URBAN POPULATION DYNAMICS DURING THE COVID-19 PANDEMIC BASED ON MOBILE PHONE DATA.

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ABSTRACT

Because of the fast expansion of the COVID-19 pandemic in 2020, many countries established lockdowns, implementing different restrictions on people's mobility. Analysing the effectiveness of these measures is crucial to better react to similar future scenarios. This research uses anonymous mobile phone data to study the impact of the Spanish lockdown on the daily dynamics of the Madrid metropolitan area. The analysis is focused on a reference week prior to the lockdown and on several weeks of the lockdown in which different restrictions were in place. For this timeframe, population distribution is compared during the day and at night and presence profiles are obtained throughout the day for each type of land use. In addition, a multiple regression analysis is carried out to determine the impact of the different land uses on the local population. The results in the reference week, pre-COVID-19, show how the population in activity areas increases in each time slot on a specific day and how in residential areas it decreases. However, during the lockdown, activity areas cease to attract population during the day and the residential areas therefore no longer show a decrease. Only basic essential commercial activities, or others that require the presence of workers maintain some activity during lockdown.

1. INTRODUCTION

The COVID-19 pandemic has abruptly changed the way in which citizens interact, move or make use of different urban activities. The change has been radical particularly in the initial phases of the pandemic, with the adoption of the most severe measures and the lockdown, which has led to the closure of most activities and changes in habits when carrying out the most basic activities. Without any warning, cities were forced to slow down, reduce and even stop much of their activity for months. Knowing how the pandemic has transformed urban dynamics and what the patterns of these dynamics are in the phases of lockdown and subsequent restrictions is essential for decision-making, establishing new measures or evaluating their effectiveness in preventing and controlling the spread of the pandemic and in understanding the city's resilience to these measures to contain severe outbreaks.

New geolocation technologies offer significant possibilities to study population mobility and the possible spread of contagious diseases are well known (Sirkeci and Yucesahin, 2020, Ferretti et al., 2020). Mobile phone data had only been rarely used in epidemiological research, but their enormous potential has been demonstrated during the COVID-19 pandemic to estimate the effectiveness of the control measures in many countries (Oliver et al., 2020b).

This research aims to study the impact of the pandemic on the dynamics of the city throughout the day and its spatial relationship with land uses, an aspect that the authors believe has not as yet been discussed in depth. The presence of the population in each area of the metropolitan area of Madrid (Spain) is calculated throughout the day using information from mobile phones. This daily distribution of the population is analysed for a typical week, and then compared with the daily distributions in the weeks of confinement decreed due to the state of emergency in Spain. During this lockdown period, we also analyse the effects of the different phases, where measures to restrict the mobility of the population and the opening of the different activities have been tightened or eased.

In order to analyse urban dynamics, mobile phone data were crossed with the distribution of land uses within each transport zone. Typical hourly activity profiles have been obtained for each land use and multiple regression models (OLS) have been calculated for four major moments in time (morning, afternoon, evening and night). The analyses carried out show the level of activity throughout the day that each type of land use has maintained according to the degree of restrictions imposed.

Madrid metropolitan area as a case study is also of special interest, given the high impact that the disease has had. Spain has been one of the countries most affected by the pandemic, with rates of confirmed cases and deaths among the highest in the world (Johns Hopkins University, 2020). Madrid, the most affected metropolitan area in Spain, was also one of the first affected areas in Europe to establish a lockdown and has also witnessed various phases in the application of the measures, which allows us to evaluate the impact of different types of measures and serves as a reference in the evaluation of the same.

2. CASE STUDY, DATA AND METHODOLOGY

2.1 Study Area and Phases

The study area consists of the municipalities included in the Morphological Urban Area (MUA) (ESPON, 2014) of Madrid that are located within the Region of Madrid. With an extension of 202,478.46 Ha, the study area enables us to analyse Madrid's behaviour on a metropolitan scale, and study in detail what happens in each of the 1,062 transport zones into which it is divided (Figures 1 and 2). Just over 5.7 million people reside in the metropolitan area of Madrid according to the 2019 census.

When it comes to the time frame, the research analyses the impact of the COVID-19 pandemic on the distribution of the population in the study area over 6 weeks (March 23 - May 10, except Easter). In these weeks, the Government of Spain had activated the State of Alarm prior to the adoption of the Transition Plan to the New Normal. They were the weeks of greatest restrictions, with various measures to regulate activities in the different phases. Additionally, the analysis extends to the week of February 14-20, 2020, taken as a reference (W0), representing the distribution of the population in a normal week, prior to the pandemic.

