Research Paper

Planned, unplanned, or in-between? A concept of the intensity of plannedness and its empirical relation to the built urban landscape across the globe

Henri Debray [a,b,*], Nicolas J. Kraff [b], Xiao Xiang Zhu [a], Hannes Taubenböck [b,c]

[a] *Data Science in Earth Observation, Technical University Munich, Munich, Germany*
[b] *German Aerospace Center (DLR), Earth Observation Center (EOC), Oberpfaffenhofen, Germany*
[c] *Institute for Geography and Geology, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*

HIGHLIGHTS

- An ontology of the intensity of plannedness, operationalized on three structural elements.
- A global enquiry on the structural complexity of the intra-urban morphology of 381 settlements.
- A large-scale statistical test of the relation between intensity of plannedness and structural complexity.

ABSTRACT

The physical appearance of the built urban landscape is the result of multiple, intertwined processes. The relationship between the existing morphology and the diversity of planning processes, however, has been little studied empirically at a global scale. In this study, we develop an ontology of planning intensity: conceptualizing intemediate categories of whether an urban structure is planned single-handedly or constantly updated by myriads of participants. Thus, we move away from the 'planned/unplanned' dichotomy and develop a continuum of Intensity of Plannedness (IoP). The focus of research is whether these conceptualized categories of IoP show demonstrable differences in morphology. Hence, we operationalized the urban structure by three structural elements: buildings, morphological units and streets. Curating geodata on 381 study sites across the globe, we empirically investigate the relation of the IoP to the structural complexity of the urban fabric. Tests of significance of difference and post hoc analyzes are performed on the statistical distribution of structural complexities of the categories of IoP. This study proves empirically that the distinct IoP has significantly contrasting structural complexities. From this, we conclude that there is indeed a relationship between both, the intensity of the process of planning and the resulting urban morphology and that this relationship is non-linear.

1. Introduction

How is the built city shaped? Sometimes, the form of the city emerges from a totally unplanned process. Occasionally, on the opposite, its design is subject to a completely planned operation. However, staying at this simplistic dichotomy does not give its credit to the rich diversity of urban processes, as a given city or settlement does not necessarily fall easily into the categories fully "planned" or totally "unplanned". In this research, we investigate a concept that we coined the Intensity of Plannedness (IoP). The Intensity of Plannedness is a scale characterizing how acutely and completely an urban space is designed. It follows the idea that there exists a conceptual continuum between two archetypical extremes of city-making that we could call "total design" and "total self-organization". Fig. 1.

Prior to the works of C. Alexander and J. Jacobs, modern and pre-modern approaches on urban making theory were attached to explain the strive of cities and the collective qualities of urban life by focusing almost exclusively on the planning of the materiality of the built-up
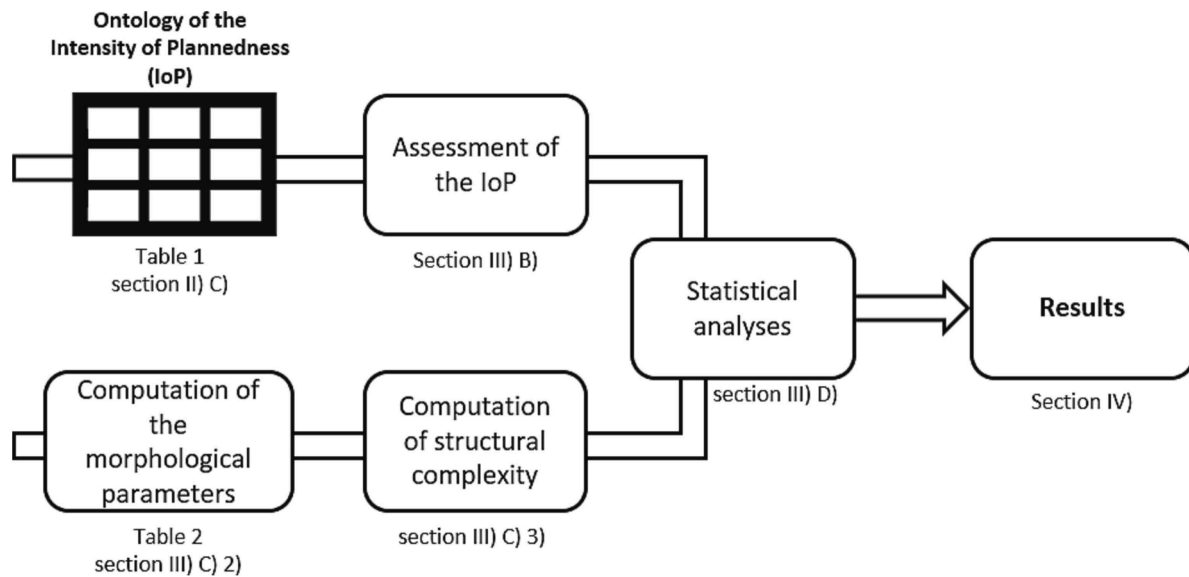

Fig. 1. Workflow of the study.

environment and the services offered in the city (Batty & Marshall, 2012). The shift proposed in (Alexander, 1965; Jacobs, 1961) was to consider these qualities of urban life in their relation to the subjective and inter-subjective aspirations of individuals and groups (Cozzolino, 2018). These new paradigms are giving their due importance to the social structure in the design and control of space (Cozzolino & Moroni, 2021; Cozzolino, 2020; Kostof, 1991b; Kropf, 2009; Lynch, 1984), the relevance of the contribution of the ordinary inhabitants (Cozzolino, 2021; Jacobs, 1961; Noizet & Clémençon, 2020; Tonkiss, 2013), because of their influence on the resulting diversity and complexity (Batty & Marshall, 2012; Batty, 2005, 2009; Bettencourt, Lobo, Helbing, Kühnert, & West, 2007; Jacobs, 1961; Moroni & Cozzolino, 2019; Portugali & Stolk, 2016; Salat, Bourdic, & Labbe, 2014), and in the ensuing enabling of incremental adaptivity (Akbar, 1988; Cozzolino, 2020; Habraken, 1998; Hakim, 2014).

In this work, we draw from this theoretical background, especially from the importance it attaches to the actions of individuals, the interactions between them, and the social processes emerging from it (Moroni & Cozzolino, 2019).More specifically, we see the IoP as both, an emerging result of the social processes, but also as the social frame to which the making of the built-up environment is conditioned to.

By acknowledging the contribution of the ordinary city dwellers to their direct environment, this shift of paradigms enabled to look past a too rigid dichotomy between "planned" and "unplanned". In their book "Collage City", Rowe and Koetter (Rowe & Koetter, 1978) developed the idea of "total design" or "total planning". This can be understood, per negative, as the acknowledgment of the existence of "non-total planning": a state below "total planning" still pertaining to the notion of "planning" thus, an in-between "planned" and "spontaneous". Later, and more conclusively, Habraken was among the first to propose to see it as a combination of top-down and bottom-up processes in relation to hierarchical overlapping of "fields of control" of different scales (Habraken, 2016, 1987, 1998); Kelso (Kelso, Portugali, & Stolk, 2016) described this intermediary state as the synergetic combination of the complementary pair "self-organization – design".

Among the research fields conceptualizing the spectrum between "spontaneous" and "planned", it is interesting to mention the contribution of the study of informal settlement. Noticeably with Kuffer et al. (Kuffer, Barros, & Sliuzas, 2014) proposing an "unplanned settlement index" to describe morphologies of informal settlements and Dovey et al. with their work (Dovey & Kamalipour, 2017; Dovey, 2020) on the morphogenesis of informal settlements proposing to consider their

morphogenesis as indexed to a gradient of formality both, at the urban design level but also at the architectural level.

Congenially, a few urban thinkers and historians employed themselves to unfold the multi-dimensionality of this spectrum: Ikeda (Ikeda, 2017) proposed to take in account the "scale of design" and the "passage of time"; stepping on these spatial and temporal extent, Cozzolino (Cozzolino, 2018) added that the "level of spontaneity" in urban context is tributary to the initial physical dimension and, more critically to the social dimension. More recently (Cozzolino, 2020) proposed a richly multi-factorial set of attributes characterizing the spectrum between "anti-adaptive neighborhoods" and "adaptive neighborhoods" including the evolution in time of the attractiveness, the scale of design, the amount of designers, the construction time, the types of planning rules, the diversity and interrelations of functions, the amount of public open spaces and the ownership system (further developed in (Cozzolino & Moroni, 2021; Cozzolino & Moroni, 2022)). Focusing on the French context, Noizet and Clémençon (Noizet & Clémençon, 2020) proposed to conceptualize a typology of "lotissement" (allotment) ranging from "*a minima*" to "*a maxima*" planning. This typology presents 6 levels based on the inter-relation of buildings, parcels, streets, "morphological urban islands", showcasing, as in the works of Ikeda and Cozzolino et al., connections with the concepts of ownership and asynchrony.

Despite this acknowledgment of intermediary states between "planned" and "spontaneous" in the literature, there exist, to the best of our knowledge, no comprehensive operationalization pertaining to the spectrum of these states fitting global scale analysis. Therefore, the first aim of this study is to develop an ontology of the IoP.

The second aim of this work is to investigate the hypothesis that form of the built-environment relates to the IoP. On one side, the assumed main tool of urban planning is, in itself, carving, in a top-down manner, a specific design in the intra-urban morphology (Batty & Marshall, 2009; Kostof, 1991b). On the other side, the self-organization as well, has its way of inscribing itself spatially in the urban morphology, this time in a bottom-up manner that is often described as presenting "organic" or "instinctually-grown" patterns (Batty & Marshall, 2009; Kostof, 1991b; Larkham, 1992). In fact, if both paradigms shape morphology, the resulting layouts cannot be more strikingly different (as exemplified in Fig. 2). As such, our hypothesis is that the continuum between both will, in turn, propose a wide range of morphological manifestations. Therefore, we want to address in this study the question whether the here conceptualized IoP is incrusted in the intra-urban morphology in a such a way that it is reflected in a spatially measurable way?

Fig. 2. (From left to right, from category Extremely spontaneous to Completely planned) Caracas, Kyoto, Paris, Chicago, Cairo).

To answer this question, we follow a qualitative and quantitative approach to study intra-urban morphology. Following studies such as (Boeing, 2019; Dibble et al., 2019; Rashid, 2017; Fleischmann et al., 2021; Pont and Olsson, 2018; Taubenböck et al., 2018b), we evaluate the statistical dependencies between quantitative morphological features and our qualitative characteristic, the IoP. Our empirical investigation is based on 381 study sites around the world.

Summarizing, the scientific contribution of this paper is twofold: 1) Develop and propose an ontology of IoP that we use to 2) empirically investigate at a cross-cultural, global scale to which extent the IoP inscribes itself into the urban physical form.

To do this, we *first* develop a conceptual basis to define the IoP of settlements in section II). We ground this concept on a literature review that allows to lay a theoretical foundation and to elaborate the practical elements needed for an empirical investigation. We collect common traits and differences of generic urban processes among cities and we abstract them to specific levels of IoP. We operationalize this by three structural elements: the buildings, the morphological units and the streets (Table 1).

Second, in section III)A), we present how we select the largest possible number of study sites across the globe where we find both, reliable specific information on the undergone urban processes' strata and where appropriate geodata is available.

Third, in section III)B), we describe how, we assess qualitatively the IoP of the structural elements for each settlement.

Fourth, we summarize in section III)C) how we estimate the structural complexity of the intra-urban morphology of our study sites on vector geodata. We first give a summary of the vector geodata we use in section III)C)1). Subsequently, in section III)C)2) we present the computation of a set of morphological features indicative of urban planning on the different structural elements. In section III)C)3), we explain how we compute, the joint entropy of the value's distribution for sets of morphological features for a settlement as a proxy for the *structural complexity* of the morphological patterns of the settlement.

Finally, in section III)D), we describe how we statistically analyze the obtained diversity measure across the categories of IoP in order to investigate whether correlations between the conceptualized IoP and physical appearance are significant.

With the concept of the IoP, we aim to contribute to the development of a theoretical foundation of the notion of intermediate degrees of plannedness of the urban form. By showing that the intra-urban morphology is charged with social values generated by different types of politic, economic and social structures, from the most monopolized to the most dispersed, we aim to highlight the relevance of the IoP for

policy making. Although the concept of IoP may not have a direct impact on local planning decisions, we believe that this conceptual tool could be useful for studies and discussions on policy design.

2. Concept and ontology of the intensity of plannedness

A. Intensity of Plannedness and intra-urban morphology: Theoretical background.

In this study we propose a conceptual framework in which we consider the morphological configuration of a city as a result of the liberty, or lack of it, with which inhabitants shape their living environment over time.

