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Giovanni Fusco

UMR ESPACE, Université Côte d'Azur, CNRS, France

Alessandro Araldi

UMR ESPACE, Université Côte d'Azur, CNRS, France

David Emsellem

Kinaxia, Septeo Group, France

Denis Overall

Kinaxia, Septeo Group, France

Taxonomy of contemporary urban forms in France: Towards an Urban Atlas through Multiple Fabric Assessment.

Abstract Bridging southern and northern Europe, France presents very diversified urban landscapes, combining vernacular cores, modernist developments, sprawling suburbia and very specific exurbs. Traditional urban and rural landscapes were different among French cultural regions, whereas more recent ones are apparently more homogeneous throughout the country. Research in urban morphology and heritage conservation produced considerable knowledge of French traditional urban forms. On the contrary, attention to more recent forms and non-residential areas, as well as to their contribution to contemporary French cityscapes is more recent. The identification and characterization of France's urban fabrics and morphological regionalization of French cities remained for long a complex task, traditionally based on in-depth assessments, restricted to specific historical, geographical and cultural contexts. Recent advancements in morphometric analysis propose innovative computer-aided protocols overcoming these limits. Among them, Multiple Fabric Assessment is a Bayesian streetscape-based urban morphometric protocol for morphological regionalization. First presented at ISUF2017, MFA has already been applied to several urban areas in different sociocultural contexts and geographical scales. MFA has been further developed and upscaled to analyse and compare wider study areas. The paper presents its implementation for four metropolitan areas of France, around the cities of Lyon, Marseille-Aix-en-Provence, Lille-Roubaix-Tourcoing, and Nice-Cannes-Antibes, allowing a multiscale comparative analysis of French urban forms. A shared taxonomy of urban fabric types (morphotypes) for the different case studies is proposed. The outcome of these analyses is a first contribution to a national atlas of morphologically regionalized metropolitan areas.

Keywords Urban Morphometrics, Streetscape, Urban Fabric, Morphotypes, Multiple Fabric Assessment, France

1. Introduction

Bridging Southern and Northern Europe, France is known for its very diversified urban landscapes, combining vernacular cores, modernist developments, sprawling suburbia and very specific exurbs. Traditional urban and rural landscapes were different among French cultural regions, as studied by the long tradition of regional geography research after Vidal de La Blache in the first half of the 20th century, whereas more recent ones are apparently more homogeneous throughout the country. Wiel (1999) can thus highlight the similar patterns in the formation of suburban landscapes across France, with the proliferation of subdivisions of detached houses and big-box retail concentrations. Research in urban morphology, urban history and heritage conservation produced considerable knowledge of French traditional urban forms (Castex et al. 1980, Borie et Denieul 1982, Bonillo et al. 1988, Cléménçon 2015, without forgetting the impressive 49-volume collection of historic atlases of French cities for which Jean-Courret and Lavaud 2013 offer an overview). On the contrary, attention to more recent forms and non-residential areas, to their perception from public space and their contribution to contemporary French cityscapes is more recent.

The identification and characterization of France's urban fabrics and morphological regionalization of French cities remained for long a complex task, traditionally based on in-depth but qualitative assessments, and restricted to specific, mainly historical, geographical and cultural contexts. Recent advancements in urban morphometric analysis propose innovative computer-aided protocols to analyse different aspects of urban form which could be used to regionalize urban space (Hillier 1996, Gil et al. 2012, Berghauser Pont et al. 2019, Fleischmann et al. 2021 etc.). Among them, Multiple Fabric Assessment (MFA, Araldi and Fusco 2019) is a computer-aided streetscape-

based urban morphometric protocol for morphological regionalization. First presented at ISUF 2017, MFA has already been applied to several urban areas in different sociocultural contexts and geographical scales (Fusco and Araldi 2017, Perez et al. 2019, Guyot et al. 2020, Fusco et al. 2021, Erin and Cubukcu 2022). Based upon these experiences, MFA has been further developed and upscaled to analyse and compare even wider study areas. This paper presents its implementation for French large metropolitan areas, allowing a multiscale comparative analysis of contemporary urban forms in France.

In the next section we will highlight the most important methodological aspects of MFA. The following section will present and map the results obtained by the application of the MFA protocol to several metropolitan areas in France: Lyon, Marseille-Aix-en-Provence, Lille-Roubaix-Tourcoing and the French Riviera. We will also show how to arrive at a general taxonomy of urban fabrics in France by comparing the results obtained for the different case studies. The final section will conclude the paper and highlight how the outcomes of the analyses are a first contribution to a national atlas of morphologically regionalized metropolitan areas.

2. Background

Identifying and describing urban fabrics

The urban fabric is the finest scale of analysis of urban form, considering the morphological composition of coherent urban fragments, generally a few blocks or interconnected streets. The form of the urban fabric is at the core of the analyses carried out by the classical schools of urban morphology. The Italian school, after Muratori (1959) and Caniggia and Maffei (1979), highlighted the contribution of building types and their historical evolution to the formation of the urban fabric. The centrality of the street in the organisation of the urban fabric is also an important contribution of the Italian school. The British school, after Conzen (1960, 2004), defined other important aspects of the morphological process (like the burgage cycle). Less concerned by the contribution of urban morphology to the architectural project, it set out the most ambitious goal of regionalizing urban space in terms of observable forms of the urban fabric (Larkham and Morton 2011). The French school, after Castex et al. (1980), Borie et Denieul (1982), like the Italian school, was particularly attentive to the contribution of morphological analysis to the architectural project and to heritage conservation policies. Its most original contribution was the study of plot patterns in the morphological process. The traditional analytical approach of all the schools of urban morphology follows several common steps. First, the components of the urban fabric are identified: streets, buildings and plots. In this phase, the Italian school is particularly attentive to the typomorphological nexus: building types must be known beforehand in order to understand their contribution to the assemblage of the urban fabric. The British school also integrates land use as an additional factor of the urban fabric. Next, the analyst produces a geometrical description of the components of the urban fabric (ex. shape and size of the plots and building types, width, length, and tortuosity of the streets, etc.). The compositional relations of the urban fabric are then analysed: are buildings facing the street? Are their façades parallel to the street? What setbacks separate the buildings from the street? Are buildings adjoining each other? Do streets cross or do they connect with T-junctions? Through the identification of typical compositional relations, specific types of the urban fabric, i.e. morphotypes, can be defined. Morphotypes are an important manifestation and a constitutive aspect of the material culture of cities at a given time of their history. These different analytical phases are traditionally carried out within a manual, expert-based procedure on a small part of the urban space and with a focus on the historical parts of the city. Indeed, urban morphology also studies the historic process behind the observed forms, i.e. the morphological processes of first development and subsequent adaptive or transformative developments resulting in the observed morphotypes. Once again, the study of the morphological processes is generally carried out for the historical neighbourhoods.

Computer-aided morphometric protocols: the Multiple Fabric Assessment protocol.

Among the several computer-aided morphometric protocols cited in the introduction, Multiple Fabric Assessment (Araldi and Fusco 2019) is the one which is most in line with the analysis of the urban fabric as proposed by the classical schools of urban morphology. Unlike Space Syntax (Hillier 2006) or Multiple Centrality Assessment (Porta et al. 2006) it is not a configurational analysis of the centrality properties of the elements of the street-network. The concept of the urban fabric lies at the core of MFA and results from a geometrical and compositional description of the built fabric, of the plot fabric and of the street network, taking into consideration the contribution of the building types. Unlike Ye and Van Ness (2014) or Berghauer Pont and Marcus (2015), MFA avoids including configurational properties in the description of the urban fabric.

At the same time, MFA was developed around a few salient specificities, in an effort to bridge the tradition of urban fabric analysis by urban morphology with the tradition of the streetscapes perceived by pedestrians walking on the street network (Lynch 1960, Harvey and Aultman-Hall 2016). As with most computer-aided morphometric protocols, the basic inputs of MFA are a vector-based database of plots, buildings, and streets, including building

heights and specialisation (LOD0+ of the CityGML data model in Biljecki et al. 2016). The most developed versions of OSM in many countries provide such a database), and a digital terrain model of the study area. Its main methodological specificities are the following (Araldi and Fusco 2019):

- MFA uses morphometric descriptors of the urban fabric as perceived by pedestrians walking on the street. Its basic elements are descriptors of the skeletal streetscapes (Harvey and Aultman-Hall 2016) in proximity bands around each street segment, the latter being a computational operationalization of Caniggia's pertinent band of the street. Examples of such descriptors are the average height of the buildings around the street, the average height-width ratio, the percentage of building façades parallel to the street edge within a 15 m proximity band, the building and plot frequency along the street, the average built-up coverage in the 50 m proximity band, etc.
- MFA uses a limited number of theory-driven morphometric descriptors, describing the buildings, the plots, the street network, the site, and the mutual relations among these components of the urban fabric (in the present research, 33 morphometric descriptors were used (Table 1).
- Network-based geostatistical analysis is used to identify significant spatial patterns for each morphometric descriptor (ILINCS, Yamada and Thill 2010): MFA introduces spatial structure before looking for morphotypes and, according to the paradigm of the pedestrian walking on the street network, it looks for statistically significant patterns of interconnected street segments consistently showing the same morphometric values for a given descriptor. Another important aspect of this geostatistical phase is its place-specific character: lower or higher values of a given morphometric parameter are evaluated with respect to the distribution within the study area.
- MFA finally uses Bayesian multivariate clustering of spatial patterns to identify morphotypes: it is the co-occurrence of the previously identified spatial patterns that defines typical forms of the urban fabric. Bayesian artificial intelligence is particularly fit for this task because it allows detecting morphotypes which share a few key characteristics, allowing for some diversity in other less important descriptors (and the key characteristics vary from one morphotype to the other). It also has the advantage of using the probabilistic framework of Bayesian reasoning, producing probabilities that a morphotype has a specific property, or that a street segment belongs to different morphotypes, given the observed data.