The weekly analysis allows us to study the impact of the different measures decreed by the government on mobility and the degree of confinement of the population.

To understand the results obtained, the phases of the lockdown decreed by the Government of Spain and the most important measures established in each of them (Table 2) must be defined. Table 1 shows the dates of the study weeks, relating them to the phases and measures indicated in Table 2.

Study weeks	Dates	Corresponding phase
W0	14-20 February	Reference week. Normal activity prior to COVID-19.
W1	23-29 March	Second week after the Declaration of the State of Alarm
W2	30 March - 5 April	First week of Extension of State of Alarm 1
W3	13-19 April	First week of Extension of State of Alarm 2
W4	20-26 April	Second week of Extension of State of Alarm 2
W5	27 April - 3 May	First week of Extension of State of Alarm 3
W6	4-10 May	Second week of Extension of State of Alarm 3 and first week of Transition Plan to New Normality: Phase 0

Table 1. Study weeks, dates and correspondence with the State of Alarm phases

Phase	Dates	Summary of measures
Declaration of a State of Alarm	14-28 March (2020)	● Suspension of face-to-face classes in all learning centers. ● Prohibition to circulate in the streets, except for: Buying food or medicine, going to health centers, going to or coming from the workplace, going to banks or insurance companies, taking care of the elderly or children. ● Recommendation of teleworking. ● Closure of most premises, shops and businesses. Exceptions: Food stores, pharmacies, medical centers, gas stations, and others. ● Closure of museums, libraries and leisure or sports centers. ● The public transport service is maintained.
Extension of State of Alarm 1	29 March - 12 April (2020)	This is the phase with the greatest restriction of activities. The measures adopted during the State of Alarm also include: ● Suspension of non-essential face-to-face work activity. Fundamentally, the following are considered essential activities: health, food and fuel distribution, public maintenance services, cleaning and waste collection, state security, postal services, funeral services and media.
Extension of State of Alarm 2	13 - 26 April (2020)	Measures relating to those defined in the previous phase: ● People are allowed to return to their workplaces for non-essential activities where teleworking measures cannot be implemented. ● Circulation of private vehicles is allowed to carry out the permitted activities.
Extension of State of Alarm 3	27 April - 10 May (2020)	Measures relating to those defined in the previous phase: ● Children under 14 years of age may go out with someone one hour a day but must not go further than one kilometer from home. ● From 2 May: Those defined by the Transition Plan to the New Normal.
Transition Plan to the New Normality: De-escalation - Phase 0	2 - 10 May (2020)	On April 28, a 4-phase Transition Plan to the New Normal was established. On May 2, Madrid enters Phase 0 of the plan, allowing: ● Departure for minors, individual non-contact sports activities and walks, once a day and at regulated hours. ● Opening of establishments by appointment for customer’s service.

Table 2. Phases, dates and measures adopted by the Spanish Government

2.2 Data

This research is based on the datasets described below:

1. **Mobile phone records**. The data used for the extraction of mobility indicators consists of a set of anonymized mobile phone records corresponding to the defined weeks of study, obtained through a collaboration agreement with one of the three main Mobile Network Operators (MNOs) in Spain, with a market share of more than 20%. The records include Call Detail Records (CDRs), produced every time a mobile phone interacts with the network through a voice call, a text message or an Internet data connection, as well as passive events coming from network probes. Among other information, each record contains an anonymized identifier of the user, a timestamp and the position of the tower to which the device is connected at that particular moment. This provides an indication of the geographical position of the user at certain moments along the day. The temporal resolution of the records depends on the frequency of use of the mobile device; most users typically generate a register at least every 15-20 minutes.

2. **Land Use data**. Land use data provided by the Directorate General for Cadastre in Spain (Cadastre), by built entity of the study area. The databases define the surface area [m^2] of each type of land use. The data set used corresponds to the update of January 24, 2020. Figure 1 represents the transport zones of the study area according to a classification of predominant land uses.

3. **Population Data**. Census data for 2019 at the census section level, obtained from the National Institute of Statistics. The data has been aggregated at the transport zone level, and it has been used as the sampling frame for expanding the sample of the MNO customers. Figure 1 shows the population distribution in the study area.

4. **Territorial boundaries**. The demarcation of the Morphological Urban Area (MUA) of Madrid has been obtained from the ESPON DATABASE project. The transport zones defined in Madrid have been obtained from the Open Data Portal of the Consorcio de Transportes de la Comunidad de Madrid.

5. **Data on State of Alarm phases and measures**. They come from the Royal Decree of the Ministry of the Presidency of the Government of Spain published in the Official State Gazette.