The physical layout of cities is the artifact of cumulative processes of construction, destruction, renovation, replacement, and replenishment (Conzen, 1960; Kostof, 1991a, 1992). Those transformative actions, those modifications, in their great majority, are sought by agents. The type of those agents and their intentions come in great diversity. It could be a speculative investor transforming open lands into marketable plots in Los Angeles (Kostof, 1991b); a centralized socialist state curating the city of Moscow with large housing estates to propose a solution to an accommodation crisis in compliance with its ideals during the Socialist Realism movement (Kostof, 1991b); or a Peruvian farmer leaving his village in the Selva, informally building a brick house in the foggy hills of San Juan de Lurigancho in north of Lima (Inostroza, 2017; Riofrío, 2003; Turner, 1967). All those actions, exemplified here, leave a trace in the morphology of a settlement with their diversity of processes, technical solutions and scales. In turn, the physical layout is the cumulative result of a plethora of such processes. To unveil the specific variations of the exact process that formed a settlement as a whole, to say who built what, how and in which purpose, is a tedious task that one could claim to achieve only with great care and abundant contextual knowledges (M. R. G. Conzen, 1960; Kostof, 1982; Kostof, 1991b). This in-depth morphogenetic analysis is a challenging goal for a single city, let alone a consistent cross-cultural global investigation.

In our study, the goal is not to achieve such a detailed investigation, rather, we propose a more abstract approach, suitable for a large-scale global cross-cultural study. As developed by (Lefebvre, 1974), cities are the projection of the sociological interactions on the ground, or in other words by (M. P. Conzen, 1980), writing about the form of cities: "*Few social values and actions are so abstract that they fail to be reflected in material forms*". Here, we aim to find in settlements the morphological reflection of the two main relations to the space defined by (Lefebvre, 1974), i.e. the appropriation of space and the domination of space.

Table 1

Ontology of the 'intensity of plannedness' using five structural categories and three defining structural element.

		Characteristic urban processes for the different categories of *intensity of plannedness*				
		Extremely spontaneous	Predominantly spontaneous	Evenly spontaneous and planned	Predominantly planned	Completely planned
Structural elements	Buildings	Buildings are mostly self-constructed individually by its future user. As such, there is no official general or organized plan for the building disposition and no explicit concerted decision to build in a certain way. As work force for building is limited, circumstances mean that the choices of structures and building materials to be used is limited. Therefore, the buildings of the overall settlement will be rudimentary, often of makeshift character, and quite limited in their diversity.	Buildings are either self-constructed by the main users with the help of other members of the local community or the construction process can be delegated to more specialized people. Both ways provide more work force and provide more elaborated structures that are disposed in an, at least implicitly, accepted manner by the community. As the workforce is typically drawn from a small pool of local people, who often share same skills, hence producing some norms of building in a manner tributary to local resources and culture. This enhances only little variety in the buildings' type.	Buildings are constructed in the frame of explicit rules such as implemented cadastral parcels division of the land and norms of constructions. The owners acquire the parcels and have the buildings renovated or built anew to their idea. As such, the owners rely on significant enough financial funds and are likely to rent the edifices for at least recovering the investment. Therefore, the users of the buildings are unlikely to be the owners. The variety of buildings can be high to the measure of the diversity of funds of each agent and of the diversity of dates of building, but is nuanced by the constraints related to the norms, already pre-existing parcels, and the homogeneous skills of different local building companies.	Buildings are constructed typically in planned zones where cadastral parcels are already systematically structured in their layout by the local planning authorities. Parcels are of middle size or composed of small sized ones that can be combined easily into single ones. This allows private individuals or real estate companies to construct buildings at a larger scale. This is reflected – by either large and/or high structures built by a single company, large low-rise residential areas commissioned to multiple building companies, or medium-scaled medium-rise residential areas built by a single company. As such, there is a tendency for standardization of building types.	Buildings often originate from large-planning policies and legally-binding land use plans. The cadastral system is generally designed at a coarse scale and the parcels are designed to host big estates. Thus, only local governances, big real estate companies or rich private individuals can afford to own them and to build on them. As a result of the dimension of the programs, a small pool of companies has the technical capacities to develop these buildings. This can lead to either single or few monumental buildings int the case of limited scale programs. Alternatively, in large programs, the economy of scale in the design, in making, in logistic, etc. tailors a masterplan based on replication, and tends to enhance a strong standardization of the buildings.
	Morphological Units	Morphological units emerge haphazardly, by conglomerating buildings for practical reasons, being mostly reducing distances for rapid access to outbuilding and annexes. People develop these units in free range, over time and in a non– or loosely concerted manner. Therefore, the morphological units exist, in the settlement, in a large variety of types of conglomeration, each specifically meant to fit the need of its direct local users.	The community implicitly, or explicitly, designed or regulated specific places as commons over time. Morphological units are constrained to form outside such areas. Those common places, being non-buildable or public places (e.g. streets or squares), define the outermost extension the private space can take in the morphological units. The inner part of the morphological unit is not constrained in the exception of possible inner streets -and squares.	The relation of the limits of the morphological units to the public places in the district or the city is explicitly regulated to ease the design of streets, for rights of way, for the access to the sunlight or for esthetic reasons. This regulation implies definitions of how the frontage of the lots of land sets back from the public place. This control of the buffer between the outer built -or owned -perimeter of the morphological units and the public places, in turn, means that the outer perimeter of the unit is defined by the lots.	Rules are implemented that seek to respect theorized optimal densities for the morphological unit as a block. The rules can concern the width, the spacing of the parcels or the depth by which they can be built. Those policies concerning the density can range from taxation system to enforcement of specific buildable space in the lots. This process often benefits from an already laid out street network hosting surveyed plots ready to be bought rendering the policies easier to apply.	The morphological unit and its constitutive buildings are the result of a single design. Due to the monetary costs of such projects, agents planning such unit might be ones having enough fund to design multiple units on larger area. The morphological units follow strictly local norms and rules such as the density and the height-distance to road ratios. As consequence of those rules, the streets are not necessarily anymore an element constraining the extent and the morphology of the morphological unit.
	Streets	The streets emerge from frequently used non-built trails and pathways that people use to connect buildings or places. In dense situations they are defined by the surrounding private spaces and thus are tributary from their shapes. They tend to follow a logical path of least energy or least commutation time making them prompt to follow the topology and avoid obstacles.	The streets of the settlements are subject to common rules of habits aiming at facilitating their overall use by granting access to the buildings and to improve the basic freedom of movement. The street network is usually renovated in this sense but it still inherits from the shapes of former patterns or is impacted by the topology.	The street network is planned according to a system. This system is thought to improve the quality of the network in regard of specific aspects through regulations (e.g. street geometry standardization). The system can concern the entire network or focus on a specific level of hierarchy.	The street network is designed to accommodate an area as large as a district. It is often planned prior to the existence of the settlement or else, in a massive renovation project. The planning follows systematically norms and a goal of optimization (most of the time to ease the circulation of vehicles).	The street network is completely designed. It originates from a single entity being in charge of deciding the layout of a new district, or a complete city with the street network being its structuring backbone. To comply with accepted theories (on the 'ideal city' or on circulation for examples), a strong hierarchy will be implemented between the different streets. This will often support the argumentation for specific designed patterns.

What Lefebvre defines as 'domination of space' are the collective measures concerning planning (urbanism ordinances, rules and codes, hygiene and security rules, planning projects, administrative and management norms, norms of real estate, police, among others), overlapping, in our case with the notion of "design control" (Cozzolino, 2020; Habraken, 1987, 1998). In summary, this comprises top-down planning rules, norms and ordinances (Portugali, 2016). The effects it has on the physical layout can be stereotyped by the extreme example of master plans that strictly design the urban environment, but also by the less extreme example of ordinances regulating the distance of buildings to the road, conferring specific aesthetic character to street corridors.

On the other side, the bottom-up initiatives such as building, renovation, decoration, occupation, cleanness, co-security, among others are what (Lefebvre, 1974) describes as 'appropriation of space'. The way this "appropriation" inscribed itself in the urban layout can be grasped in its cumulation when considering the uncoordinated apparition of informal settlements, shaped by the accretion of individually built buildings in a seeming haphazardly arrangement. Or, more discreetly, by the way specific buildings are renovated, making them standing out of its neighbors, despite having been originally built in the exact same way at the same time.

In our conceptual frame, we argue that the physical layout of the city is the evolving compromise of the transformative actions originating from those two social relations to the urban space, the complex dialectic relation between bottom-up and top-down processes.

As the relative importance of both types of processes exist in many variations and equilibria, cities, quarters, neighborhoods, or plots can vary from extremely spontaneous to completely planned, although a large number of urban areas falls in between these two extremes. Our goal is to formulate a categorization that covers the breadth and variety of morphological manifestations and that establishes the relation to their "planned" or "spontaneous" origin, by highlighting the characteristics of their formations. In this scope, we focus on actions that have a direct impact on the physical layout of cities, ranging from bottom-up, appropriation processes of ordinary urbanism (Cozzolino, 2021; Noizet & Clémençon, 2020; Tonkiss, 2013) to top-down, control sought actions and incentives of urban planning (Habraken, 2016; Kelso et al., 2016).

Both processes shape cities, each in their own ways. Literature shows that different policies (orientation of urban planning process) (Kostof, 1991a; Taubenböck, Murawski, & Wurm, 2018b) or lack of policies (room for spontaneous urban process) (Dovey, 2020; Kohli, Sliuzas, Kerle, & Stein, 2012; Kraff, Wurm, & Taubenbock, 2020a; Kraff, Wurm, & Taubenböck, 2020b; Taubenböck & Kraff, 2014) lead to different patterns. We additionally formulate the hypothesis that different nuances of mixtures lead to different patterns as well. Although the combinations of spontaneous and planning process are maybe as numerous as the number of cities on Earth through its whole history, we propose an abstraction to few categories, i.e. we conceptualize an ontology enabling the comparison between mixtures. To do so, we define a gradient scale ordering these mixtures based on the relative importance of spontaneous urban processes against urban planning processes. We draw on the categorizations and scales from the works of (Cozzolino, 2020; Dovey, 2020; Kuffer, Van Maarseveen, Sliuzas, & Pfeffer, 2017; Noizet & Clémençon, 2020; Taubenböck, Kraff, & Wurm, 2018a). In the following, this scale is what we refer to as the *'intensity of plannedness' (IoP)* of cities.

We do not envisage *a priori* the IoP to be a quantitative measure, rather, we consider it as a qualitative assessment of a level on the gradient between unplanned and planned. To be able to assess the IoP of a settlement could be, alone, a challenging work of research in the vein of the works of scholars such as M.R.G. Conzen (M. R. G. Conzen, 1960) or S. Kostof (Kostof, 1991b, 1992). Their work should be a *memento* to us, not to forget the complexity to endeavor understanding the rich social dynamics of a place across the epochs down to the last iota of detail. Nonetheless, in the sake of producing data on the IoP, we have to resort to alternatives. Here, we used a hybrid approach, using literature on contextual and general urban planning history.

Along with our conceptual considerations, one can envision the IoP as a rough estimate of the balance between the number of people whose actions created and shaped the city (Moroni & Cozzolino, 2019) and the number of people living and performing activities in the city. As such, the layout of a city with a low IoP is understood as the physical result of the cumulative actions of a large part of its inhabitants. On the opposite, the design of a city with a high IoP will originate from the intervention of one single, or very few agents (local governances, big real estate companies, etc.) (Cozzolino, 2020; Moroni & Cozzolino, 2019). Although we believe the scale between low and high IoP to be potentially continuous, we aggregate to five main categories covering this continuum. Thus, we are able to conceptualize and describe these categories. Each IoP category is representative of a relative importance of spontaneous urban processes vs urban planning in their combination. The IoP is presented in Table 1. The conceptualized categories are: *Extremely spontaneous*; *Predominantly spontaneous*; *Evenly spontaneous and planned*; *Predominantly planned*; *Completely planned*. These five categories are exemplified in Fig. 2: From 'organic" and complex, i.e. extremely spontaneous, to geometric and ordered, i.e. completely planned.

B. The Intensity of Plannedness of Structural elements.

The five settlements shown in Fig. 2 exemplify stereotypizations of the five conceptualized categories of the IoP. However, among the large variety of urban processes across the globe, a lot of settlements stray from these stereotypes. For instance, it is not rare that a street network is *predominantly planned* in a gridiron, whereas the buildings are *evenly spontaneous and planned* or even are *predominantly spontaneous*. Indeed, different structural elements of the settlements' physical layout do not result necessarily from the same processes. As such, this non-correlation of the IoP across different structural elements is depending on the asynchrony between them, and on the hierarchical nesting of the power of the different urban agents (Cozzolino, 2020; Noizet & Clémençon, 2020).

For the operationalization of measurability in the physical appearance of cities, we detail our ontology further, so these differences between structural elements can be addressed. Following the Conzenian tradition, the physical layout of a city is sketched by its buildings, streets, and the arrangement of its plots and open spaces (M. R. G. Conzen, 1960; Kostof, 1991b; Kostof, 1992; Kropf, 1993; Salat, 2011). Hence, we propose to use three major structural elements, the *buildings*, the *morphological units* and, the *streets* as illustrated in Fig. 3. We consider *buildings* being any type of built structure purposely sheltering people, wares or activities. We understand the *morphological units (MUs)* as the structural element formed by the aggregation of plots (Kropf, 1993), i.e., the buildings and their bounded open spaces. Hence, we define the MUs as the surface on which a collection of buildings in direct vicinity sits, sharing the same type of topological relationship. The MUs are understood as an extension of the concept of 'street blocks' to acknowledge a specific type of building conglomeration that emerges in contexts of a low IoP, where building conglomerations may not be defined by streets. Last, we understand the *streets* in their large definition of ways where the public circulation of people and goods is enabled. The computation of the structural elements is further described in the data section III) b).