Multiple Fabric Assessment: latest improvements

Within the present research, several important improvements were made to the original MFA protocol. The goal was both more precision to extract the most morphological content from the available databases, more robustness and scalability of the calculus to analyse larger study areas, and finally a protocol allowing for the comparison of results from different study areas. The new protocol was conceived to be applied to each of the 101 departments of France. Except for the Paris region, where 8 departments must be merged to cover the huge metropolitan area of the capital city, departments are practical and appropriate study areas for urbanisation in France. Established since the French Revolution, they were hardly modified over more than two centuries, have comparable spatial extent (between 3,000 and 10,000 square km outside of the Paris region) and were defined around a main city that serves as department capital. Some departments roughly correspond to metropolitan areas; others, in more rural regions, contain several small cities that are not connected within a functional area (as defined, for example, by journey to work trips). However, geography of metropolitan and functional areas is evolving considerably over the years (Aguilera et al. 2005), at a pace which is not comparable to the morphological processes which produced the different observed morphotypes. The whole of France is covered by an official vector database of metric precision (BD TOPO by the National Institute of Geographic and Forest Information, IGN 2020), which is also structured at the Department level.

This specific research context motivated the following improvements to the MFA protocol:

- In order to improve the geometric description of streetscapes, morphometric descriptors are now calculated through perpendicular and tangent sightlines on the street segment every 3 m, increasing the focus on pedestrian visibility of elements within the proximity bands.
- A building typology was produced for ordinary buildings in the whole of France before morphotype detection through MFA (Araldi et al. 2022). The same model of Bayesian AI was used on a limited number of morphometric descriptors of the building hulls (footprint surface, elongation, convexity, number of floors, number of adjoining neighbours and number of dwellings). Sixteen basic types were thus identified among the 28.8 million ordinary buildings (Figure 1). The remaining 10.5 million specialised buildings were considered as an additional category for MFA, but no specific typology was proposed for them.
- Gaussian mixture models (Duda et al. 1973) are used to identify low, intermediary, and high values for each morphometric descriptor in each study area. Geostatistical patterns of homogeneously intermediary values are thus added (in addition to significant patterns of low and high values, and heterogeneous patterns) to differentiate them from areas where the same overall average values derive from heterogeneous combinations of locally high, low, and intermediary values. This improvement still preserves and strengthens the place-specific character of the morphological patterns identified in each study area.

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- A new specific Bayesian clustering algorithm has been developed for the MFA: INBIAC (Iterative Naive Bayesian Inference Agglomerative Clustering, Araldi et al. 2022). The efficiency of the new algorithm allows the production of 1100 models for each French department (exploring the 10 to 20 clusters solutions with 100 models each). The log-likelihood parameter allows selecting a very limited number of best models (normally 4 to 6) in each study area, with a different number of clusters.

- Urban fragments which are always in the same clusters in these best models become kernels that constitute the starting point of a final hierarchical clustering algorithm (HCA). The latter is performed on a distance matrix between the kernels using the Gower dissimilarity measure and weighing each kernel by the number of street segments it represents. The final result is a nested taxonomy of morphotypes for each study area. For each study area, the final result is thus the combination of the 4-6 best models selected over 1100 models produced by the INBIAC algorithm. Each set of morphotypes are specific to a given French department.

The sophistication of the morphometrics, geostatistical analysis, Bayesian clustering and hierarchical clustering is necessary in order to obtain meaningful results at the different stages of the MFA protocol. In the next section, the new MFA protocol will be applied to four French departments using version 3.0 of BD TOPO (IGN 2020): Nord (ID 59), in northern France, Rhône (ID 69) in central France, Bouches-du-Rhône (ID 13) and Alpes-Maritimes (ID 06), both on the Mediterranean coast.

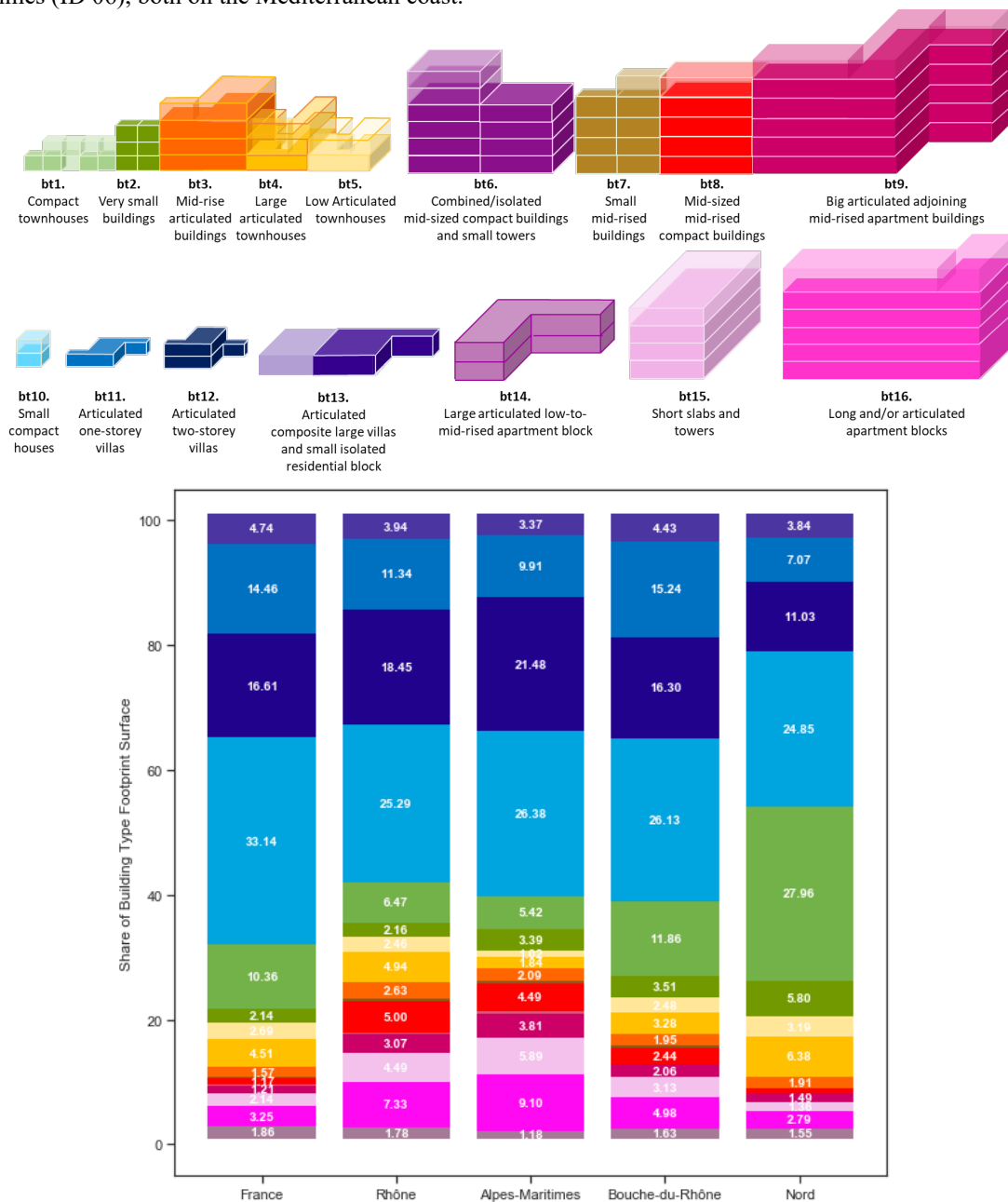


Figure 1. Typology of ordinary buildings in France and shares of the types in France and in the study areas.