To extract meaningful mobility indicators, the sample is expanded to the total population of the study area. The expansion factor is calculated as the ratio between the number of residents of the district according to the census information and the sample of users with their home location at the given district.

In the present study the mobile phone records were used to build OD matrices with origin and/or destination in the 1,062 zones of the study area. The matrices were segmented by day and start time of the trip, considering 24-time segments.

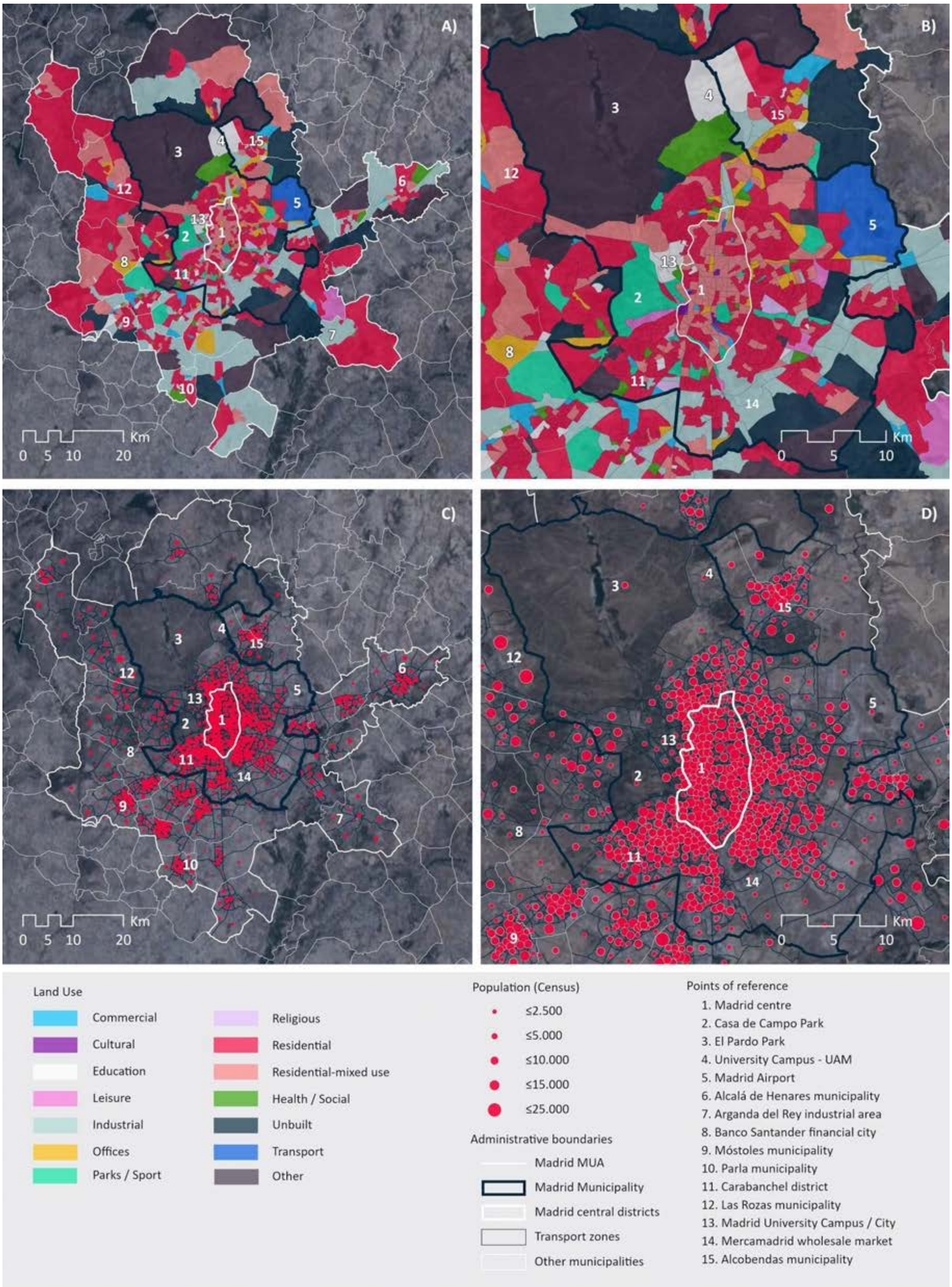

Figure 1: Land Use and Distribution of population (in the reference week at night) in the study area

2.3 **Study of the spatial distribution of population according to time slot**

Because of the different activities carried out, population distribution in the study area varies throughout the day. For analysis purposes, the number of people present in each transport zone for each hour and week was estimated from the O-D matrices. The following criteria were considered:

1. A single matrix of hourly trips per week was obtained, in which the average number of trips for each O-D pair is the average of the trips made between Monday and Thursday of that week.
2. It was considered that the number of people in the census corresponds to the number of people present in each transport zone at 02:00, when the lowest number of trips generated in W0 in the study area is observed.
3. The number of people present in each transport zone per hour was estimated as those indicated in the census (situation 02:00 hours) plus the sum of average weekly trips of people attracted to that transport zone, between 02:00 and the corresponding time, minus the sum of average trips for the week generated in that transport zone for the same time period.