We believe that the interplay of these three structural elements provides an exhaustive overview of the main observable physical layout of settlements. Beyond, we see these structural elements as direct targets of transformative actions of urban processes, top-down and bottom-up alike (Cataldi et al., n.d; Kostof, 1992; Mangin & Panerai, 1999; Panerai, Demorgon, & Depaule, 1999).

C. Ontology of the intensity of plannedness.

Based on all these considerations, we conceptualize, describe and

Fig. 3. Structural elements illustrated for the example of Trier (Treves), Germany. (From left to right) buildings; morphological units; streets.

summarize the mixture of processes at stake for each of the three structural elements and for each of the five categories of IoP. The proposed ontology is presented in the following Table 1.

3. Experimental set-up

A. Study sites

We understand study sites here as samples representative of a type of urban process. As a city generally is composed of multiple areas tributary from different (intra-)urban processes, we select and delineate as samples, areas where the urban process shaping the physical appearance is as much as possible homogeneous, close to the definition of *Morphological* or *Morphogenetic Regions* (M. G. Conzen, 1988; Gu, 2019; Whitehand, 2001), or *Sanctuary Areas* (Dibble et al., 2019). These sample settlements are typically of the size of a district (typically ranging between 0.5 km^2 and 10 km^2), often following actual district borders, having their singular histories and, as a result, presenting a unique IoP.

We are aware that in different cultural regions, similar urban processes might shape different physical urban appearances (Kostof, 1991b). Thus, we attach importance to the fact that the different categories of plannedness are also covered at different cultural regions across the globe.

Another factor that we take in account for selecting the study sites is that we need to access appropriate data covering the different structural elements.

The selection of study sites is, therefore, based on the following criteria: We aim at reaching the highest possible number of settlements, that represent examples from all across the world; that are representative of the large variety of intra-urban morphologies; that high-resolution vector geodata are accessible, depicting accurately buildings and roads and that the Mus can be derived from it; and, that literature references allow us to infer the category of the IoP for the selected settlements.

Following these criteria, our sample selection are 381 study sites with consistent information to infer the IoP of the settlement (see Fig. 4). Among these 381 study sites, a subset of 260 is used for the *buildings* and

Fig. 4. Map of the aggregated number of study sites and their geographical distribution (points without number signify only one study site at this location).

the *morphological units*, and a different subset of 296 is used for the *streets*. Out of the 381 study sites, 69 are located in Africa, 107 are located in Asia, 36 in Central and South America, 98 in Europe, 55 in North America and 16 in Oceania. In this selection, some cities provided multiple study sites, given the distinctly different properties of their morphologies or their process of planning. Overall, this sample covers more than 150 independent cities. Additional maps of the geographical distribution of the study sites used specifically for *buildings, morphological units* and the *streets* can be found in Appendix A.

B. Assessment of the 'intensity of plannedness' of a settlement.

There does not exist yet a comprehensive guideline to perform the assessment of the IoP in to the categories. Thus, we have developed a systematic workflow to qualitatively perform this categorization on the base of literature and other exegetical data. This workflow is a decision tree that can be applied for each of the three structural elements. The develop decision tree is introduced in Fig. 5 and the steps are described in detail below.

- For each of these study sites, we *first* gather literature and other exegetical data, pertaining to the history of the urban development phases and processes that affected the study site considered.

  Ideally, we would rely on information for each and every specific individual transformative action involved in the creation and the transformation the built-environment underwent, with knowledge on which agent instigated and contributed to each transformation. Unfortunately, data with this type of information is almost never openly available, is based on knowledge from many different actors, or does not even exist. Therefore, we build the assessment of the IoP on the inference of urban processes at a macro-level based on aggregated information sourced in literature.

  With this regard, drawing from (Cozzolino, 2020; Noizet & Clémençon, 2020), specific attention is given to the search of information on planning rules, ownership systems, amount of designers, observable scale of design, mix or segregation of functions, and to the construction time and changes. To gather this broad range of nature of information, the search is performed across multiple types of source (academic literature, official documents, planning survey, historical maps, historical aerial pictures and to some extent grey literature and local knowledge).

- *Second*, using this information, we identify the decisive characteristics of the major original urban process at stake in the study site.

  Namely these characteristics are: the type of planning rules and codes (prescriptive or proscriptive (Cozzolino, 2020)), the frame of these rules and codes (formal, *para*-formal, informal (Dovey & Kamalipour, 2017; Tonkiss, 2013)), the type of participants to the urban process (institutional or private entities, organizations, distinct agents) and amount of participants in relation to the scale of the area (Cozzolino, 2020) (in this study, we propose the four following tiers: Single (one participant responsible of the whole area); Few (typically less than 5 for 1 km^2); Medium (typically between 5 and 50 for an area of 1 km^2), High (typically more than 50 per km^2)).

  Then, following a descending chain of *a minima* conditions on the combination of the characteristics, we can evaluate the IoP of the founding urban process of the study site.

- *Third*, we identify the evolutions the study site underwent since the founding urban process. This crucial step helps us to navigate from the IoP of the original state to the current one, considering the layers of history the study site went through.

  Following (Cozzolino, 2020), we distinguish two major trends of evolution, namely: "incremental changes" done by additional participant being, in amount, at least as many as the original participants and over a longer term than the founding process; "restructuring led by comparatively less participants and happening

comparatively in a more sudden way than during the founding process.

- *Last*, using the evaluation of the original IoP and the identification of the subsequent phases of evolutions in the study site, we formulate the assessment of its current IoP into the categories 'Extremely spontaneous', 'Predominantly spontaneous', 'Evenly spontaneous and planned', 'Predominantly planned' and 'Completely planned'.

Among academic sources used to infer urban processes, none were as instrumentally valuable as the works of S. Kostof (Kostof, 1992, 1991a, 1991b). As much for his encyclopedic knowledge of cities across the world as for his deep understanding of urban processes from the most motivated ones to the most ordinary ones. For the systematic overview of this information, which is the basis for the qualitative classification of the sample to an IoP category, we refer to Supplementary Material 1.

C. Estimation of the intra-urban morphology by the structural complexity.
1. Geodata base for analysis of the urban layout

We predominantly rely on geodata from the collaborative worldwide mapping project OpenStreetMap (OSM) using the python library developed by Boeing (2017). As OSM is based on volunteered contributions, the completeness of its data relies on the involvement of mappers, local or not, that chose their working site. As such, places of secondary interest for worldwide mappers and places with few or none voluntary mappers often are omitted or only superficially covered (Herfort, Lautenbach, Porto de Albuquerque, Anderson, & Zipf, 2021; Seto, Kanasugi, & Nishimura, 2020). This omittance mostly happens in poorer places or less densely populated places (Herfort et al., 2021). Conversely, settlements with complex morphologies like slums, or of small size such as villages are less represented. Further, the incompleteness of the OSM project is more important for buildings than for road data (Herfort et al., 2021). Overall, this creates an imbalance going against our goal of multi-dimensional representativity in data, study sites and thus, our categories of IoP. Therefore, we complete our dataset by data from the study of (Taubenböck et al., 2018a) covering deprived places across the globe on building level and by manual digitization when Open Street Map do not provide consistent or comprehensive enough data. When digitizing, we remain consistent with the OSM format.

Overall, our 381 study sites reflect a selection of settlements where we could confirm visually that in our geodata not more than ~10 % of the structural elements were missing or that the missing data would influence drastically the quantitative estimation of the intra-urban morphology.

For the empirical examination of the intra-urban morphology, we use the structural elements of *buildings, morphological units*, and *streets*, as outlined in section II) B).

For the structural element *buildings*, we gather solely building's footprints as the building height is yet not consistently present in OSM data. The rooftop represents a single building and is used as proxy information for a building's ground area. For details about manual mapping in complex urban areas we rely on (Kraff et al., 2020a).

As for the *streets*, we extract them as geographical network, composed of nodes and edges as done by (Boeing, 2019). As no information on width could be persistently used, we limit ourselves, here, to consider streets as linear objects.

For the *Morphological Units* (*MUs*), as discuss in section II)b), we see this structural element as a generalization of the "aggregate of lots" (Kropf, 1993). As discussed in (Fleischmann, Feliciotti, Romice, & Porta, 2020) retrieving individual lots, or plots (beyond considerations on their existence outside of formal estate economy) is no trivial task as the data is mostly unavailable. Therefore, we extract the MUs as the polygons constrained by street meshes when the streets form such a mesh, following the street-dependent acceptation of the definition proposed in
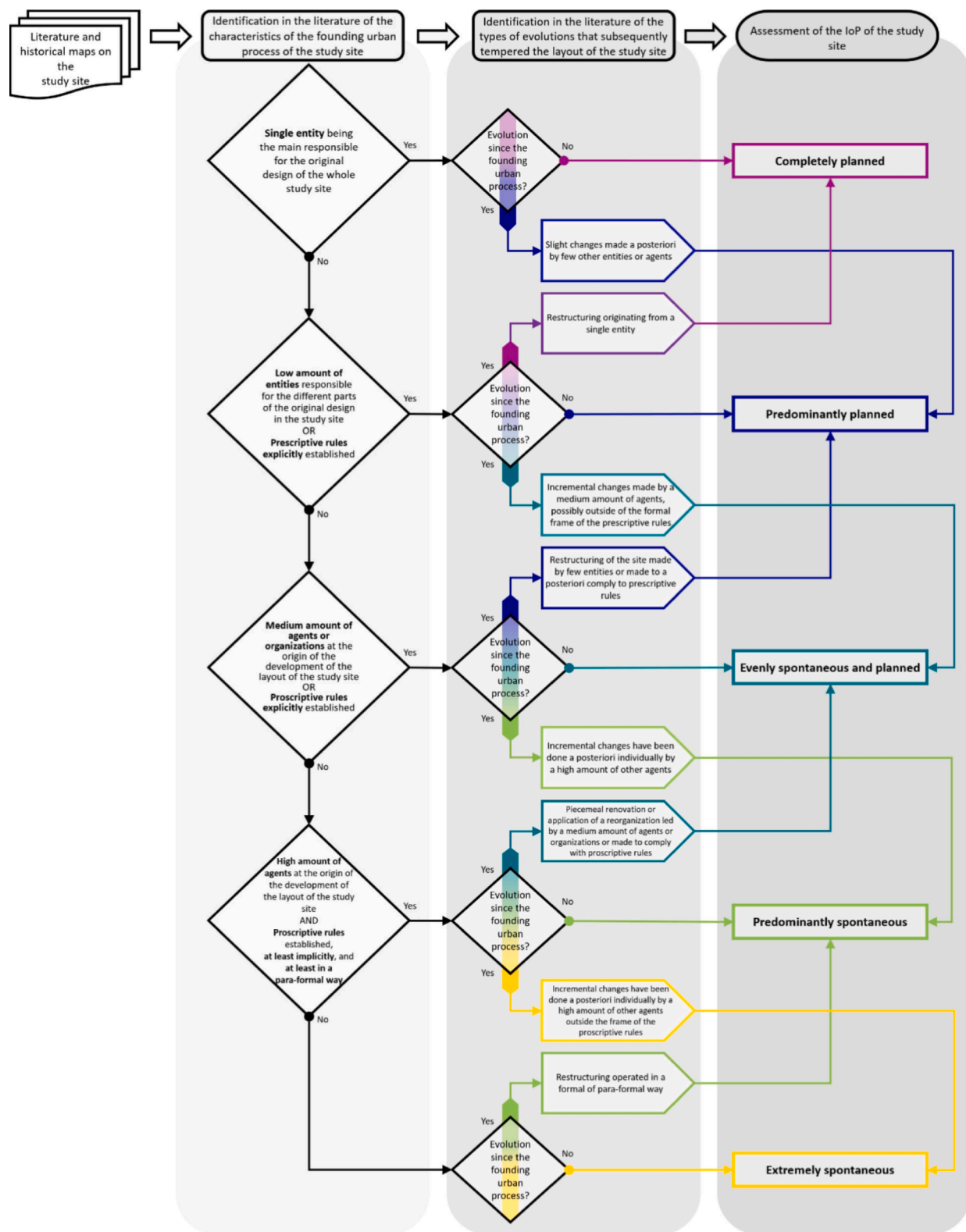
Fig. 5. Workflow of the assessment of the IoP of a study site.

([Kropf, 1993](#)). When streets do not form meshes (mostly in *Extremely Spontaneous* settlements), we propose the production of the outlines using an aggregation algorithm based on an adapted spatial version of the OPTICS clustering ([Ankerst, Breunig, Kriegel, & Sander, 1999](#)). The process of production of the outlines is introduced in Appendix B.

