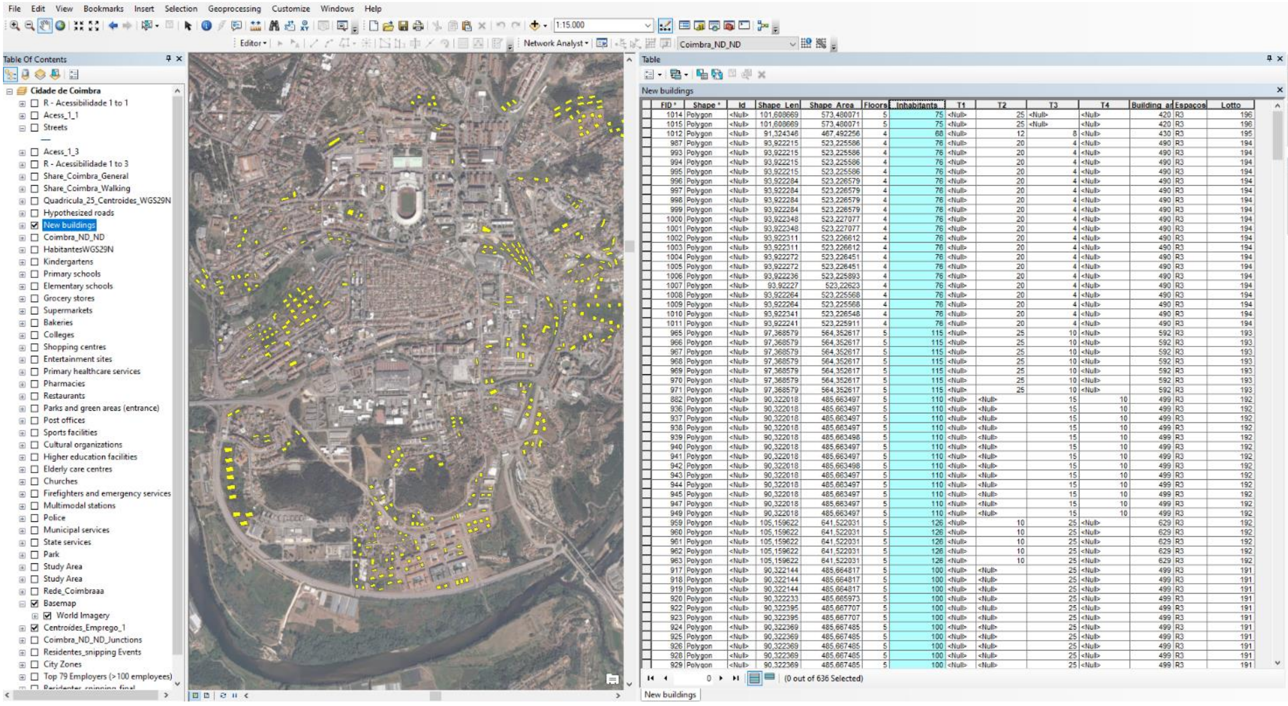
2. Excetuam-se do disposto no número anterior:

a) A ampliação de edifícios pré-existentes desde que assegurem uma correta relação com os edifícios vizinhos, nomeadamente no respeito pela altura da edificação e ou altura da fachada da frente urbana respetiva e da confrontante;

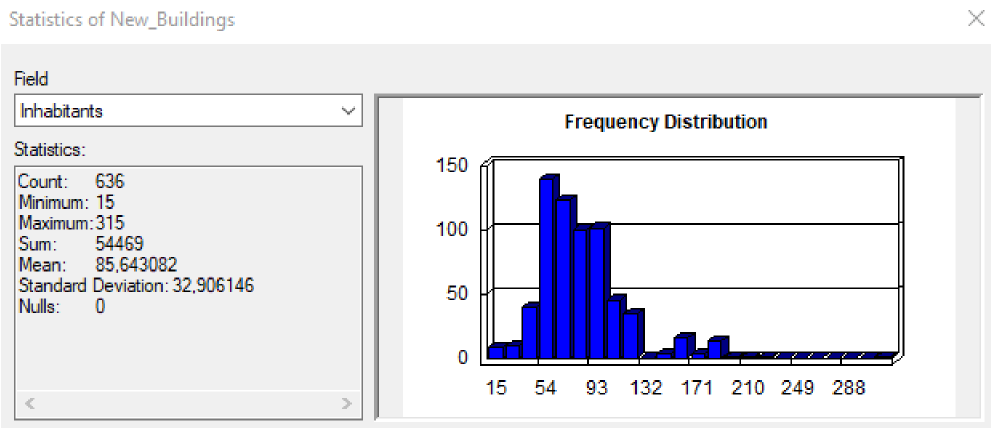
b) Os espaços de colmatação, nos quais a edificação respeitará o alinhamento, recuo e profundidade dos edifícios contíguos e estabelecerá a articulação volumétrica desses mesmos edifícios;

47

Figure 17 Regulamento Municipal de Urbanização e Edificação (RMUE, Regulation number 381/2017 and revision 08/2018)



Screenshot 1 : an ArcGIS working window



Screenshot 2 : Statistics of the "Inhabitants" column, from "New Buildings" layer