Firstly, we explored the data through video-visualization, which represents the evolution of the population density [people/km^2] for each time slot in the reference week (W0) and the week of greatest restrictions (W2).

Secondly, bivariate Ordinary Least Squares (OLS) analyses were performed in order to compare the different population distributions according to time slots for each of the study weeks: Morning (08:00 to 14:00), Afternoon (14:00 to 19:00), Evening (19:00 to 22:00) and Night (22:00 to 00:00). The coefficient of determination indicates the degree of overlap between population distributions, while the regression residual maps show where differences (positive or negative) between time slot distributions emerge. This analysis was focused on differences between the reference time slot (night) and the rest of the time slots for each of the study weeks. These differences are expected to be especially high in the reference week W0 (people move within the city without restrictions) and particularly low during the week of strictest home confinement W2 (most people stay at home).

2.4 Analysis of temporal profiles according to predominant land use

Population presence according to predominant land use were calculated for each time slot and study week and represented through different temporal profiles. The total number of people present in a zone was assigned to the predominant land use in the zone, and then the total number of people according to land use was added up for each time slot in order to obtain the specific temporal profile of each land use in each study week.

With the aim of performing this temporal analysis, the percentage of built-up area pertaining to each land use in each transport zone was calculated based on cadastral data. Firstly, three main types of transport zones were distinguished: residential (when more than 66.6% of built-up area in the zone is residential), activity (when more than the 66.6% is non-residential, e.g. offices, industry, retail or education) and mixed residential (all other cases).

Secondly, activity (non-residential) areas were classified in 10 types: offices, industry, retail, health, education, culture, entertainment, large transport terminals, parks and others.

3.RESULTS

3.1 Spatial distribution of population according to time slot

The visual analysis of the spatial distribution of population according to time slope in weeks W0 and W2 shows a very clear picture of the impact of the measures restricting mobility and performance of activities established with the decree of the State of Alarm. During the lockdown week (W2), the population variations with respect to night-time distribution are minimal, which is also shown in the animated graph that represents the evolution of the population in each type of urban area according to the basic classification of predominant land use: residential, mixed residential and activity. However, a more detailed visual inspection reveals more significant changes in specific areas of the city, where activity registers a particularly sharp decline (for example in educational, financial or office areas) or where it remains at outstanding levels (some areas of logistics or health). Figure 2 shows a screenshot of the video-visualization, which is attached as supplementary material in this paper.