2. Morphological parameters.

We aim at investigating in quantitative manner whether the IoP has a relation on the three structural elements considered here: *buildings, morphological units* and *streets*. We therefore rely on measurements of specific characteristics of these structural elements. Furthermore,

Table 2

Description of parameters of structural elements and of the specifics for measurement. (See below-mentioned references for further information.)

Structural element	Parameter	Description	Illustration	Equation	Bin size
Buildings	Building dimensions	*Building dimensions* is a feature measuring the width and the depth of buildings footprints. We define the buildings dimension as the double of values (L,l), L being the long side of the bounding box of the building and l its small side. Dimensions of buildings give information on their functions and on the financial context as well as land availability when the buildings were constructed.		(L, l)	(5m; 5m)
Buildings	Compacity	*Compacity* is a geometrical feature describing the shape of buildings. We compute the geometrical compacity of buildings by considering the ratio between the perimeter of the building and the square root of its surface. Here we consider the compacity of a building as a proxy for the specific design of the building's footprint, from simple to complex ones.		$\dfrac{P}{\sqrt{A}}$	0.1
Buildings	Wall-to-wall distance to neighbors	*Wall-to-wall distance to neighbors* is a parameter defined as the mean distance to the two closest neighbors of the building. The wall-to-wall distance to neighbors sheds light on the types of mutual distances the buildings have in their vicinities with each other. It is a very local measure of building density.		$\dfrac{\varepsilon_1 + \varepsilon_2}{2}$	0.5m
Morphological units	Girth index	*Girth index* is a ratio describing the nominal thickness of a shape. It is computed as the ratio of the thickness of the layer insulating the innermost core of the shape from its periphery and the radius of a circle with the same area as the shape. This indicator proposed by Angel (2010) translates the relation between the core of the morphological unit and its boundaries. In other words, this reflects how deep the morphological unit is.		$\dfrac{D}{R}$	0.01
Morphological units	Detour index	*Detour index* is a measure computed as the ratio between the perimeter of an equal-area circle and the perimeter of the convex hull of a shape. This index proposed by Angel (2010) reflects the typical distance one has to walk to skirt a shape. Here, we use it as a proxy for the design of the morphological units.		$\dfrac{P_{Circle}}{P_{Convex\ Hull}}$	0.01
Morphological units	Order of magnitude of number of buildings	*Order of magnitude of number of buildings* is computed by taking the logarithm of its raw number of buildings. This parameter indicates how many buildings are located within a morphological unit while acknowledging that there are more differences between small headcounts (e.g. of 5 and 6 six buildings) than between large headcounts (e.g. of 100 and 101 buildings).		$\log_{10}(N + 1)$	0.1dit
Streets	Length of street section	*Length of street section* is a geometric feature measuring the length between two crossroads. This parameter is a proxy of the regularity of the mesh size in the street network.		L	5m
Streets	Curviness	Curviness is a geometric measurement of how bent and counter-bent a section of a road is. We compute it as the mean of the angles between the segments of the road, weighted by the length of the segments. This measure quantifies the design of the curvature through the settlement.		$\displaystyle\sum_{i=1}^{n}\dfrac{\alpha_i * (l_i + l_{i+1})}{2 * \sum_i l_i}$	0.1°
Streets	Symmetricity of crossroads	*Symmetricity of crossroads* is measured as the doublet (α, β) which is respectively the mean angle of the paths protruding from both ends of a section of road. Here we use this couple of values as a proxy for the design of crossroads emerging from a road section.		$(\overline{\alpha_i}, \overline{\beta_j})$	(5°; 5°)

following (Batty, 1974, 2016; Boeing, 2019; Cozzolino, 2021; Habraken, 2016; Jacobs, 1961; Kostof, 1991b), we specifically believe that the diversity of the urban morphology is negatively corelated to processes of norms and standardization. Therefore, to probe the IoP within settlements, we propose to compute the diversity of sets of three parameters for each of the structural elements. Later, we refer to this diversity as the *structural complexity*.

The morphologic features considered here are mostly geometric measurements, or *morphometric characters* (Dibble et al., 2019). We choose them because they encompass features directly or indirectly impacted by planning ordinances and norms. We describe these parameters, their computation and their relevance with respect to urban planning in Table 2.

3. Structural complexity as joint entropy of morphological parameters.

For operationalization of the *structural complexity*, we compute for each settlement the normalized Shannon entropy (Shannon, 1948) of the individual parameter distributions and the normalized joint-entropy (Cover & Thomas, 2005) of the set of three parameters for each structural element (see Table 2). The entropy and joint entropy are computed by approximating, in each individual settlement, the parameters' distribution by their histograms as in (Purwani, Nahar, & Twining, 2017). The bin-widths for each parameter is chosen with respect to the scale of its physical reality and is noted in Table 2. Shannon entropy is a measure of a system's diversity, or information complexity. Here, we use it to assess the dispersion of values computed for both individual parameters and for sets of parameters. This is motivated by its presumed information related to convergence to, or divergence from, uniformity, fostered by planning, ordinances, rules, or contextual constraints. Respectively,

the joint entropy mathematically represents the individual entropies of its variables reduced by their mutual information (Cover & Thomas, 2005). In our case, we understand it as the specific diversity for a structural element of the combined triplet of morphological parameters in a given settlement. We further refer to the joint entropy of a *structural element* in a settlement as its *structural complexity*. Equations on normalized entropy and normalized joint entropy can be found in the Appendix C.

The introduced parameters in Table 2 are common spatial metrics in this domain. However, it is clear that any selection of spatial metrics cannot be comprehensive. To make sure that these selected metrics do not produce statistical randomness in the measurement of the urban layout, we calculated 139 additional metrics and analyzed to what extent the results obtained with these metrics hold up (see Supplementary material 2).

4. Statistical analyses on the relation between the Intensity of Plannedness and the structural complexity.

The crucial point in our study is to demonstrate the relation between the categorized IoP derived from the literature and the output of the *structural complexity* computed on the structural elements.

To demonstrate this, we analyze whether the values of *structural complexity* differ significantly between the five categories of IoP. To do so, we analyze the variance among the distributions of the different categories. As the distribution of the *structural complexity* measures is not assumed to trivially follow normal gaussian distributions, we resort to a non-parametric version of the analysis of variance (ANOVA) (Fisher, 1925): the Kruskal-Wallis test (Kruskal & Wallis, 1952). The Kruskal-Wallis test indicates whether the H0 (null hypothesis) is respected, i.
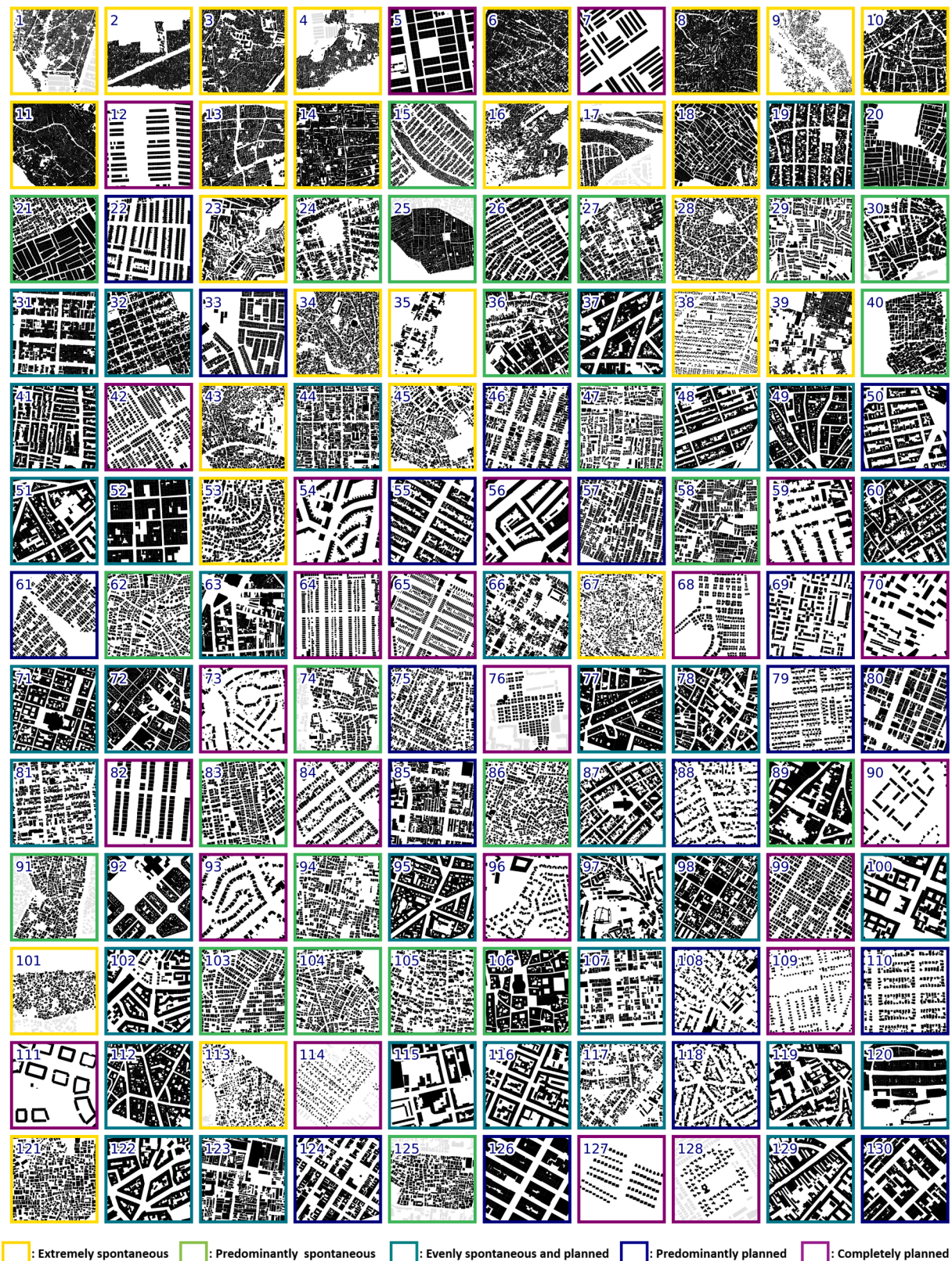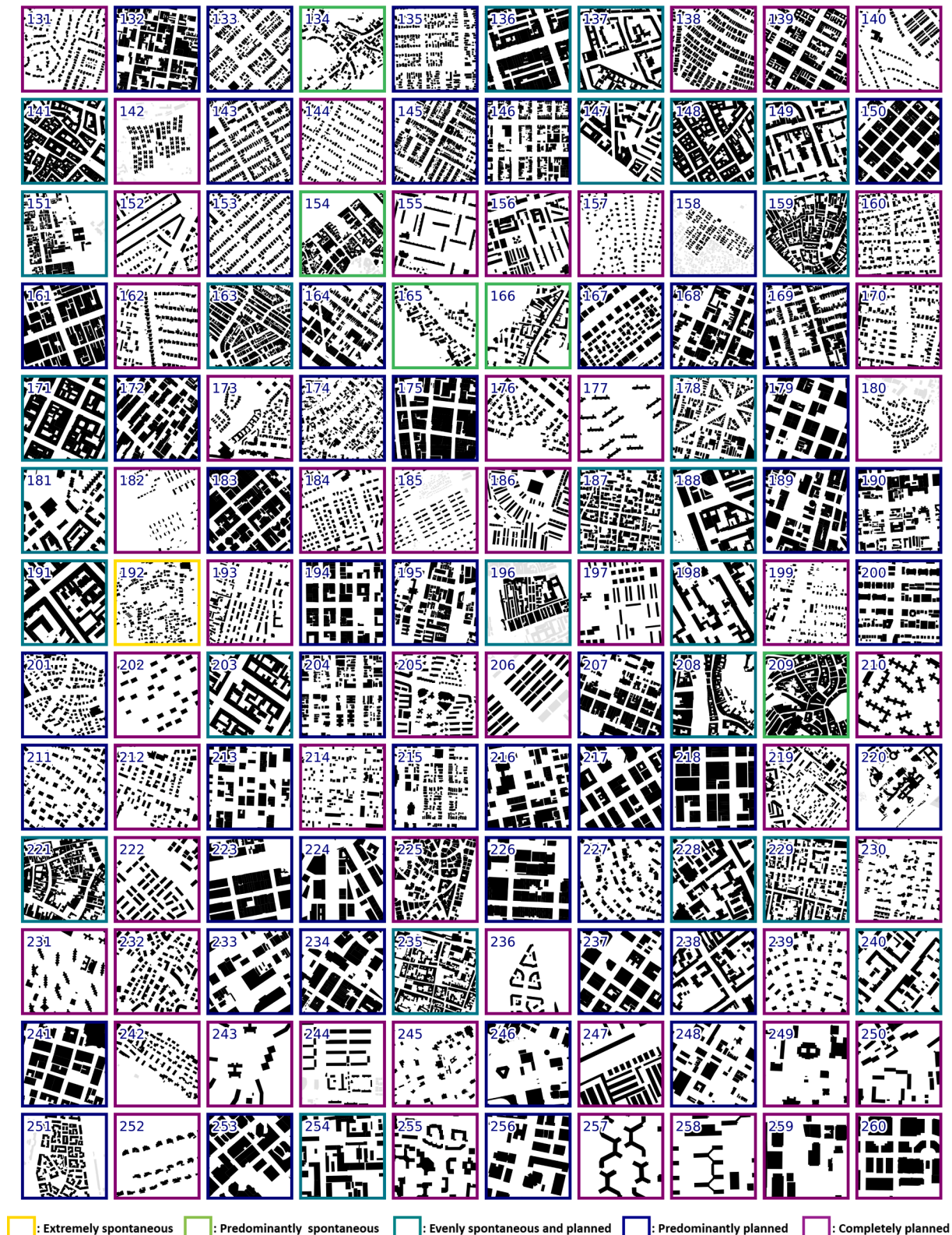
Fig. 6a. Figure-ground diagram snippets of a 500 m × 500 m subset of each study site used for the analysis of the structural element 'buildings'. The snippets are ordered by the measured increasing structural complexity and framed in color with respect to their IoP. Buildings in black are part of the study site, the ones in faded grey are not. List of the study sites below.