Table 1. The streetscape morphometric indicators used by MFA protocols applied to the departments of France

Urban Form	Indicator Name	UM	Range
Street	ST-Street Tortuosity	[-]	[0: +∞)
	SL-Street Length	[m]	[3: +∞)
	N1-Nodes degree 1	%	[0, 0.5]
	N4-Nodes degree 4	%	[0, 0.5, 1]
	N35-Nodes degree 3,5+	%	[0, 0.5, 1]
Street-Plot Relationship	PF-Plot Frequency	[-]	[0: +∞)
	PD-Plot Depth	[m]	[0:50]
Street-Building Relationship	OS-Open Space	Value	[0:50]
	SB-Set Back	Value	[0:50]
	H-Building Height	[m]	[0: +∞)
	HW-Height-Width Ratio	[-]	(0: +∞)
	PF-Relative Parallel Façades (10m)	%	[0:1]
	CR-Coverage Ratio (50m)	%	[0:1]
	BF- Building Frequency	[-]	[0: +∞)
	SV- Street View depth (bidirectional up to 300m)	[m]	[0:600]
Building types	BT _n -Building Type <i>n</i> (<i>n</i> =[1:16]) Prevalence(50m)	%	[0:1]
	BTs-Specialised Building Type Prevalence(50m)	%	[0:1]
Street-Site morphology	SA-Street Acclivity	%	[0:1]

Multiple Fabric Assessment at different scales: from place-specific to national morphotypes

The place-specific approach was essential in the geostatistical analysis and in the determination of the local morphotypes. Nonetheless, it also prevents a quantitative comparative analysis between the diverse morphotypes obtained from different urban regions. Thus, a further methodological step has been specifically developed, with the goal of converging and comparing MFA outcomes from different study areas.

The statistical distributions of the original 33 morphometric indicators are used to study the similarity/dissimilarity among the morphotypes of different urban areas. To achieve this goal, we discretize the statistical distributions of the indicators of each morphotype over the ranges of the *n* quantiles (with *n* varying between 2 and 30) obtained from the cumulative distribution of the four study areas. Not all indicators are discretized in the same way and with the same number of intervals: indeed, the number and dimension of the intervals depend both on the nature (continuous/categorical) and on the statistical distribution (strong skewness and/or bimodality) of each indicator. Thus, specific intervals for each statistical distribution of each morphological indicator are obtained.

Afterwards, a dissimilarity matrix between place-specific morphotypes is calculated through the Gower distance by weighting each interval of each indicator by the frequency of appearance over the set of study areas. This specific matrix of weights offers two main advantages. Firstly, it allows to equally assess all indicators (and not proportionally to the number of intervals); regardless of the number of the chosen intervals, each indicator assumes a unit value when calculating the distance matrix between different urban fabrics. Secondly, and more important, for each morphometric descriptor, intervals that are relatively rare count less than those which are more frequent in the overall study areas, and thus giving more importance to the most informative content of each indicator. On the dissimilarity matrix obtained, we apply, here again, a hierarchical agglomerative clustering (HAC) algorithm (using centroid-linkage agglomerative principle among clusters). As for the HAC performed for each study area, we weigh each place-specific morphotype by the number of street segments it represents. Thus, we identify four different levels of aggregation from the highest depth values of the resulting HAC dendrogram. Performing a second hierarchical clustering of place-specific morphotypes produces a shared nested taxonomy of general morphotypes for all the study areas (and in the future for the whole of France), thus making morphotypes comparable across study areas at larger scales while still preserving the local specificities of the urban form.

A final point should be highlighted: an essential aspect differentiates between the MFA clustering producing the place-specific morphotypes and the clustering at the origin of the overall morphotype taxonomy. The first one is a clustering of street-constrained spatial patterns of streetscape morphometric descriptors. It integrates the spatial dimension because an urban fabric is by definition an assemblage of connected streetscapes sharing common properties. The second one is a clustering of the statistical distribution of the morphometric descriptors within each morphotype. That is to say, the spatial arrangement of morphotypes is not considered in the resulting taxonomy; but as we are combining characteristics of place-specific morphotypes, we know that these already define patterns in space. At the same time, two morphotypes of two different regions with a very high similarity value, might be differently located within their relative metropolitan context.

3. Results: Contemporary Urban forms in French Metropolitan Areas

The four French departments analysed through MFA correspond to the four most important metropolitan areas of France, after Paris: Lyon (Rhône), Marseille-Aix-en-Provence (Bouches-du-Rhône), Lille-Roubaix-Tourcoing (Nord) and Nice-Cannes-Antibes (Alpes-Maritimes), respectively. The metropolisation process during the last decades has produced massive urban expansion, in the form of big housing projects until the 1970s and later in more sprawled suburban subdivisions. Peripheral old villages and rural areas have also been integrated in the urban growth around the metropolitan centres, resulting in village expansion and ex-urban scattered housing in rural and natural areas. A wave of new massive urban projects in the metropolitan centres has also characterised the last three decades, the most remarkable being Confluence in Lyon, Euroméditerranée in Marseille, and Lille-Europe in Lille.

We will remark that the urban fabrics in the metropolitan areas of Nice-Cannes-Antibes, i.e. the French Riviera, and Marseille-Aix-en-Provence were previously studied with the old version of the MFA protocol (Fusco and Araldi 2017, Fusco et al. 2021). This allowed us to assess the better performance of the new version of the protocol, both in terms of morphotype detection and characterization.

Before applying MFA to identify urban fabric morphotypes, the shares of the different building types in the four departments should be taken into account (Figure 1). The Nord department is thus characterised by a much larger share of townhouses (bt1) with 28% of the total footprint surface of ordinary buildings. In Bouches-du-Rhône the share of townhouses is slightly more than the national average, at around 10%, while in Rhône and Alpes-Maritimes, it is roughly half of the national average. The share of compact houses (bt10) is particularly important in the four study areas, at roughly a quarter of the whole building stock, even if less than the national average. Villas and large articulated houses, whether 1-storey (bt11) or 2-storey (bt12) are less important in Nord, than in the other three departments, just like isolated longitudinal buildings (bt15 and bt16). Large and very large adjoining buildings (bt8 and bt9, respectively) are particularly important in Alpes-Maritimes, and underrepresented in Nord. Conversely, very small adjoining buildings (bt2) make up 5.8 % of ordinary buildings in Nord, but only 2.16% in Rhône. These proportions being calculated on the stock of ordinary buildings, the share of specialised types must also be considered. This is the lowest in the more tourism-oriented French Riviera (less than 30%) and much more important in Rhône and Nord (more than 43% in each of them). Of course, the morphometric indicators used in MFA are not these overall values at the department level, but the local share of the different building types in the 50-metre proximity band around each street segment. The department-wide statistics are nevertheless useful to understand the patterns of low, average and high values in the different study areas.

Next, geostatistical analysis allows us to identify and characterise two specific subspaces in each study area, using two key morphological descriptors: built-up coverage and prevalence of specialised buildings. The first is undeveloped space (US), whether natural or agricultural, without statistically significant presence of buildings. It normally lies beyond the limits of the urbanised areas, and exceptionally within it, as in the case of vast urban parks. MFA is not conceived to characterise further categories of this empty space (in terms of buildings, of course, not of functions or vegetation) and we will exclude it altogether from the analysis. The second is specialised space (SS), whether industrial, commercial, logistical (ports, airports, logistics centres) or service-oriented (university campuses, business districts). This space is characterised by statistically significant high prevalence of specialised buildings (even if a few ordinary buildings can be present within it), is an important constituent of the metropolitan areas, with different possible locations, and can be characterised as a distinct morphotype (in order to identify more specific specialised morphotypes a typological analysis of specialised buildings should be carried out).

We can now apply the MFA protocol proper to all the street segments outside of these two subspaces within each of the four metropolitan departments. Highways for motorised traffic giving no direct access to built-up plots were also excluded from MFA calculus. In each case, MFA identified around 20 morphotypes. For the Rhône department, the INBIAC algorithm identified 6 best models with 11, 12, 13, 15, 18 and 19 clusters, respectively. The subsequent hierarchical clustering found a relevant 19-cluster solution which, together with the specialised class, results in 20 morphotypes. For the Nord department, too, INBIAC identified 6 best models (12, 13, 14, 16, 18 and 19 clusters) and hierarchical clustering combined them in an optimal 21-cluster solution. Considering the additional specialised class, 22 morphotypes were finally identified. For Bouches-du-Rhône, the INBIAC best models are only 4 (12, 14, 16 and 18 clusters, respectively), combined in a 18-cluster solution by the hierarchical clustering, hence 19 morphotypes when adding the specialised fabrics. Finally, for Alpes-Maritimes, the INBIAC best models were 5 (11, 12, 14, 16 and 18 clusters), combined in a 19-cluster solution by the HAC and resulting in 20 morphotypes, once the specialised class is accounted for.

The maps in Figures 3, 4, 5 and 6, centred around the main cities of each department, project in space the morphotypes found in each case study. The colour-codes used in these maps were carefully chosen, in order to convey the similarities found in the characterization of the different morphotypes. The maps also show the

capacity of the projected morphotypes to regionalize these important French urban agglomerations morphologically according to the characteristics of their urban fabrics. Figure 7 provides the share of morphotypes for each study area, measured in terms of both street length and number of street segments.