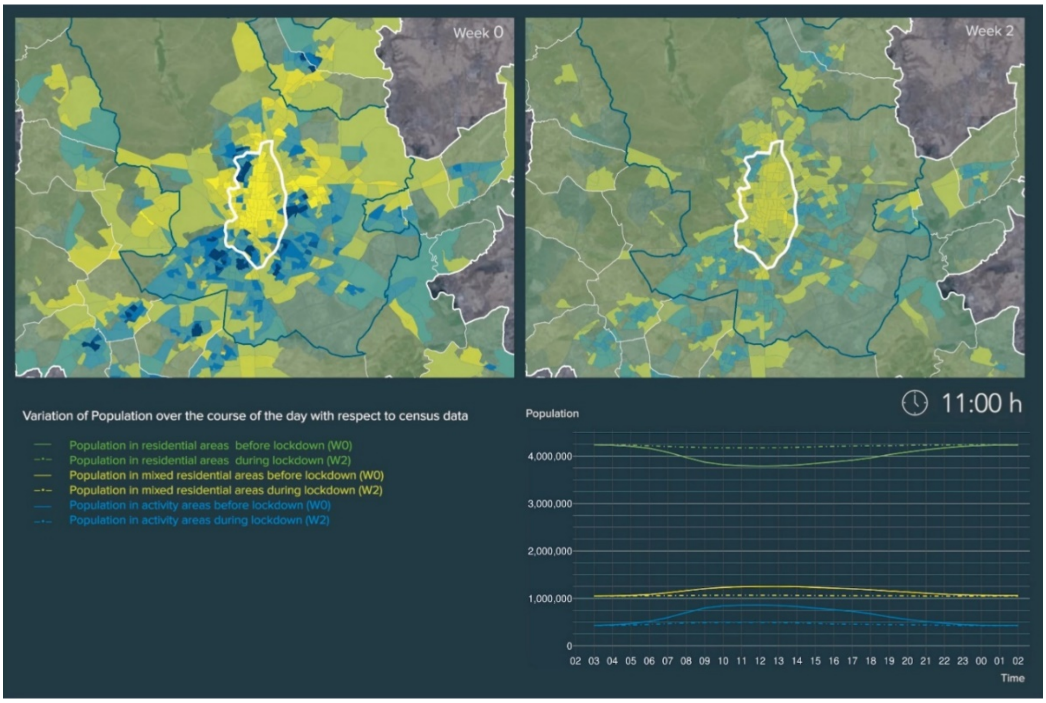

Figure 2: Layout of the video-visualization representing the variation of population density according to time slot for the reference week (W0) and the second week of the

lockdown (W2).

The first visual approximation is complemented by the weekly bivariate analysis between large time slots, allowing us to obtain a numerical indicator for comparing the different scenarios. Taking night-time as the base period, the differences in distributions of the population throughout the day can be analysed from bivariate correlations (Table 3). Madrid and its metropolitan area have a high mix of land uses, meaning that the coefficients of determination are high in all cases. The biggest differences are between night-time (residence) and morning (activities). On the contrary, between Night-time - Afternoon and, especially, between Night-time - Evening the correlations are very high, because many people have already returned to their areas of residence. The confinement situation makes the correlations between night-time and the rest of the time slots practically equal to 1.

Week	Morning 08:00 to 14:00	Afternoon 14:00 to 19:00	Evening 19:00 to 22:00	Night 22:00 to 00:00
W0 Night (22:00 to 24:00)	0.711***	0.814***	0.978***	1
W1 Night	0.987***	0.996***	0.999***	1
W2 Night	0.994***	0.998***	0.999***	1
W4 Night	0.984***	0.996***	0.999***	1
W6 Night	0.976***	0.993***	0.998***	1

*** P Value < 0.001

Table 3. Relationships in the distribution of population according to time slot (r^2)

A very different spatial behavior between night-time and morning in weeks W0 and W2 (Figure 3) is shown by the mapping of the correlation residuals. In a normal situation (W0), the morning activity spaces become highly active (positive residual in yellow), such as office areas (Points of interest 1 and 8) and mixed areas of the center, industrial areas (Points 4, 7 or 9), large facilities, university campuses (Point 2) or hospitals, as well as transport terminals, such as railway stations or the airport (Point 3). Whereas residential areas have high negative residues (blue color).

During the week of greatest restrictions (W2) the intensity of the residuals is very low. Some equipment areas are shut off (for example, Ciudad Universitaria - Point 2) and the intensity of activity is significantly reduced in the central office spaces (Points 1 and 8). On the other hand, some industrial spaces on the periphery now show the greatest deviations (Points 4, 7 and 9), together with strategic logistics facilities, such as Mercamadrid (Point 5).

Mercamadrid is the largest wholesale market in Spain, and presents an even greater deviation than in the reference week (W0), which is related to the fact that supermarkets increased sales during the first weeks of the state of alarm.

Finally, attention should be drawn to the activity detected in specific points of the city, such as the Feria de Madrid-IFEMA (6), which was converted into the largest emergency hospital in Madrid during the State of Alarm.