e., whether the distributions of each category of IoP are all equivalent to each other. As a threshold to decide whether H0 is respected, we consider the generally accepted value of $\alpha = 0,05$ (Glantz, 2012). H0 is respected if the p_{KW} value of the Kruskal-Wallis test is above this threshold. If the H0 is not verified, we assume that at least one statistical distribution is different from the rest. To observe which statistical distribution differs from the rest, we proceed with a post-hoc pair-wise comparison of significant differences among the individual categories' distributions using the Mann-Whitney test (Mann & Whitney, 1947; Wilcoxon, 1945). Here as well, we consider a pair of distributions to be significantly different if $p_{MW} \le 0,05$.

□ : Extremely spontaneous   □ : Predominantly spontaneous   □ : Evenly spontaneous and planned   □ : Predominantly planned   □ : Completely planned

(caption on next page)

Fig. 6b. Figure-ground diagram snippets of a 500 m × 500 m subset of each study site used for the analysis of the structural element 'buildings'. The snippets are ordered by the measured increasing structural complexity and framed in color with respect to their IoP. Buildings in black are part of the study site, the ones in faded grey are not. List of the study sites below

1. Manila North Cemetery
2. Manila Tondo
3. Mumbai Dharavi
4. Mumbai Bharat Nagar
5. Khartoum Al-Sahafa
6. Lagos Makoko
7. Chandigarh Sector 59 East
8. Caracas Petare
9. Afgooye Lafoole Refugee Camp
10. Mexico City Magdalena Contreras
11. Nairobi Kibera
12. Qazvin Navvab Safavi
13. Mumbai Santosh Nagar
14. Beijing Dashilanr
15. Cape Town Silver Town
16. Rio De Janeiro Turano
17. Cape Town Victoria Merge
18. Cairo Manshiet Nasser
19. Santiago De Chile Lo Prado
20. Cairo Imbaba
21. Tunis Cite Ettadhamen
22. North Philadelphia
23. Lima Comas
24. Bucharest Tei Toboc
25. Dhaka Islambagh
26. Teheran Eslamshahr
27. Ho Chi Minh Khu pho2
28. Dar es Salaam Tandika
29. Kyoto West
30. Lisbon Cova
31. Rio de Janeiro Morro do Cantagalo
32. Sliven Nadezhda
33. Brasilia Paranoa
34. Dar es Salaam Keko
35. Madrid Canada Real
36. Rio de Janeiro Morro Do Valongo
37. Brussels Molenbeek
38. Al Zaatari Refugee Camp
39. Dhaka Kadamtali
40. Shenzhen Baishizhou
41. Athens Agios Panteleimonas
42. Calcutta Sector 1
43. Dar es Salaam Lugalo Golf
44. Kyoto Nakagyo Ward
45. Izmir Kadifekale
46. Los Angeles West Addams
47. Kyoto Yamashina Ward
48. Amsterdam Jordaan
49. Madrid Centro Madrid
50. New York Lower Manhattan
51. Brussels Anneessens
52. Budpest Monserrat
53. Istanbul Gulsuyu Gulensu
54. Edinburgh Greenbank
55. Manhattan East Village
56. Edinburgh West End
57. Hyderabad Boudha Naga
58. Hyderabad Gandhinagar
59. Edinburgh The Grange
60. Merida Old Center
61. Tokyo Urayasu
62. Tokyo Minamimagome
63. Sao Paulo Centro
64. Riverside North Lawndale
65. Forest Hill Forest Hill
66. Ho Chi Minh Binh Tho
67. Lusaka Misisi
68. Bangkok Panthiya Village

69. Bogota Polo Club
70. Madrid Moratalaz
71. Pavia Old Center
72. Barcelona Ciutat Vella
73. Edinburgh Trinity
74. Kyoto Minamieganosho
75. Dar es Salaam Kiwalani
76. Seoul Hankuk University
77. Paris Central Arrondissements
78. Boston North End
79. Obihiro Jominami
80. Tokyo Shinbashi
81. Nagoya Naka Ward
82. Brasilia Lago Sul
83. Seoul Mangwon-dong
84. Sydney Padstow
85. Porto Alegre Menino Deus
86. Katmandu Anamnagar
87. Naarden Naarden
88. Paris Gagny
89. Trier Hauptmarkt
90. Columbia Maryland Owen Brown
91. Katmandu Kalopul-Ratopul Rd
92. Barcelona Eixample
93. Edinburgh Craiglockhart
94. Calcutta Lake Market
95. Paris 9 Arrondissement
96. Toulouse Le Mirail
97. Lisbon Alfama
98. Bogota La Canderlaria
99. Delhi Karol Bagh
100. Berlin Kreuzberg
101. Dar es Salaam Kigamboni Edge
102. Munich Marienplatz
103. Calcutta Lake Garden
104. Tokyo Shimokitazawa
105. Nagoya Arakocho
106. Rome Municipio I
107. Tokyo Sumida
108. Paris Adamville
109. Gaborone 8/10/11/12 Extensions
110. Miami Little Havana
111. Madrid Horcajo
112. Paris 6 Arrondissement
113. Lusaka Bauleni
114. Lusaka Luburma Central
115. Dublin Temple Bar
116. Munich Maxvorstadt
117. Dar es Salaam Kigamboni
118. Paris Clamart
119. Paris Belleville
120. Bern Innere Stadt
121. Dhaka Motijheel
122. Prague Prague
123. Historic Centre of Mexico City
124. New York Bronx
125. Katmandu Bagbazar
126. Manhattan Midtown
127. Qazvin Artesh Hospital
128. Calcutta Sector 1 Block CC
129. Bratislava Old Town
130. San Francisco South Of Market
131. Brie Comte Robert
132. Philadelphia Center City
133. Denver Five Points
134. Trier Im Falschen Biewertal
135. Miami Allapattah
136. Edinburgh New Town

137. Berlin Europa City
138. Delhi Greater Kailash
139. Manhattan Washington Heights
140. Charlottesville Fry's Spring
141. Vienna Innenstadt
142. Antananarivo Antsahamamy
143. Ottawa Downtown
144. Charlottesville Belmont
145. Perth Center
146. Washington Downtown
147. London Westminster
148. Budapest Inner City
149. Edinburgh Old Town
150. Cape Town Central Business District
151. Phnom Penh Sangkat Srah Chak
152. Munich Harlaching
153. Dallas Junius Heights
154. Antananarivo Central Station
155. Sarcelles HLM
156. London Tower Hamlet
157. Oslo Nordberg
158. Lusaka Bauleni West
159. Venice San Polo
160. Munich Obermenzing
161. Melbourne Central Business District
162. Edinburgh East Craigs
163. Nairobi Central
164. Richmond Downtown
165. Suloszowa Linear City
166. Pavia Borgo Ticino
167. Abu Dhabi AL Danah
168. Wellington Te Aro
169. Toronto Old Toronto
170. Munich Bogenhausen Nord
171. Oslo Sentrum
172. Downtown Los Angeles
173. Evry Evry-Courcouronnes
174. Dar es Salaam Masaki
175. Sydney Central Business District
176. Trier Petrisberg
177. Teheran Ekbatan South East
178. Belo Horizonte Santo Agostinho
179. Downtown Portland
180. Antananarivo Cite Belle Vue
181. Oslo Frogner
182. Dar es Salaam Mikoroshoni
183. Brisbane Central Business District
184. Pavia Parco Leopardi
185. Dar es Salaam Mikoroshoni (West)
186. Delhi Laxmi Bai Nagar
187. Bairut Hamra
188. Warsaw Srodmiescie
189. Auckland Central Business District
190. Pretoria Central
191. St Petersburg Admiralteysky District
192. Nakatsugawa Ochiai
193. Pavia Via Umberto Olevano
194. Downtown San Diego
195. Colombo Fort
196. Venice Castello
197. Brasilia North Wing

198. Saint-PBurg Vasileostrovsky District
199. Glendale Glendale
200. Vancouver Fairview
201. Rabat Administrative Sector
202. Brasilia Lago Sul Lake
203. Saint-Petersburgh Smolninskoye
204. Denver North Capitol Hill
205. Shanghai Tianping Res District
206. Brasilia ASA Sul
207. Charlottesville North Downtown
208. Ljubljana Center District
209. Sienna Old Center
210. Manhattan StuyTown
211. Budpest Gellerthegy
212. Ferrara Via Comacchio
213. Kansas Downtown
214. Bishkek Park
215. Indianapolis Mile Square
216. Chicago Central Business District
217. Downtown Seattle
218. Chicago Loop
219. Ferrara Ippodromo
220. Antananarivo Lake Anosy
221. Venice Giudecca
222. Reston North West
223. Durban Central
224. Detroit Downtown
225. Cairo Garden City
226. Calgary Downtown Commercial
227. Oslo Holmenkollen
228. Moscow Tverskoy District
229. Ferrara University District
230. Johannesburg Robin Acres
231. Manhattan Williams Bridge
232. Sienna San Prospero
233. Cleveland Downtown
234. Downtown Atlanta
235. Ferrara Doro
236. Paris Amerique
237. Houston central business district
238. Minsk City Center
239. Oslo Ulvoya
240. Kiev Pechers'kyi
241. St Louis Downtown
242. Sienna Ravacciano
243. Minsk Syerabranka
244. Seoul Bupyeong 1
245. Delhi Meena Bagh
246. Tokyo Shinjuku Center
247. Saint-Petersburgh Municipal Okrug
248. Minneapolis Downtown West
249. Minsk Kamennaya Gorka
250. Minsk Kastrycnicki Raion North
251. Venice Castello West
252. Madrid La Finca
253. Charlotte City Center
254. Saint-Petersburgh Moskovskaya Zastava
255. Munich Arabella park
256. Tokyo Chiyoda
257. Teheran Ekbatan Phase 2
258. Teheran Ekbatan Phase 1
259. Columbia Maryland Town Center
260. Reston Town Center

.

4. Results

In general, our findings empirically show, that the elements of the built landscape result in a physical form that reflects the intensity of the underlying human planning, i.e. it relates to the conceptualized IoP. In this section, we first illustrate the distribution of the entropy per individual parameter as well as for each structural element in general. Beyond this, we reveal the result of their statistical significance tests.