The characterization of the morphotypes is done through the analysis of their probabilistic profiles in terms of the associated spatial patterns of morphometric indicators, as always in MFA (see Fusco and Araldi 2017, Araldi and Fusco 2019). Rather than presenting the MFA results of each urban area individually (which might result in a long juxtaposition of four individual idiosyncratic descriptions), we use the morphotype taxonomy produced by the final HAC to focus and discuss about meaningful similarities and dissimilarities between the urban forms of the four study areas. The graph in Figure 2 will guide us in this task: it provides a synthetical representation of the dendrogram generated by the final HAC, where only the 4 most significant levels are represented (corresponding to the four highest distances between subsequent clusters of the original dendrogram). They correspond to 42-, 19- and 9- group partitions and to a very broad 4-group partition assembling the overall morphotypes in 4 sectors within the circular diagram. This graph plots the hierarchical relationships between the morphotypes: on the outer circle we find the 77 original urban fabrics of the 4 departments. Proceeding toward the centre, the morphotypes are gathered until the complete amalgamation. Morphotypes with higher similarity are assembled at the first steps (toward the periphery of the graph). Conversely, morphotypes, and aggregations thereof, with lower similarity, thus standing out for their distinctive features, are merged at the final section of the hierarchy (toward the centre of the graph).

The first and largest sector of aggregated morphotypes into the 4-group partition gathers all the low-density areas. At the 9-group level, a first major distinction is operated between, on the one side, extremely low-density rural and undeveloped space (both having their own category at the 19-level partition), and, on the other, the forms of residential sprawl around the urban cores. The latter is further divided into four main families of morphotypes at the 19-group level. These are, from left to right in Figure 2: i) heterogeneous urban subdivisions of houses and expansions of faubourg; ii) heterogeneous fabrics of suburban fringes; iii) suburban/ex-urban fabrics of scattered houses or villas; iv) homogeneous suburban subdivision of houses and villas. Each one of the 4- and 9- level groups presented so far is made up of morphotypes from all the four departments, supporting the hypothesis of a very standardised suburban landscape in France.

A second sector of the 4-group partition gathers denser and more heterogeneous fabrics. Three components can be outlined at the 9-group level: i) dense heterogeneous faubourgs, and historical centres from the four departments; ii) mid-density alignment of houses, and low-density heterogeneous centres/hamlets, from the Nord and Rhône departments together with modernised urban fabrics combining townhouses with more recent apartment buildings (this last, combining morphotypes from the Bouche-du-Rhône and Nord departments); iii) one specific morphotype of townhouses over a gridded street layout which is very specific to the Bouche-du-Rhône department.

Modernist discontinuous morphotypes converge in a third specific sector of the 4-group partition which doesn't even split at the 9-group level, highlighting the outstanding specificity of the purest modernist morphotypes, present in all the study areas.

A final sector of the 4-group partition covers dense, compact, grid-based fabrics with more or less homogeneity of building types. Here, already the 9-group partition splits this coarse aggregation in 4 different groups, some of them specific to just one or two departments. The grid-based compact city is thus much more place-specific in its observed forms and will be the starting point of the following detailed presentation.

The morphotypes of the grid-based compact city

These morphotypes correspond to the last sector of the 4-group partition of the diagram in Figure 2. Among them, we can identify and characterise the morphotype of the classical compact grid-based urban fabric both in the Rhône and in the Alpes-Maritimes departments. In this overall morphotype, street segments have a very high probability of showing high street frontages, average height-width ratios, small or no setbacks, high façades parallelism in the first 10 metres from street edge and high building coverage in the first 50 metres.

Most buildings are mid-rise, mid-sized adjoining ones (bt8), but bigger and smaller adjoining buildings (bt9 and bt7), as well as specialised ones, are also present. The street system is a relatively regular orthogonal grid. Even if the probabilities and the morphological thresholds are not exactly the same in the two study areas, the same morphological characterization can be given to the two local morphotypes R19 (Rhône 19) and AM18 (Alpes-Maritimes 18): it is the urban fabric of the classical city, planned in the cities of Lyon and Nice during the XVIII and XIX centuries, namely the Perrache and Morand plans in Lyon (Rau 2013) and the Regulatory Plans by the Consiglio d'Ornato in Nice, as well as the neighbourhood plans of the end of the XIX century inspired by the tradition of Consiglio d'Ornato (Graff 2000). Relatively vast morphological regions delineated by this morphotype can thus be found in the central areas of Lyon and Nice. A smaller area of the classical city fabric also exists in the central area of Cannes, on the French Riviera. Cities in the Nord and Bouches-du-Rhône departments don't possess this morphotype.

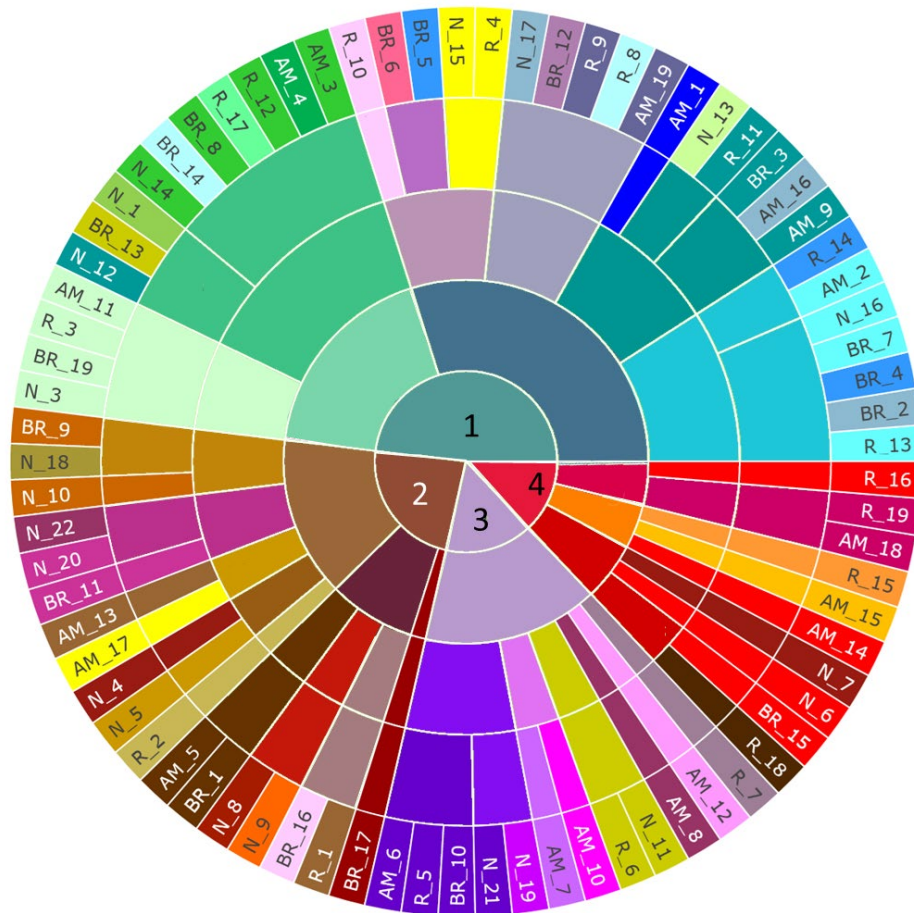


Figure 2. Five nested levels of aggregation (42,19,9 and 4 groups) of the overall morphotype taxonomy. The starting points are the 77 place-specific morphotypes.