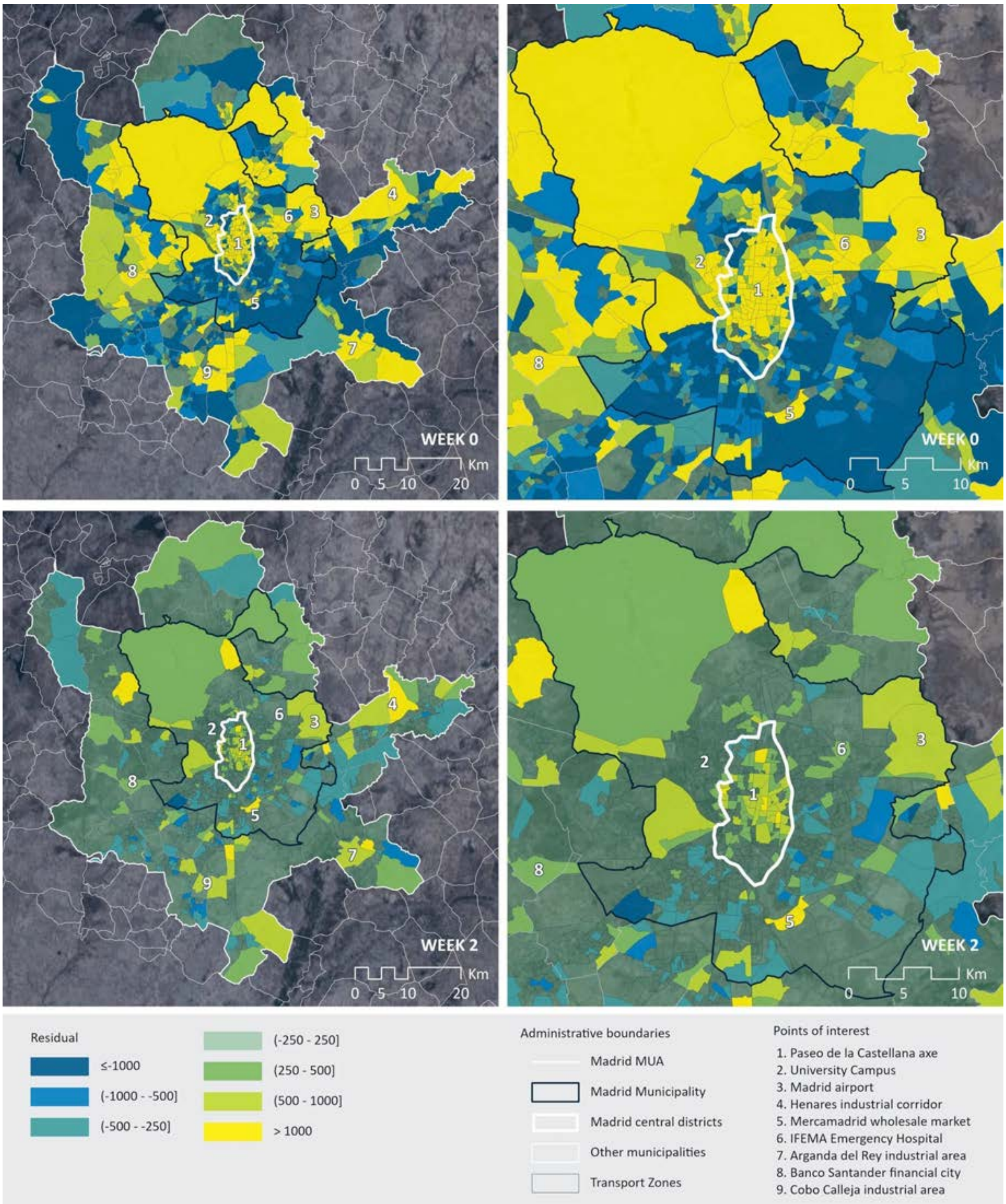

Figure 3: Residuals in the bivariate correlations of the distribution of population at night and in the morning

On the contrary, residential areas tend to lose a large part of their population during the hours of activity during the reference week (W0), while these losses have decreased substantially between night and morning in the week with the highest restrictions (W2).

3.2 Temporal profiles according to predominant land use

Population distribution according to land use and time slots for the reference week (W0) is shown in figure 4a. Most of the population can be found in residential areas during all time slots. Although residential use is dominant in these transport zones, other activities, mainly commercial, services and equipment can also be found. Many of these areas therefore maintain a high population presence also during working hours (morning and afternoon).

Temporal profiles according to large types of land use and their behavior during the weeks of the pandemic are very different from the reference week (Figures 4). In week W0, the departure of the population from residential areas does not compensate for arrivals. The areas of activity show an opposite profile, with very important gains in the morning and falling during the afternoon. The mixed areas have an intermediate situation. However, during the pandemic, the three curves have tended to flatten significantly. Data also show the evolution of the different phases.