In the following paragraphs, we first present the results with Figs. 6a and 6b. This figure is composed of snippets of 500 m × 500 m of figure-ground diagrams, each displaying, the morphology of *buildings* per settlement. The color of the snippet's border relates to its IoP category. The
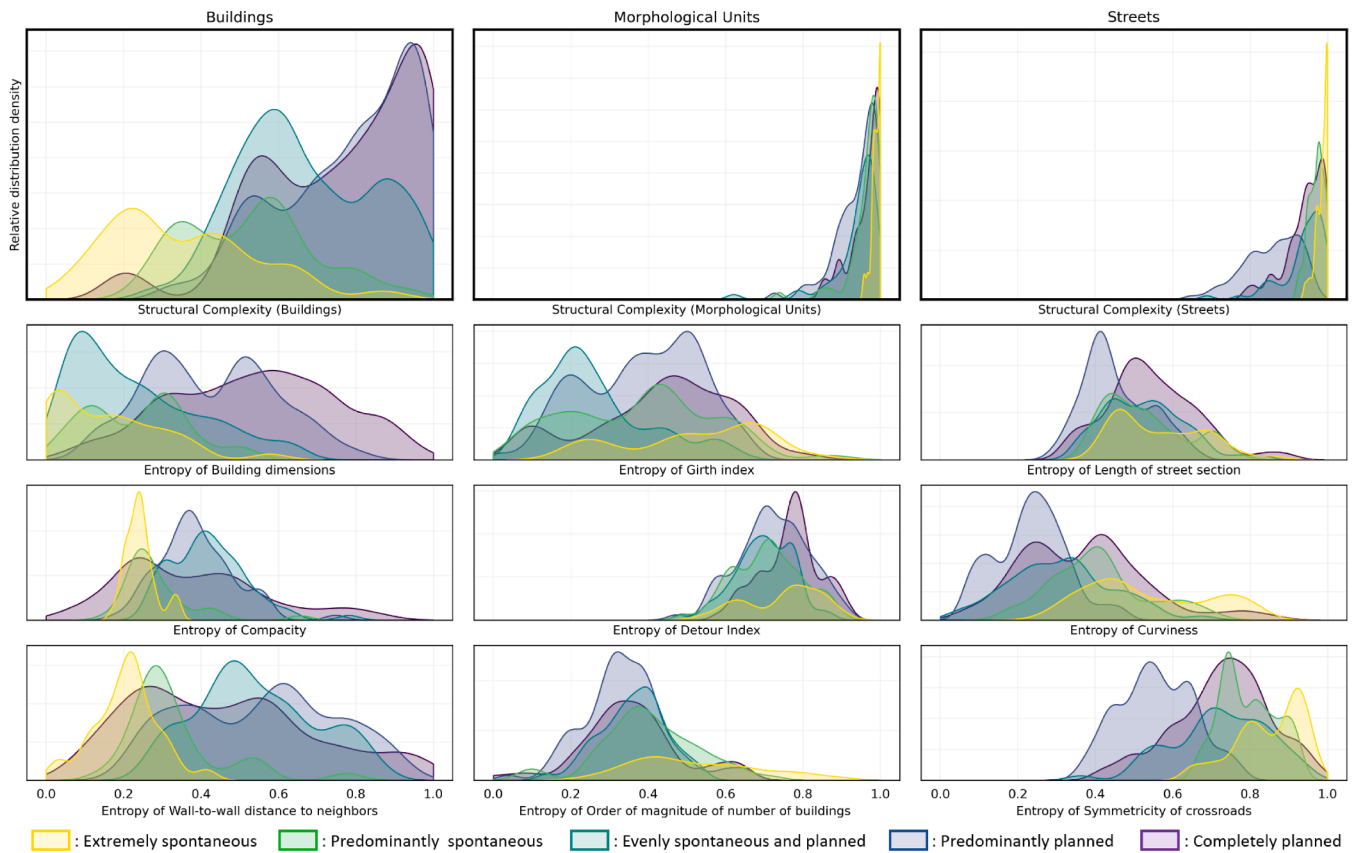
Fig. 7. Distribution of the structural complexity (top row) and distribution of the individual entropies of the three parameters, grouped and colored by category of IoP for each of the three structural elements.

snippets are ordered by increasing *structural complexity* of the element *buildings*. The equivalent figures for, respectively the structural element *morphological units* and the structural element *streets* can be found in the Appendix, respectively Appendixes D1 – E2.

Subsequently, we illustrate the statistical distribution of the structural complexity in Fig. 7. For each structural element, the statistical distribution of the values of our metric per settlement grouped by categories of IoP is displayed. In this figure, as a supplementary information, we also plot the statistical distribution of the entropy for each individual parameter which the structural complexity is based on. Finally, we discuss the statistical relationships between the categories of IoP and the *structural complexity* for each structural element.

For the structural element *buildings*, as observed in F. 6 and Fig. 7, the different categories of IoP tend to overlap, however, still distinguishable trends are measured. For the parameter *building dimension*, a consistent increase of the entropy with increasing IoP is found. In comparison, *compacity* presents a slightly different profile. The entropy is quite consistently low for a low IoP. It increases to a relative maximum with the category *Evenly spontaneous and planned* and a decrease again with the category *Completely planned.* This category shows a large spectrum of entropy possible but, on the majority, as low as the *Extremely spontaneous* settlements. For the third parameter, the *wall-to-wall distance to neighbors,* there is a clear pattern of, on average, increasing entropy with increasing IoP, with a slight recess for the category *Evenly spontaneous and planned.* When combined, the set of the three parameters concerning the *buildings* show an increasing structural complexity along with the ranks of categories of plannedness.

Statistically, the distributions of the structural complexity for the structural element *building* reveal differences. With 260 settlements, the result of the Kruskal-Wallis analysis shows a p_{KW} value of 2 e-17, which

is far below the threshold of 0,05. Hence, we conclude that categories of IoP feature at least one category significantly different from the others for the *buildings.*

This is generally confirmed by the Mann-Whitney analysis (Table 3). With the exception of the two categories with the highest IoP – *Predominantly planned* and *Completely planned* – we measure significant differences in term of structural complexity for all other categories. Thus, we conclude that for the structural element *buildings*, settlements of different IoP categories are discernable based on their structural complexity.

For the *morphological units*, the two first parameters seem to present more compact distributions of entropies for the settlements of different categories of IoP. For the *girth index*, even though clumped together, we discern a trend of decrease and then increase of the entropy with higher IoP, with a minimum for the *Evenly spontaneous and planned* category. The *detour index,* on the other hand, presents less discernable differences in terms of entropy, except for an ever so slight decline with increasing IoP. The last parameter of the *morphological units* distinguishes itself and offers a less packed profile: The entropy of the *order of magnitude of number of buildings* is decreasing and then re-increasing with ascending categories of IoP, just as the *girth index* but in a more discernable way. The structural complexity of the *morphological units*, being the joint entropy of all three parameters, shows for all categories a high entropy indicating high variability of the individual parameters with regard to each other's. We observe that for the MUs as well, the different categories of IoP tend to overlap. but some trends exist. Here, we find a slight decrease and then a secondary increase with a minimum for the category *Evenly spontaneous and planned.*

With the test being led on 260 individual settlements, the result of the Kruskal-Wallis analysis shows a p_{KW} value of 1 e-08, which is below

Table 3
Symmetric matrix of the pairwise results of the Mann-Whitney significance test for structural element Buildings. A value of $p_{MW} \leq 0,05$ indicates that the two categories are significantly different in term of structural complexity. For ease of understanding, we crossed the values above the threshold.

Structural element: **Buildings**	Extremely spontaneous	Predominantly spontaneous	Evenly spontaneous and planned	Predominantly planned	Completely planned
Extremely spontaneous		…	…	…	…
Predominantly spontaneous	$6,9 \times 10^{-3}$		…	…	…
Evenly spontaneous and planned	$3,9 \times 10^{-8}$	$5,5 \times 10^{-3}$		…	…
Predominantly planned	$5,7 \times 10^{-11}$	$7,0 \times 10^{-7}$	$7,9 \times 10^{-3}$		…
Completely planned	$3,0 \times 10^{-10}$	$4,1 \times 10^{-6}$	$1,9 \times 10^{-2}$	~~1,0~~	

Table 4
Symmetric matrix of the pairwise results of the Mann-Whitney significance test for structural element MUs. A value of $p_{MW} \leq 0,05$ indicates that the two categories are significantly different in term of structural complexity. For ease of understanding, we crossed the values above the threshold.

Structural element: **Morphological Units**	Extremely spontaneous	Predominantly spontaneous	Evenly spontaneous and planned	Predominantly planned	Completely planned
Extremely spontaneous		…	…	…	…
Predominantly spontaneous	$1,9 \times 10^{-3}$		…	…	…
Evenly spontaneous and planned	$3,1 \times 10^{-8}$	$1,3 \times 10^{-2}$		…	…
Predominantly planned	$2,3 \times 10^{-6}$	~~$6,7 \times 10^{-2}$~~	~~1,0~~		…
Completely planned	$3,1 \times 10^{-2}$	~~1,0~~	$2,4 \times 10^{-2}$	~~$6,3 \times 10^{-2}$~~	

Table 5
Symmetric matrix of the pairwise results of the Mann-Whitney significance test for structural element Streets. A value of $p_{MW} \leq 0,05$ indicates that the two categories are significantly different in term of structural complexity. For ease of understanding, we crossed the values above the threshold.

Structural element: **Streets**	Extremely spontaneous	Predominantly spontaneous	Evenly spontaneous and planned	Predominantly planned	Completely planned
Extremely spontaneous		…	…	…	…
Predominantly spontaneous	$5,0 \times 10^{-4}$		…	…	…
Evenly spontaneous and planned	$1,0 \times 10^{-7}$	$2,7 \times 10^{-2}$		…	…
Predominantly planned	$7,7 \times 10^{-17}$	$7,8 \times 10^{-18}$	$8,0 \times 10^{-10}$		…
Completely planned	$1,8 \times 10^{-7}$	~~$6,2 \times 10^{-2}$~~	~~1,0~~	$2,5 \times 10^{-13}$	

the threshold of 0,05. However, this value is higher and closer to it than for the *buildings*. We conclude that categories of IoP present at least one category significantly different from the others. The Mann-Whitney analysis results in the following matrix (Table 4):

We conclude for the structural element *morphological units* that most of the categories of IoP are discernable based on their structural complexity. Still, two pairs of categories that are relatively close, '*Evenly spontaneous and planned/Predominantly planned*' and '*Predominantly*

planned/Completely planned' cannot be considered as significantly different. Further, for this structural element, two categories with high differences of IoP '*Predominantly spontaneous/Completely planned*' feature the same types of structural complexity and '*Predominantly spontaneous and Predominantly planned*' are not significantly different.

For the structural element *streets*, we observe again a different statistical trend for the different individual parameters. First, for the *length of street section*, although presenting slight but still discernable

differences of entropy between the different categories of IoP, there is no major trend identifiable. Rather, the distribution fluctuates back and forth around the main mode of the entropy distribution of the *Extremely spontaneous* category. For the *curviness*, the profile gives a clearer trend: the entropy decreases constantly with ascending IoP and only increases again for the category *Completely planned*. For the *symmetricity of cross-roads*, the categories of IoP reveal mostly distinctive entropies with again the same trend as previously observed: Values decrease progressively with increasing IoP, except for the *Completely planned* category where we observe a re-increase. In summary, we observe for the structural complexity of the *streets*, the same type of trend as for the *morphological units*, an overall clustering of the categories in the high values of the spectrum.

The result of the Kruskal-Wallis analysis led on 296 settlements shows a p_{KW} value of 3 e-19, which is even further below the threshold of 0,05 than for the *buildings*. Hence, we conclude that categories of IoP present at least one category significantly different from the others. The results of Mann-Whitney analysis are presented in Table 5.

For the structural element of *streets*, we generally ascertain significative differences in term of structural complexity of the different categories of IoP. The exception is the category *Completely planned* being similar to the category *Evenly spontaneous and planned* and not significantly different from the category *Predominantly spontaneous*. Noteworthy is the fact that these two last categories are, between them, significantly different. Further, contrary to the two previous structural elements, the difference between *Predominantly planned* and *Completely planned* is highly significant.

To summarize, from the analyzes on the three structural elements, it is empirically clear that the built landscape does not correlate linearly or one-to-one with the degree of planning. In general, however, our results prove a difference in the particular distributions of the parameters. In other words, despite overlapping in the distributions, a definite trend is emerging that reveals empirically that the built landscape reflects the degree of planning.

5. Discussion

In most cases, the physical structure of cities repeatedly undergoes a chain of transformation processes over time. The resulting morphology is an artifact that we have to observe through the scope of these successive modification sought by people. This scope allows us to understand the intra-urban morphology as the crystallization of urban processes whose main drivers are societal in nature. Despite the knowledge of this relationship between urban forms and undergone urban processes, to unveil the later from the first is a challenge.

In this paper, we proposed a conceptual frame of bottom-up and top-down planning to examine the intra-urban morphology in this regard and to empirically reveal the intertwined relation of urban processes and built forms. We developed a categorical scale of the IoP for urban processes and we tested empirically whether this scale is adequate to observe significant physical differences in the measured *structural complexity* operationalized by three main structural elements of the urban fabric: the *buildings*, the *morphological units* and the *streets*. We used an unprecedented large sample of 381 settlements from as many different cultural zones of vernacular architecture as we could find reliable information on.

In our experiments, we were able to empirically prove what has often been described in the literature in a theoretical manner: There exist generally and globally significant morphological appearances arising from distinct types of urban processes, here understood as different categories of IoP. Additionally, the pairwise comparisons of *structural complexities* of different categories of IoP expose, in most cases, largely statistically significant differences in their morphologies, as estimated by our set of parameters. For the buildings, 9 out of 10 pairwise comparisons show significant differences in the *structural complexity* of the categories of IoP. For the Morphological Units, 6 out of 10 and for the

streets, 8 out of 10 present significant differences.

Interestingly, no manifest co-evolution between the *structural complexity* and the IoP can be showcased here. As a rule of thumb, one might have expected the *structural complexity* to be at its lowest when the process of standardization is at its strongest. In consequence, the *structural complexity* was expected to decrease with an increasing IoP. What we observed, on the contrary, is that the *structural complexity* of the *buildings, morphological units* and *streets* evolve very differently with regard to their IoP. Although anecdotical for this study, this specific secondary result seems interesting and is suggested e the for further studies.