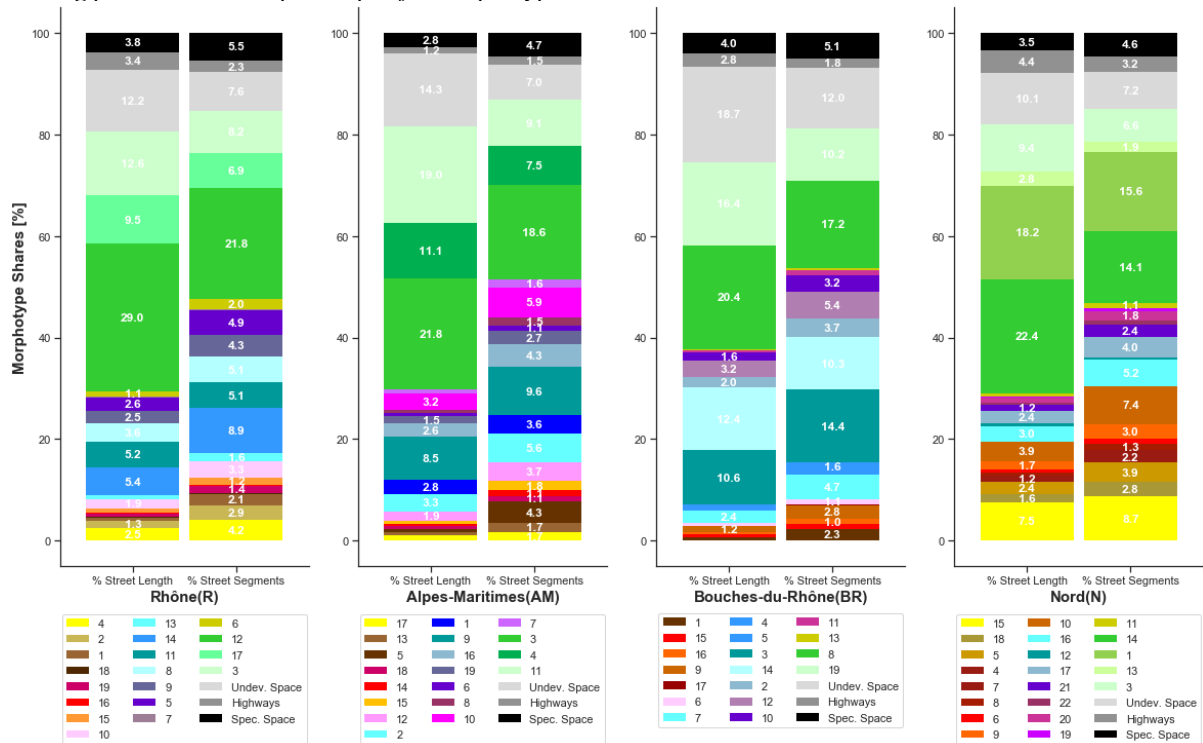


Figure 3. Place-specific morphotypes and their shares in the four departments (Rhône, Alpes-Maritimes, Bouches-du-Rhône, Nord) expressed in terms of % of street length and % of street segments.

A more heterogeneous grid-based urban fabric of aligned adjoining buildings can indeed be found in the main cities of all four departments. The urban extensions in Marseille, Aix-en-Provence (BR15) and Lille (N6), originally planned in the 17th and 18th centuries, underwent important adaptations and building replacements and differ considerably from the classical city fabric. These morphotypes converge with two more specific ones. In the Rhône department, it is a specific morphotype of highly compact, irregular-grid-based and vertical old city fabric, which can be found in Lyon (R18), both in its vernacular form (the old city on the west bank of the Saone River) and in its 18th-19th century version (the Croix-Rousse and Guillotière neighbourhoods). The homogeneity of adjoining collective building types (bt2, bt7, bt8) makes up for some irregularities in the street grid and distinguishes this place-specific morphotype from those found in the next section. In the Nord department, it is a specific modernised and densified old city fabric (N7), characterising the oldest core of Lille's city-centre. Morphological transformation of the old city started with the opening of break-through routes in Hausmann's style in the second half of the 19th century and continued after the destructions of WWI.

Other heterogeneous grid-based forms of the compact city are found in Lyon (R16) and on the French Riviera in Nice, Antibes and Cannes (AM14). These morphotypes are located in semi-central areas beyond the planned compact city of the 19th century. Like with BR15 and N6, many more building types make up the observed urban fabric, the grids are less regular, plot and building frequencies along the street increase (because of the presence of smaller buildings). The overall compactness of the street frontages and coverage of the proximity bands are comparable to what can be observed in the classical city in BR15 and N6, and somehow lower in R16 and AM14 fabrics. The latter are often surrounded by further areas of densified continuous/discontinuous grid-based urban fabrics (AM15, R15). Once again, the probabilities and the morphometric thresholds vary among the four departments, as well as the exact building type composition of this morphotype, reflecting some cultural specificities (for example the presence of townhouses in the northern cities).

The morphotypes of the irregular and heterogeneous compact city

These morphotypes are assembled in sector 2 of the 4-group partition of Figure 2 and constitute alternative forms of the compact city. Vernacular fabrics of old cities and villages, and faubourg fabric can be found, with slightly different characteristics, in all four departments, as well as, with the exception of Bouches-du-Rhône, discontinuous expansions of faubourgs and hamlets. We already presented the very specific and relatively homogeneous vernacular compact city of Lyon. Outside of Lyon, the fabrics of the villages in the Rhône department (R1) are similar to those of the urban faubourg, with continuous street frontages of lower buildings. In Alpes-Maritimes, the old city of Nice could not be identified as a specific morphotype because, although just as vertical as Lyon's old city (in both cases small compact buildings with 4-5 floors are prevalent), it shares many other morphometric characteristics with the lower-rise villages and old city centres of the French Riviera (AM5): very dense and compact street frontages and plot coverage, organic street network, very high plot and building frequency, extremely low open space between the street frontages, etc. Indeed, three mediaeval bastide towns (Valbonne, Vallauris and Mouans-Sartoux) as well as the reconstructed village of Roquebillière in the alpine hinterland, share the same morphotype, despite being built on a regular street grid. This morphotype is extremely similar to the one found in the villages and old city centres of Bouches-du-Rhône (BR1), reflecting the same provençal traditional heritage between the eastern section of the French Riviera and the Aix-Marseille region. AM5 and BR1 are thus rapidly aggregated at the 42-group partition.

Both the Nord and the Rhône departments show specific morphotypes of lower density villages and faubourgs (N18, R2), but with some dissimilarities among them, accounting for their aggregation only at the 9-group level. In Bouches-du-Rhône, densified urban subdivisions can also produce heterogeneous forms of the compact city by mixing individual houses and townhouses (BR9). A specific morphotype of compact residential subdivisions of aligned townhouses is to be found in the Nord department (N10) where they are the 20th century version of a much older tradition of working-class townhouses. Despite the different origins, these morphotypes are aggregated, together with heterogeneous fragments with prevalence of townhouses (N18), at the 19-group level.

The original model for fabrics of aligned townhouses in the Nord department dates back to the 19th century and is locally named *corons*. It is a compact fabric with extremely continuous frontages (N9) which is to be found in the pericentral areas of many cities of the Nord department. A somewhat similar morphotype (BR16) also exists in the northern periphery of Marseille, near the port and its traditional industrial districts. These morphotypes contribute to the compact urban fabrics in Nord and Bouches-du-Rhône. However, our analysis reveals that the most similar fabric to the *corons* are the irregularly meshed continuous urban fabric with an important presence of aligned townhouses (N8) which make up much of the city centres in the Nord department.

All together, planned grid-based and unplanned irregular, compact urban fabrics, make up only a small fraction of the contemporary metropolis (less than 5% of street length in all our study areas), characterising the urban cores of the big cities and a constellation of old villages around them. Housing subdivisions and discontinuous fabrics of modernist buildings were gradually developed around these urban cores.

Morphotypes of urban/suburban subdivisions and ex-urban space

Urban and suburban subdivisions are different morphotypes within the large sector 1 in the 4-group partition of Figure 2. The former are generally denser with small houses aligned on the street network, the latter are less dense but also more diverse in their forms. Ex-urban morphotypes are a different group within sector 1 and are definitely the less dense form of residential occupation of space.

Late 19th and early 20th century urban subdivisions of aligned houses on irregularly meshed networks exist in different morphotypes in all four departments. The purest form of subdivisions of independent houses are found in the Rhône and Bouches-du-Rhône departments (R10 and BR6, respectively). Their morphological regions make up a peripheral halo around the compact cores of Lyon (especially in its eastern periphery). Around Marseille, this morphotype is more concentrated in the north-eastern periphery, where the Montolivet sector constitutes a vast morphological region. An originally similar morphotype exists in the Alpes-Maritimes (AM12), but the initial urban subdivisions underwent adaptation through some building substitutions (mainly modernist isolated small-to-mid-sized buildings). The morphotype is thus presently very specific but ends up being aggregated in the modernist sector at the 4-group level. Here too, however, the corresponding morphological regions make up a first peripheral belt around the compact cores of Nice, Cannes and Antibes, as well as smaller cities of the French Riviera (like Cagnes-sur-Mer and Villefrance-sur-Mer). French Riviera cities also have a densified and more compact version of these urban subdivisions with infilling and substitutions producing a few more continuous street frontages mixing adjoining and isolated types (the already seen AM15) and making a transition between the grid-based compact city and the first peripheral belt.

Suburban fabrics are generally more peripheral and definitely discontinuous. Suburban residential fabrics of homogeneous subdivisions of houses exist in all four departments (AM2, BR7, N16, R13) and are all merged between the two first levels of aggregation, confirming the overall assessment by Wiel (1999): it is a distinctive production of the last five decades, departing from the more traditional urban subdivisions. In the latter, compact lots were sold to households and small developers to build houses aligned on the street edges with a small setback. In the suburban case, the developer homogeneously builds the whole subdivision, often proposing new cultural schemes (in terms of alignment, setback, street network topology, sometimes even building types). Tree-like networks are thus much more frequent in this suburban fabric. This morphotype accounts for around 6% of the total street frontages in all the departments, with the exception of the Rhône, where R13 is more seldom (2%). Here, a suburban residential fabric combining houses and villas (R14), but presenting many of the same characteristics (and, indeed somehow more similar to AM2 on the French Riviera), is much more widespread and accounts for 10.5% of the street segments. This morphotype constitutes much of a second peripheral belt around the city of Lyon. Two other morphotypes are present in the Bouches-du-Rhône with similar suburban characteristics, although more heterogeneous in their composition: subdivisions of partially-aligned houses and 1-storey villas (BR4) and an heterogeneous suburban fringe which often include the presence of some specialised buildings (BR2). They account for 1% and 4.6% of street segments, respectively, reflecting the importance of suburban fabrics in Bouches-du-Rhône.