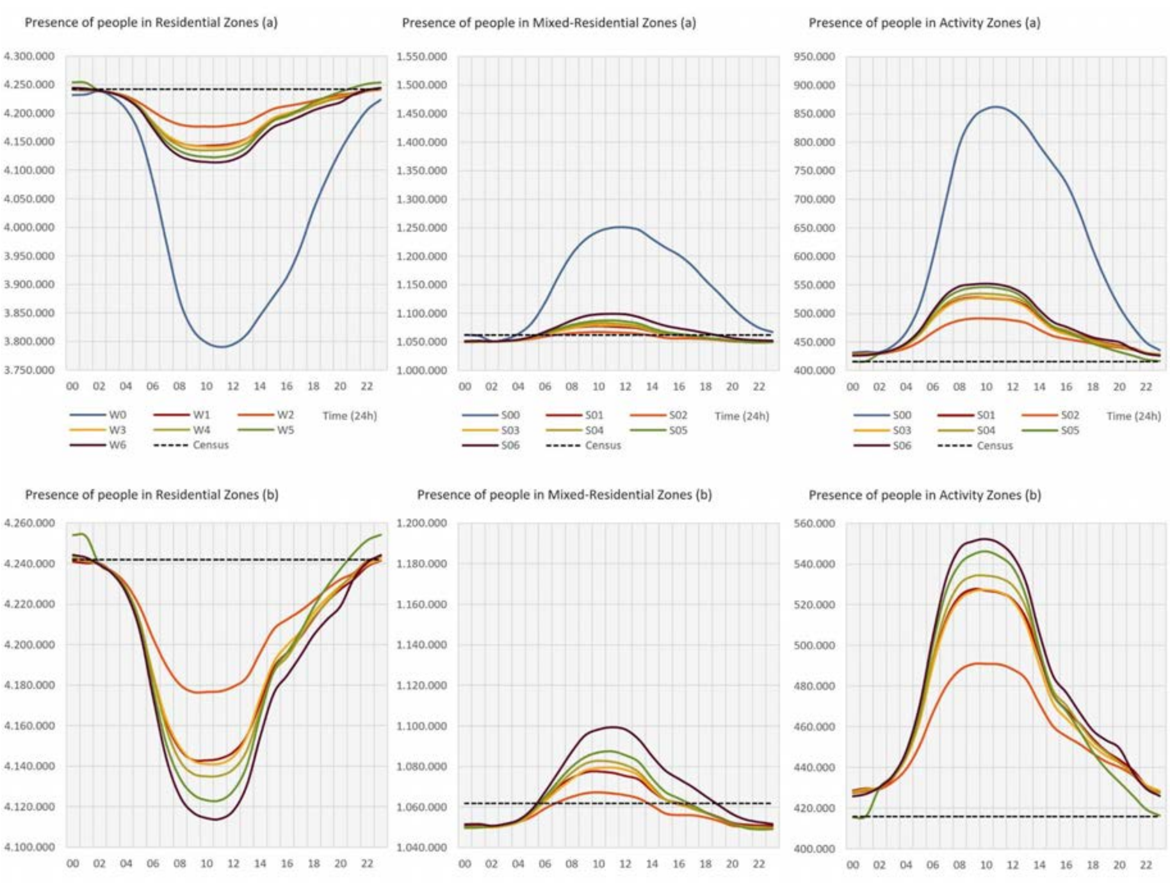

Figure 4: Population distribution profiles throughout the day during the study weeks (W1-W6), including the reference week W0 (a) and without it (b).

The temporal distribution of the population in the activity areas shows different profiles and different behaviors during the study weeks according to the characteristics of their activity (Figure 5). For instance, during the reference week (W0), the curves of office or industrial activities are very similar, however their behavior is different during the pandemic.
Office workers have been able to implement teleworking to a greater extent, so that the presence of the population in these spaces has been reduced very significantly, to the point of practically flattening the profiles.