Despite our approach demonstrating the connection between the IoP and our estimator of the urban morphology – the *structural complexity* – this study also highlights some nuances: For each structural element, a few pairs of distinct categories of IoP present hardly distinguishable *structural complexities*. Also, in the case of every structural element, the juxtaposition of the *structural complexity* with the individual entropy of each constitutive parameter brings forth a complex situation of mutual information between parameters that was not quantified here.

Although these nuances are not impeding our demonstration of the relation between the IoP and the intra-urban morphology, they raise interesting limitations of the use of the *structural complexity* as an unequivocal estimator of the intra-urban morphology outside of the scope of this study.

We acknowledge that the specific set of morphological parameters we have chosen, despite being based on known urban processes, is non-exhaustive. We do not see this set of parameters as being necessarily the only one possible for the demonstration intended here. Therefore, beside the *structural complexity* and its constituent morphological parameters presented in the main body of this article, we investigated the relation between IoP and other morphological parameters. We tested 58 additional parameters (resp. 60) for the buildings and the Morphological Units proposed in (Fleischmann, 2019) and consolidated with the additions presented in (Fleischmann et al., 2020). For the streets, we computed 21 additional parameters issued in (Boeing, 2017, 2019). On these additional parameters, we computed the individual normalized entropy when fitting, and then proceeded to the Kruskal-Wallis test and, when required, the Mann-Whitney test. The results of this additional analysis concur with the empirical relations achieved with the *structural complexity* and are compiled in Supplementary material 2. That is, among the pairs of categories of IoP, in general, significant differences are showcased by most of these parameters. With it, we show that the literature-based selection of the spatial parameters has not led to space-statistical coincidence. These additional parameters paint a more complete picture of what are relevant parameters showing contrast in the morphology of different categories of IoP (see Supplementary material 2). This was not investigated here and could be at focus in further studies. In this article, we focus specifically on the *structural complexity* as its constitutive parameters are clearly linked to the urban processes, simple enough in their formulation and they have established themselves to be suitable to answer our research question.

On a more general ground, we believe that shallow statistics, such as the parameters used here, are limited in their capacities to unveil, in their uttermost depth, the interdependencies between urban process and resulting morphologies. Partially or completely overlapping distributions of *structural complexities* established this. Therefore, it is not our claim here that the IoP can be automatically classified using this *structural complexity* metric or other morphological parameters out of comparable geodata.

This lack of direct prediction power from our quantitative measure was to be foreseen in the face of the complexity of the intertwined path dependencies of urban forms and processes but does not deter any qualitative prevision regarding the morphology displayed by these processes (Moroni & Cozzolino, 2019).

Beyond these considerations on the validity of the *structural complexity* as an unequivocal estimator of the intra-urban morphology, we do want to acknowledge observed limitations within our study. The

origins of these limitations were kept, by the authors, as circumscribed as possible not to mitigate the overall analysis.

The first limitation is tied to the nature of the data used. Despite being of really high spatial resolution, OSM data, and other manually digitized data are prompted to be inconsistent across settlements. For example, the way buildings are digitized can vary from one polygon for a continuous built street block, to multiple polygons for a single-family house as they can vary from interpreter to interpreter (Kraff et al., 2020a). We paid attention to this while curating the data to eliminate gross inconsistencies. Still, residual inconsistencies remained in our dataset. This type of inconsistencies occurring across our samples tend to blur the computation of the *structural complexity* and, as a consequence, impact the analysis by an unknown factor. Datasets of large coverage in the likes of (Microsoft, 2020) would be of great interest in future studies to help eliminate further residual inconsistencies.

The second limitation is related to the residual uncertainties in the qualitative assessment of the IoP. While a great deal of effort has been made in assessing the categories of IoP for each type of structural element per settlement based on an extensive literature research, we acknowledge that an irreducible part of uncertainties remains. Levels of certainty in the assessments of the IoP can originate both, in the quality of sources available and in the clarity of our ontology. E.g., whereas categories at the ends of the spectrum of our IoP concept, i.e. *Extremely spontaneous* and *Completely planned* are easy to identify, intermediary categories – from our experience – are less unambiguous when classifying along our ontology. In Supplementary Material 1, we propose a self-evaluation of our level of certainty with respect to the assessment of the IoP. In addition, while in that scope of this explorative study, this relative uncertainty was not a deterrent, we encourage future research to further refine and detail the ontology and the operationalization of the assessment of levels of the IoP to curb as much as possible the part of uncertainty.

Despite the existence of these limitations within our study, we argue that the validity of the quantitative measure of the *structural complexity* and the qualitative assessment of the IoP is transparent according to a clear literature-based approach. Moreover, we argue that the high amount of sample used for each statistical test, further add to the reliability of the global analysis and of our empirical demonstration.

The primary scientific aim of this study is to elaborate the concept of the IoP and to empirically investigate its relation to the built-up form.

With the concept of the IoP, we aim to bring forward the under-theorized political and societal component of the making of the intra-urban morphology. Therefore, the IoP shall serve as a stable conceptual ground to renew the study of a large body of topics where the built-up form stands at the interface with societal matters.

In his work (Alexander, 1979), Christopher Alexander put forth "a quality without a name" of prosperous urban spaces. Although we do not claim here that the IoP of an urban space explains altogether the actual existence or not of this "quality without a name" within it, we nonetheless do believe that it is indeed one of the underlying tenets to this quality. As such, a field of study, trailblazing the "unnamed" quality as suggested by Alexander and where we do believe in the relevance of the integration of the ontology of the IoP is the study of the "urban quality of life" (Higueras, Román, & Fariña, 2021).

This field of study has already proven relevance in the analysis of urban fabric's form to investigate multiple facets of individual and collective qualities of urban life (McDonald, Wise, & Harris, 2008; Mouratidis, 2018; Sapena et al., 2020, 2021). It has already been shown that the form of the built-up environment share a relation with aspects driving the urban quality of life such as (among others) well-being, physical health, mental health (Frank & Engelke, 2001; Hajrasoulih,

del Rio, Francis, & Edmondson, 2018; Krefis, Augustin, Schlünzen, Oßenbrügge, & Augustin, 2018; McDonald et al., 2008; Mouratidis & Poortinga, 2020; von Szombathely et al., 2017), and social relations (Legeby, Berghauser Pont, & Marcus, 2015; Mouratidis & Poortinga, 2020; Mouratidis, 2018). Nonetheless, this field of study displayed so far some limitations in fully explaining how the material features of the built-up environment do influence these aspects of the urban quality of life (Berghauser Pont, Haupt, Berg, Alstäde, & Heyman, 2021; Hajrasoulih et al., 2018). As such, the body of literature on this topic acknowledges the great complexity of it that fail to be captured by physical features alone (Hajrasoulih et al., 2018; von Szombathely et al., 2017). Therefore, numerous arguments could be made in favor of integrating the IoP ontology in this field of study, on the base of its unique characteristic to be at the interface between the material and the social part of the built-environment. Yet, one decisive argument for the relevance of the IoP to this field of study is related to one of the important aspects of the urban quality of life proposed in (Higueras et al., 2021), namely the levels of freedom of the inhabitants. We argue that this aspect relates greatly to the notion of self-agency of the population in the making and adapting of their urban environment that we argue to be a key factor of the ontology of the IoP.

Although we see the study of the urban quality of life as a privileged field of research where the ontology of the IoP could be key to operationalize this multi-faceted, complex phenomenon, we do not see a limitation of its relevance to this field only. We also argue firmly that its benefits extend to the wider scope of study of the empirical signs of the collective, social, economic or even esthetical prosperity urban spaces at large.

Therefore, we suggest to integrate the use of the concept of IoP to the study in a large range of urban topics such as, the capacity of communities to form in cities (Mouratidis & Poortinga, 2020; Tonkiss, 2013), the possibility for informal micro-economy to emerge (Salat & Bourdic, 2012; H. Thai, Stevens, & Rogers, 2020; H. M. H. Thai, Stevens, & Rogers, 2019), capacity to adapt to the lack of surplus of housing (Zhang & Zhao, 2018), or the esthetical appreciation of cities (Cozzolino, 2021), or even the emergence of land-use patterns (M. R. G. Conzen, 1960) among many more….

We ultimately regard the ontology of the IoP to be an adequate conceptual frame to compare different urban planning policies and their subsequent impacts. We consider that such investigations would nourish the discourses and theories on urban planning policies and therefore, we deeply encourage these fields of study to seize for themselves and utilize the concept of the IoP.

6. Conclusion

For a long time, urban geography was rich in theories and poor in data, at least at a global context. Developments in remote sensing and crowd-sourcing approaches, however, now make it increasingly possible to support or reject theories with empirical findings – at least for the built urban landscapes.

Physicalist approaches of town and city planning theory outline the deep impact that the configuration of built environment has on the communities it hosts (Batty & Marshall, 2009). The built-up density, the height of buildings, the amount of green space per capita, the distance to amenities, among others are applied for the assessment of the quality of the built-up environment through the perspective of a physicalism (Batty & Marshall, 2009). And still, statistical approaches solely focusing on the material part of urban morphology display conflicting evidences of its impact in a comprehensive manner (Hajrasoulih et al., 2018; Krefis et al., 2018).

We argue that a new approach can focus on taking a look at the effects of the physical environment on communities through the prism of the IoP. This is motivated by the fact that the IoP is a synthetic information of the brawls and struggles the society went and is going through. We have the intuition that our concept could reveal itself particularly fitting to the study of individual and collective urban qualities that have yet been hard to grasp through shallow-statistic approaches, such as social well-being and individual quality of life, economical and communities thrive and resilience.

Based on these considerations, we suggest empirical work analyzing in which way specific types of the IoP are statistically related to these urban qualities. From such work, we expect new insights and new tools for the practice of the city-making to allow for the desired balance between bottom-up democratic expression of the inhabitants and users' needs, and top-down control of a protection of commons (Cozzolino, 2020; Ostrom, 1990; Shipley & Utz, 2012).

With this research we attempt to lay a foundation – conceptually and empirically – to measure the built morphology and to relate to what can be read in it with respect to the IoP. As data on built morphology are becoming more and more available, this is intended to be a conceptual as well as empirical basis for large-scale or global studies of cities, their structure, their planning processes and their comparisons to understand the regularities, similarities and specifics in more detail. With these considerations, we encourage further studies willing to investigate the *Intensity of Plannedness* to enrich the ontology we propose in Table 1.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

Funding

Appendix A

Figs. A1–A3.

Fig. A1. Map of the geographic distribution of the study sites used for their buildings

Fig. A2. Map of the geographic distribution of the study sites used for their morphological units

Fig. A3. Map of the geographic distribution of the study sites used for their streets

Appendix B

The definition we proposed for the MUs in section II)b) as being the surface on which a collection of buildings sharing collective spatial relationship sits, relies on the definition given, in its street-independent acceptation. Nonetheless, in relatively planned areas (categories *Predominantly spontaneous* to *Completely planned*), we acknowledge the relevance of streets in the definition of MUs and their methodological pertinence. Therefore, in these cases, we extract our MUs as the polygons constrained by street meshes.

In the context of not strongly planned MUs, where streets are often not defining the Morphological Units (cf. Table 1), this strategy is not possible. Thus, in *Extremely Spontaneous* settlements, we then consider the following: The definition of MUs is understood as groups of buildings being spatially grouped together with consistent density and arrangement. Using the main principles of differential-density-based OPTICS clustering (Ankerst et al., 1999), we propose an aggregation algorithm. We automatize the MUs computation in these cases as follows (Fig. C1): in Python 3 (Software, 2020) firstly, for each building of a settlement, we compute the wall-to-wall distance (Shapely 1.7.1 Documentation, 2021) to the next closest buildings. Secondly, we group buildings being, with a slight tolerance of 5%, symmetrically the closest one from each other. That is, if the closest neighbor of a building A is a building B, and vice versa – which is not trivially always the case. Then, for each of the groups formed (with more than one building), we operate a morphological dilation for each of the buildings being paired, by a radius of length equal their wall-to-wall distance to their closest neighbor. Finally, we operate a morphological closing of a radius of 1m (being, to our view, the width of the narrowest street a pedestrian could walk). Additionally, we consider the buildings left aside by the second step as single buildings Morphological Units. We consider the polygons then produced as being the boundaries of each MU (Fig. C1).

Pseudo-code:

```
For each building i:
    For each building j ≠ i:
        Compute wall-to-wall distance d(i,j)        #Mutual distances computation
    Get min(d(i,*))
    For each building j ≠ i:
        If d(i,j) ≤ min(d(i,*))*1.05:        #Symmetry check with confidence interval of 5%
            Add j to the group to which i belongs        #Aggregation
For each group K:
    Compute max(min(d(i,*))) (over all buildings i in K)
    For each buildings i in K:
        Perform dilation of max(min(d(i,*)))        #Creation of the area of control
        Perform a negative dilation of 1m        #Refinement of the MUs
```

Appendix C

Once all the values for the parameters are computed, we divide, in each and every settlement, each parameter's distribution into equal-sized bins to do their histogram. We do so with respect to the scale of the physical reality the specific parameter is related to. This is to be understood as abstracting two values of a parameter as being close enough to each other to be considered approximately equal in dimension (e.g.: a first section of a road being 20 meters long, is approximately as long as a second section being 22 meters long and comparatively different from a third being 100 meters long). The specific bin size of each of the parameters is noted in Table 2.