Taking into consideration the relative share of the different morphotypes is particularly important when characterising the changing landscapes of the metropolitan peripheries. Thus, a morphotype of scattered ex-urban housing, in second and often even third peripheral belts around the urban cores, is present in all four departments (AM9, BR3, N12, R12), even with a few local specificities. For example, it is spatially limited to the hilly and sloped pre-alpine areas in the Alpes-Maritimes, it is particularly heterogeneous in terms of building types in the Bouches-du-Rhône and it is much more fragmented in the Nord. More particularly, the built-up elements are so diluted in the latter, that the HCA merges it with rural morphotypes and not with the three other ex-urban ones. What is more striking, though, is the relative importance of the ex-urban morphotype in the different study areas: almost 18% in Bouches-du-Rhône, 11% in Alpes-Maritimes, 6% in Rhône but less than 1% in Nord. The Mediterranean departments, and more specifically Bouches-du-Rhône, have allowed this extremely sprawled morphotype, whereas it remains an exception in the Nord department.

Modernist morphotypes

Modernist morphotypes correspond roughly to sector 3 in the 4-group partition of Figure 2, although some modernised morphotypes are aggregated in sector 2.

Modernist discontinuous fabrics of isolated big buildings, typical of the housing projects between the 1950s and 1980s, are also to be found in all four departments. Its purest forms, relatively comparable between the four departments, accounts for 5.7% of the street segments in the Rhône department (R5, mainly in and around Lyon), 4% in Bouches-du-Rhône (BR10), 3.6% in Nord (N21 and N19), but only 1.2% in Alpes-Maritimes (AM6). These morphotypes are located in and around all the main cities of the four departments, within their first peripheral belt. In the Nord department, though, two additional relatively modernist morphotypes are identified (N20 and N22), often interspersed with pre-existing fragments of townhouses and other building types. They are more the result of the modernization of fragments of the compact city through infill and building substitution and are thus

accounted for in sector 2 of the 4-group partition. The same is true for BR11 in Bouches-du-Rhône. All four modernistic/modernised morphotypes together account for 6.7% of the street segments of the Nord department. Modernised fabrics in Alpes-Maritimes (AM8) are aggregated with the other modernist morphotypes because they hardly contain fragments of townhouses and little adjoining buildings, unlike in Nord and Bouches-du-Rhône. Moreover, in Alpes-Maritimes, two similar and heterogeneous morphotypes contribute to the discontinuous modernist fabric, compensating the weaker presence of pure modernist forms: AM10 (6.8%), alternating fragments of modern isolated big buildings with fragments of houses in more peripheral areas, and AM7 (1.9%), alternating modern buildings and houses often on the same streets. In Bouches-du-Rhône, morphotype BR12 shows a similar pattern of fragments of houses and groups of modernist buildings, but is geographically and typologically more suburban.

Overall, the importance of modernist fabric is comparable in the four case studies, with the purest forms more important in and around Lyon, and the fragmented ones in the Mediterranean departments.

Specialised and rural morphotypes

All metropolitan areas also show important regions of specialised space (industrial, commercial, logistical or service-oriented). In MFA, their identification is based on geostatistical analysis of specialised types before applying the INBIAC algorithm and are thus not represented in the diagram of Figure 2, although present in the maps in Figures 3-6. The exact geography of these specialised areas is sometimes dictated by the specificities of the urban site (as the presence of the port on the northern shores of the city of Marseille). Much more often we can observe a general pattern of specialised sectors in peripheral belts around the urban cores, interconnected by the highway network. The case of Lyon is remarkable for the massive presence of specialised space, with a clear west-to-east divide, opposing the residential and agricultural west to the more industrial and commercial east.

Morphotypes were also found in the rural space, within the large sector 1 of the 4-group partition in Figure 2. Within them, some specific distinctions are made in the Nord department, where two major rural fabrics with big plots are opposed. The first (N14, 16.6% of the study area in terms of street segments, but considerably more if street length is considered) is characterised by homogeneously scattered buildings and is particularly present in the Hainaut and Haut Pay d'Artois regions (northern and southern regions of North department). The second (N1, 18.3% of the study area) alternates built-up spaces (grouping a few buildings) and open spaces and is particularly present in the Artois and Cambresis rural region (southwestern part). However, the MFA protocol was specifically conceived to distinguish and characterise urban fabrics and a pertinent identification of morphotypes of rural (and natural) landscapes should use different morphometric descriptors. We will just highlight the presence, in all study areas, of an interface of hardly built-up areas between suburban and ex-urban fabrics and the further undeveloped land: AM11, BR19, N3 and R19 are easily identified from the HCA and merged since the 49-group partition.

In order to assess the quality of the results of the present research, we can draw a comparison with results already found for the French Riviera (Fusco and Araldi 2017) and Marseille (Fusco et al. 2021). In both cases, the old version of MFA was applied on slightly different perimeters. The French Riviera metropolitan area as studied in Fusco and Araldi (2017) is only the coastal and peri-coastal band of Alpes-Maritimes (although it accounts for more than 95% of its population). Marseille was analysed both within its municipal boundaries (242 km², much less than the Bouches-du-Rhône department) and a wider defined metropolitan area including the whole of Bouches-du-Rhône and the western section of the neighbouring Var department. Nine morphotypes were identified on the French Riviera, and nine for Marseille (more precisely eight in the city-wide analysis and eight in the metropolitan areas, with two more specific urban fabrics identified for the urban core in the former, and two more specific suburban and ex-urban ones identified in the latter). Compared to the 20 and 19 morphotypes identified in the present research for Alpes-Maritimes and Bouches-du-Rhône, we can assess the capacity of the new version of MFA to identify and characterise much more specific forms of the urban fabric. The more general morphotypes of the previous analyses are generally split in two or three more specific ones by the new algorithms. For one, the traditional urban fabric of adjoining buildings previously identified as being the core of the main cities of the French Riviera, is now much more specifically subdivided in the three morphotypes of the classical compact grid-based urban fabric (AM18), of the more heterogeneous compact grid-based urban fabric (AM14) and even, in the more peripheral areas, of the fabric of densified urban subdivision of houses (AM15), with frequent fragments of more compact urban frontages. Even within the old constrained historic urban fabrics, a distinction is now made between the old villages and city-centres (AM5) and the faubourgs (AM13). In the Bouches-du-Rhône department, faubourgs and old villages are still grouped within the same morphotype (BR1), but they were previously undistinguished within the broader category of the compact, continuous urban fabric. Sometimes new morphotypes are also found as intermediate forms at the margin of two broader ones, like the modernised fabrics with aligned buildings (AM8, BR11), which have intermediate characteristics between the compact city and the modernist one.