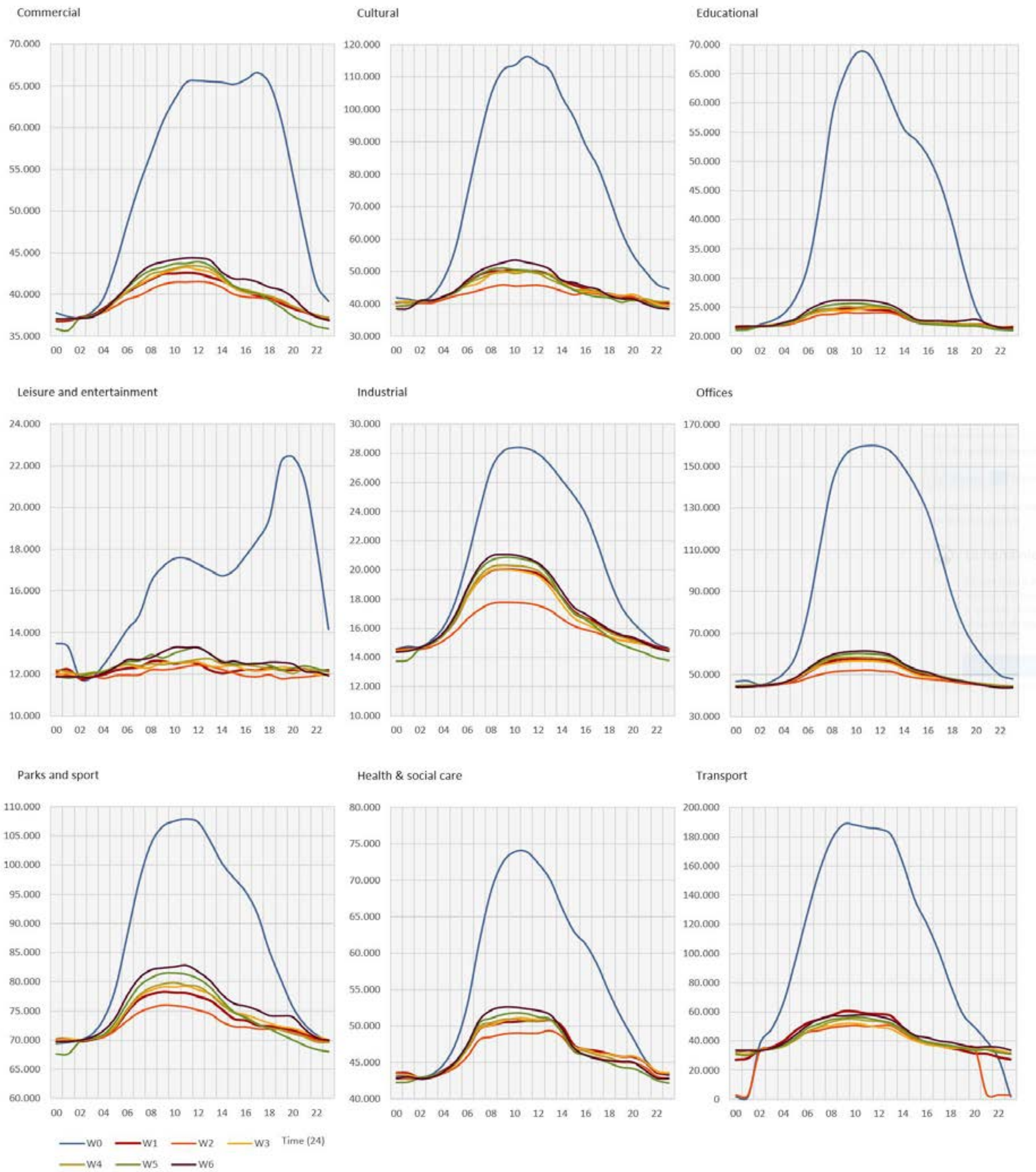

Figure 5: Population distribution throughout the day in the different activity areas during the study weeks (W0-W6).

4.CONCLUSIONS

The first visual analysis allowed us to explore the variation in population in the different urban areas throughout the day, comparing the reference week prior to the lockdown (W0) with that with the greatest restrictions on mobility (W2), showing very significant changes.

The second analysis, based on the study of bivariate correlations of population distributions between large time slots, allowed us to obtain a numerical indicator to globally compare the impact of the lockdown measures in the different study weeks. The city of Madrid presents a high mix of land use, so that even in a reference week (W0) the correlations between the strips are very high. However, while in week W0 the correlations between morning and night decreased, due to the differences between residential and activity spaces, correlations were practically 1 during the lockdown, showing a similar distribution of the population in all time bands at night. The mapping of the residuals of these correlations showed that the few active zones during the morning hours were mainly logistics and industrial areas (positive residues).

In addition, the hourly population distribution profiles for the dominant land use in each zone also showed a radical change with respect to the reference week (W0), especially in the weeks of greatest restrictions (W2). These profiles are simplified, since they consider only the dominant use, when in most areas there are several uses of the land. However, the results explicitly showed the drastic reduction in population in activity spaces in the morning and afternoon, while residential spaces conserve the population in those time bands. All profile curves tended to flatten significantly, but once again the activities related to industry, commerce or health maintained more active profiles, compared to very subdued educational, leisure or office areas.

The different analyses carried out provide helpful information for pandemic management and post-recovery planning. First, they enable us to improve our knowledge of urban dynamics during each of the confinement phases and the degree of restricted mobility of the population. Changes in population density according to mobility restrictions help to assess the level of follow-up of the measures. Second, they help us to determine in which spaces and activities a greater presence of the population is concentrated during the weeks with restrictions and those when the restrictions are lifted. This is of interest to identify the areas of the city, the activities and the population groups associated with them, which remain functional and, consequently, pose a greater risk of virus transmission. In addition, once the restrictions are lifted, these analyses will show the pace of the city's recovery and the different recovery speeds of each urban activity.

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