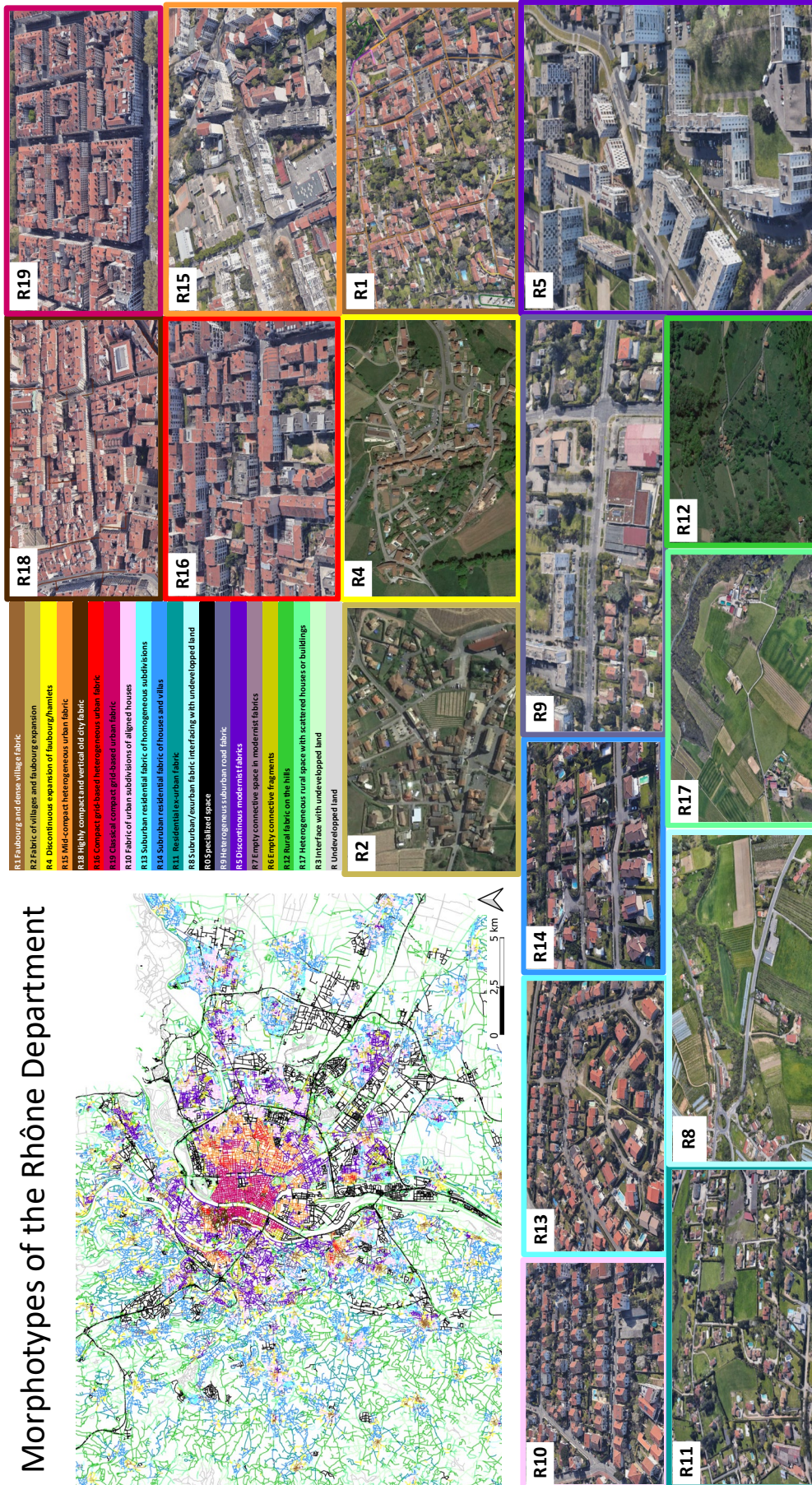


Figure 4. Projection in the geographical space of the MFA results in the Rhône department, centred on Lyon metropolitan region.

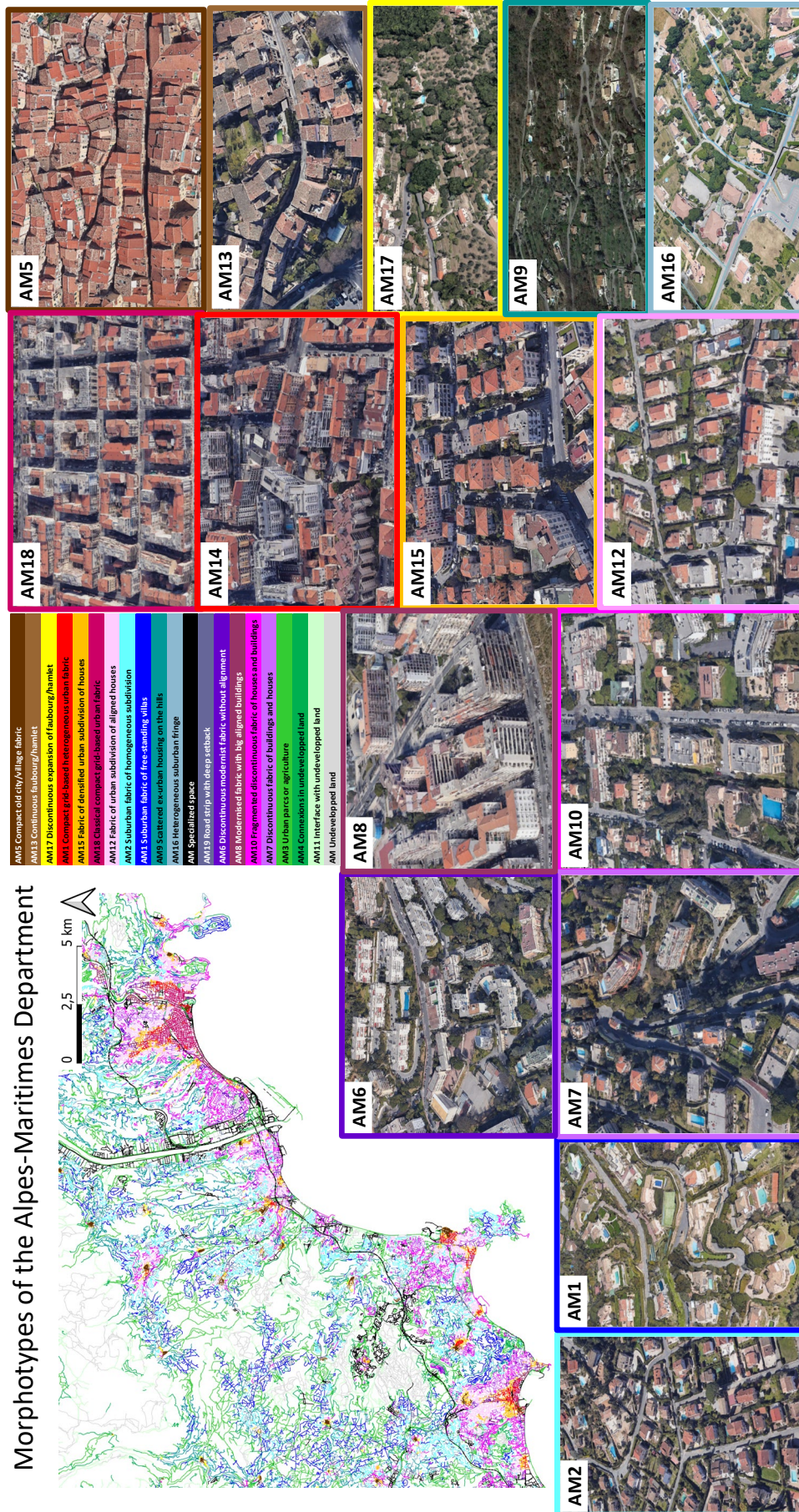


Figure 5. Projection in the geographical space of the MFA results in the Alpes-Maritimes department, centred on Nice-Antibes-Cannes conurbation.

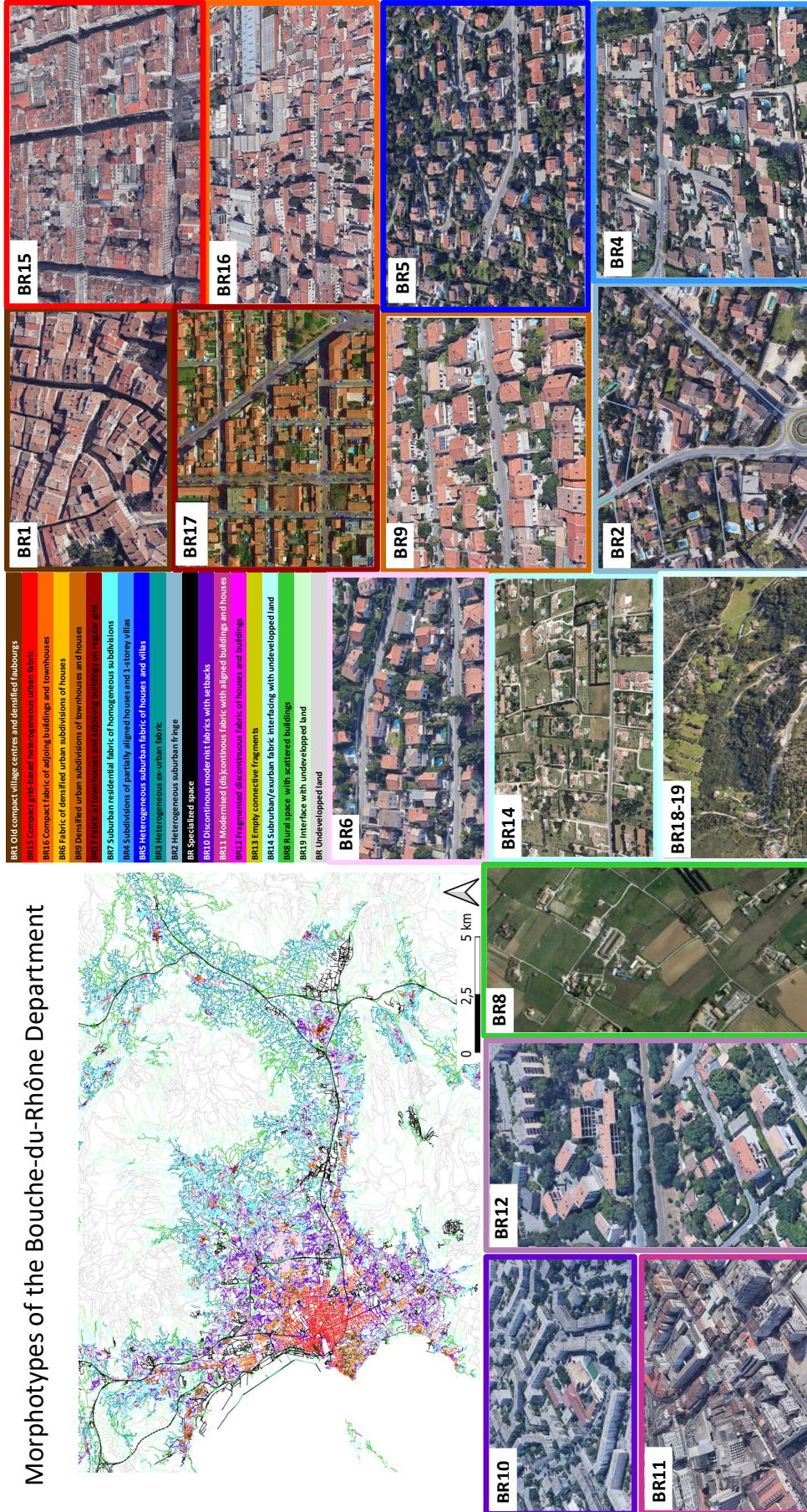


Figure 6. Projection in the geographical space of the MFA results in the Bouche-du-Rhône department, centred on Marseille metropolitan region.

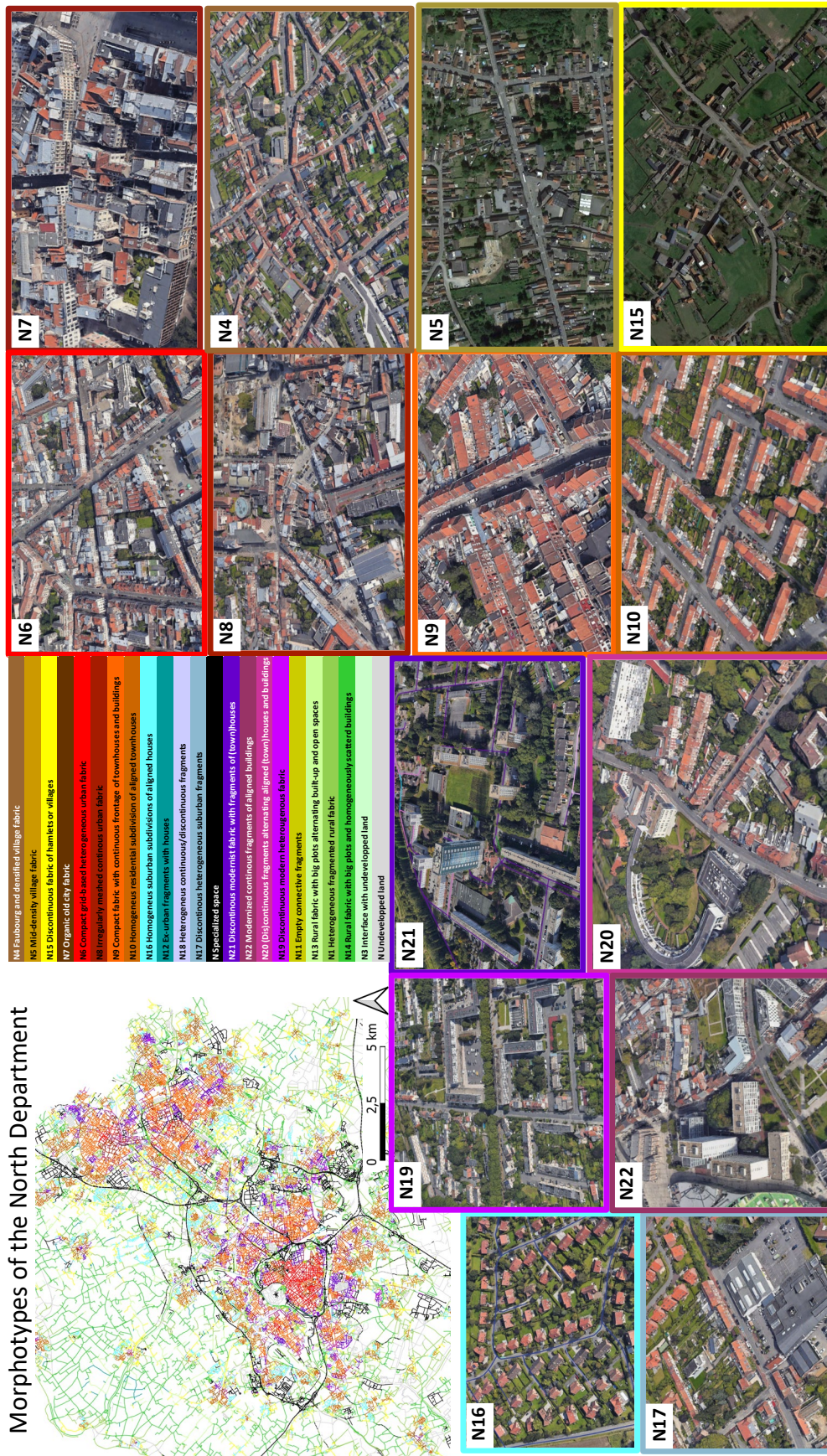


Figure 7. Projection in the geographical space of the MFA results in the North department, centred on Lille metropolitan region.

4. Conclusions

This paper presented the first results of an improved version of the MFA protocol, whose original version had been introduced by Araldi and Fusco (2019). An additional methodology has also been specifically developed to allow the comparative analysis of MFA outcomes between different metropolitan areas. We are thus able to produce a hierarchical clustering of place-specific morphotypes offering a shared nested taxonomy of more general morphotypes for different study areas.

In this paper, the protocol has been tested in four departments with important metropolitan areas: Alpes-Maritimes, Bouche-du-Rhône, Rhône and Nord. The four French metropolitan areas present each place-specific morphotypes, but resemblances and correspondences exist, allowing us to identify meaningful nested partitions of the 77 different place-specific morphotypes. Overall, there are two broad families of morphotypes corresponding to the compact city : grid-based and more irregular and heterogeneous. The latter includes vernacular forms, faubourgs, densified urban subdivisions and modernised fabrics. Taken together, these morphotypes are, nevertheless, a minority within the French metropolitan areas we considered. Modernistic discontinuous fabrics account for another minority space within the study area, but were produced all in the after-war period. The most important morphotypes in terms of spatial extent are those of the suburban/ ex-urban fabrics of scattered houses or villas and the urban/suburban subdivision of houses and villas. Any discussion on the forms of the contemporary metropolis in France cannot omit these important morphotypes, characterising much of its peripheral expansion during the 20th and 21st centuries.

The methodological developments here presented and implemented show how by passing from place-specific to general morphotypes, we open the way to consistent comparison of morphotypes found by MFA across different case studies. General morphotypes can also be organised in meaningful nested partitions, producing a multi-level taxonomy of the forms of the urban fabric over large and diverse study areas.

Several research perspectives can be outlined. From the methodological point of view, our next goal is to develop a specific protocol for the identification of archetypical spatial organisations of the morphological regions corresponding to recurrent patterns of articulation of morphotypes in space. This will be possible through the spatial analysis of the morphotypes within each region. Another aspect requiring a specific attention concerns the assessment of the resulting morphotypes. Validation of large study areas morphotypes always represents a challenging task, even more for computer-aided protocols. No exhaustive database exists, for any country in the world, describing and delineating the morphotypes which could be used as ground truth to calibrate and assess clustering protocols at a level of detail comparable with MFA results (without even considering the pedestrian point of view of the streetscape which is specific to the MFA approach). The assessment and validation of the morphotypes is, so far, implemented at the internal level of the protocol, with the final goal to assess its internal robustness (although the relatively high number of combinations of parameters would require a very large amount of work). The external validation of results, where morphotypes are assessed compared to the empirical observation, is today realised through an expert-based work, including the study of the specific urbanisation process of each study area, supported by the comparison with historical maps and official zoning documents. Nonetheless, these documents should not be considered as a ground truth either: the former are often historical maps/plans of cities at a certain time in history which might or might not have been preserved/implemented in their original form. The latter are contemporary prescriptive zoning plans, partitioning the urban space into subspaces and providing specific guidelines for their future. One possible solution is to solicit groups of urban morphologists and urban practitioners from each region in order to collaborate in the assessment of the results. In the present work, we could assess the improvements of the new MFA protocol by comparing the results of the two case studies in southern France with those obtained in previous research, using the old MFA protocol, which had already been validated by expert knowledge and different morphological analyses. In both cases, we doubled the number of place-specific morphotypes detected by the algorithm (passing from 9 to around 20) and remaining consistent with the previous less detailed results.

Finally, our ongoing research project aims at producing a morphological atlas of France, for the morphological research on the forms of contemporary French urbanisation. While methodological improvements of MFA were motivated by the French case studies, the same protocol has been conceived to be generalizable to other vector databases (like OSM), and could potentially be applied for the study of urban morphology in other geographical contexts.

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