After binning the values for every settlement, as a measure of diversity, we rely on the Shannon entropy (Shannon, 1948). Shannon entropy is a measure of a system's diversity, or information complexity. Here we use it to assess, in each settlement, the dispersion of values computed for both individual parameters and for sets of parameters. More specifically, we compute the individual entropy as:

$$Entropy_\lambda(A) = \frac{-\sum_i P(\lambda_i)*\log_2 P(\lambda_i)}{-\log_2 n} \tag{1}$$

With:

$$\sum_i P(\lambda_i) = 1$$

Where A is the given settlement where the entropy is measured; λ is a parameter listed in Table 2; i is an individual bin of this parameter and n is the number of objects of the structural element λ is computed on.

And we compute the *structural complexity* of a structural element in a settlement as the normalized joint entropy of its set of three parameters
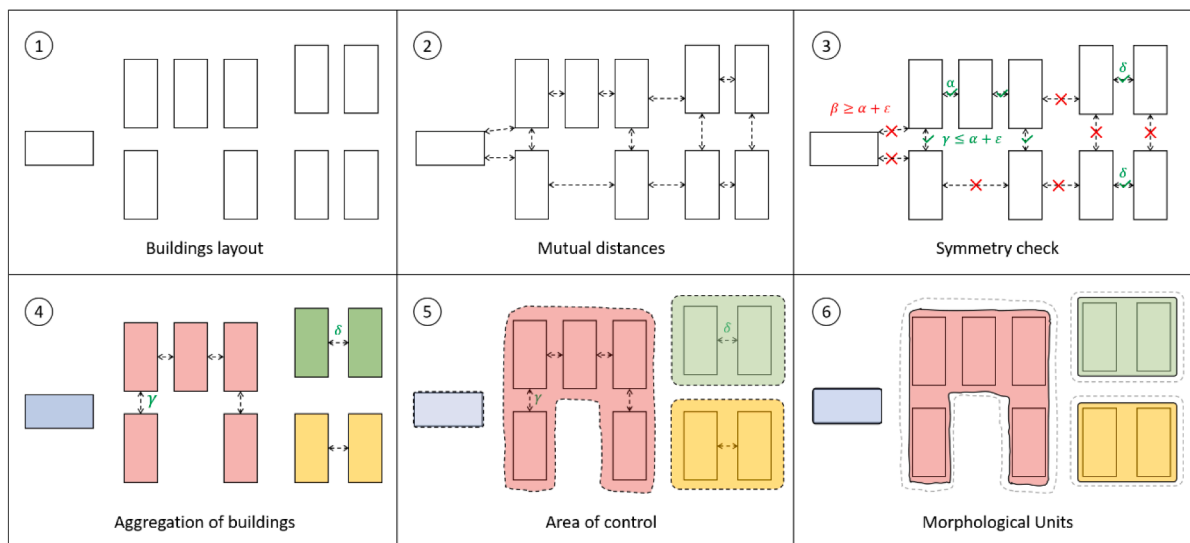

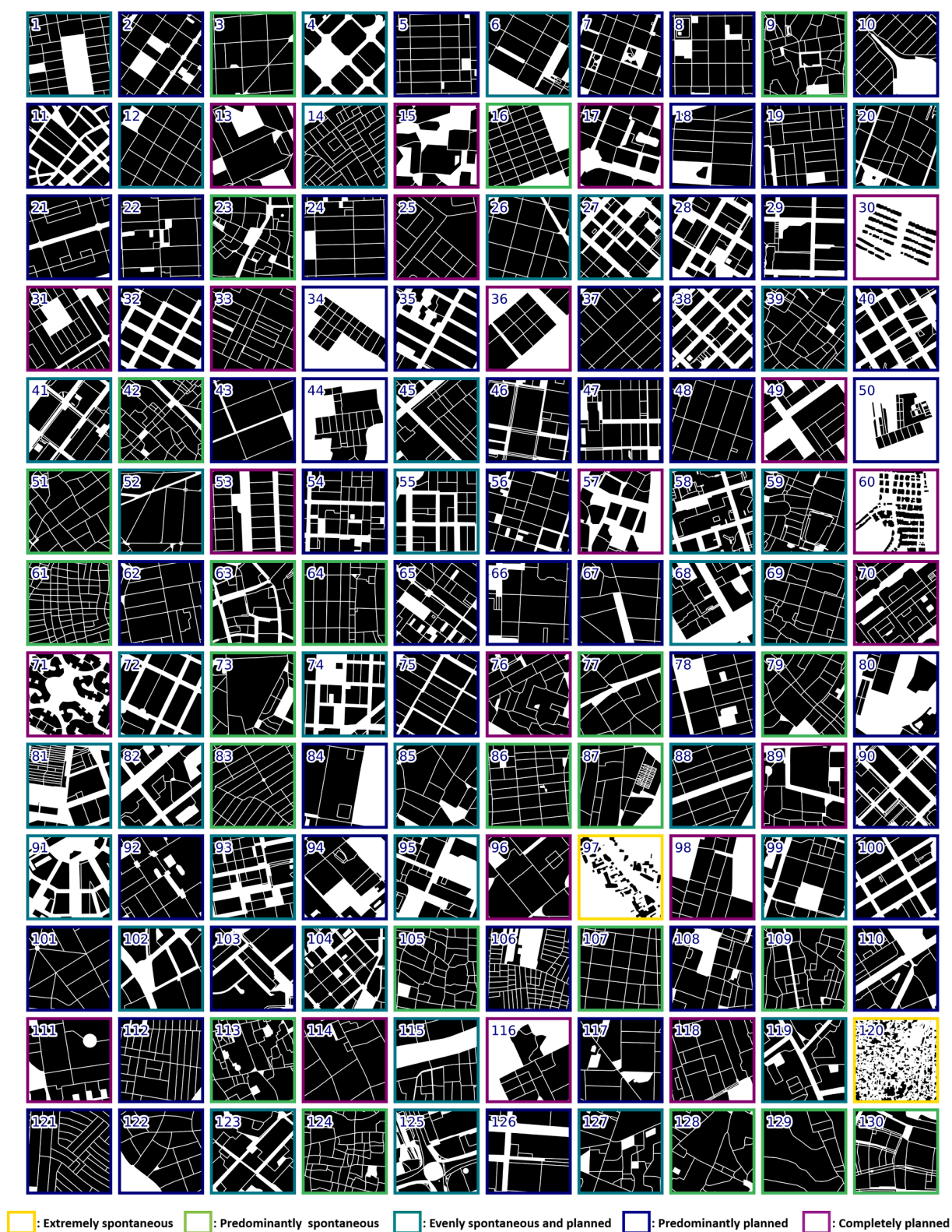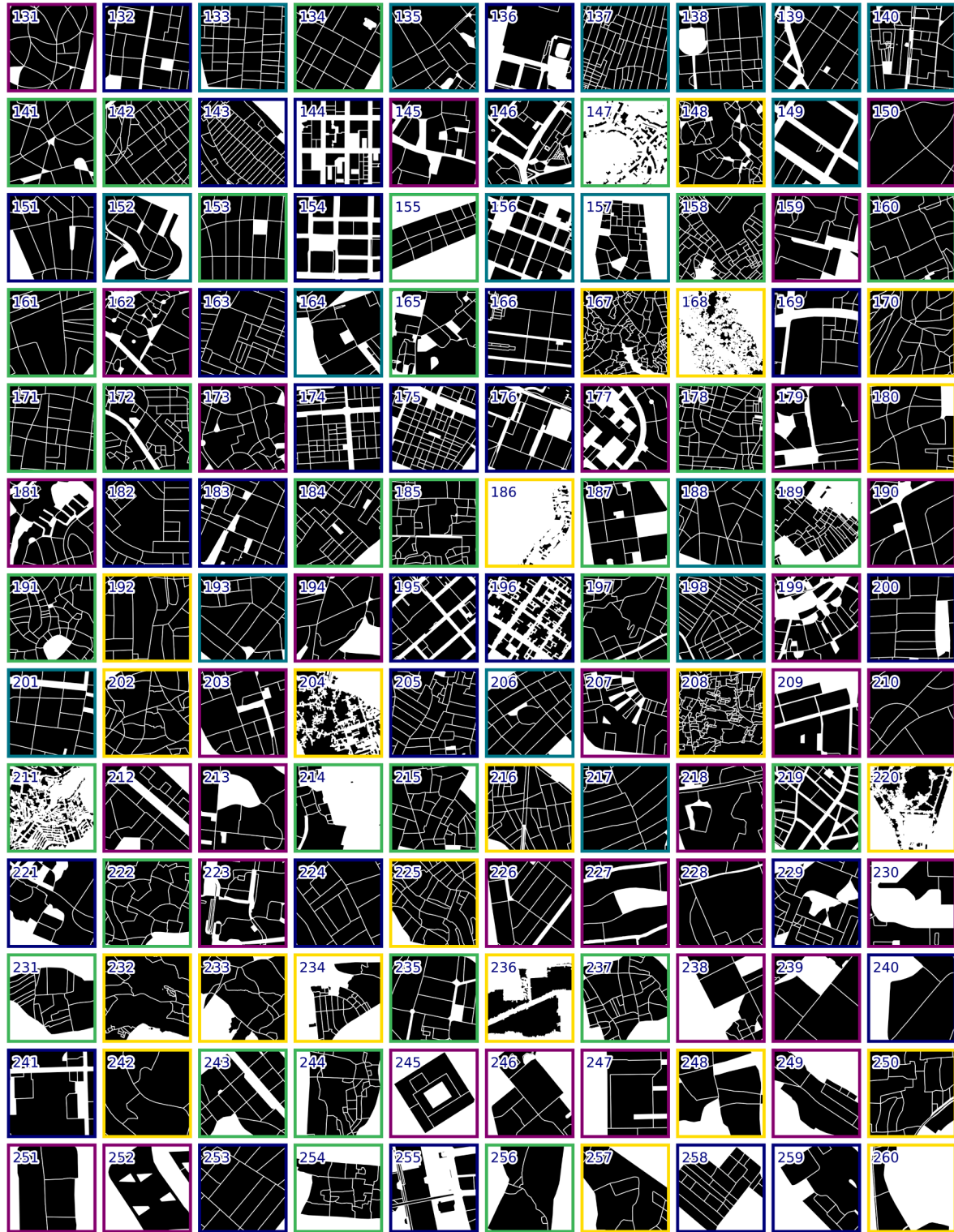**Fig. C1.** Steps to compute the Morphological Units

Fig. D1. Figure-ground diagram snippets of a 500m × 500m subset of each study site used for the analysis of the structural element MUs. The snippets are ordered by increasing structural complexity and framed in color with respect to their IoP. List of the study sites below

described in Table 2, as:

$$Structural\ complexity_{element\ X}(A) = \frac{-\sum_{i,j,k}P(\{\alpha,\beta,\gamma\}_{i,j,k})*\log_2 P(\{\alpha,\beta,\gamma\}_{i,j,k})}{-\log_2 n} \tag{2}$$

With:

☐ : Extremely spontaneous   ☐ : Predominantly spontaneous   ☐ : Evenly spontaneous and planned   ☐ : Predominantly planned   ☐ : Completely planned

(caption on next page)

Fig. D2. Figure-ground diagram snippets of a 500m × 500m subset of each study site used for the analysis of the structural element MUs. The snippets are ordered by increasing structural complexity and framed in color with respect to their IoP. List of the study sites below

1. Khartoum Al-Sahafa
2. Houston central business district
3. Budpest Monserrat
4. Barcelona Eixample
5. Riverside North Lawndale
6. Manhattan Midtown
7. Downtown Portland
8. Downtown San Diego
9. Madrid Centro Madrid
10. Tokyo Urayasu
11. New York Lower Manhattan
12. Bogota La Canderlaria
13. Saint-Petersburgh Municipal Okrug
14. Tunis Cite Ettadhamen
15. Minsk Kamennaya Gorka
16. Sliven Nadezhda
17. Madrid Horcajo
18. Rio de Janeiro Morro do Cantagalo
19. Obihiro Jominami
20. Paris Central Arrondissements
21. Edinburgh New Town
22. Miami Allapattah
23. Rome Municipio I
24. Miami Little Havana
25. Gaborone 8/10/11/12 Extensions
26. Belo Horizonte Santo Agostinho
27. Cape Town Central Business District
28. Minneapolis Downtown West
29. Vancouver Fairview
30. Qazvin Artesh Hospital
31. Calcutta Sector 1
32. Manhattan Washington Heights
33. Forest Hill Forest Hill
34. Lusaka Bauleni West
35. Manhattan East Village
36. Brasilia ASA Sul
37. Dallas Junius Heights
38. Denver Five Points
39. Vienna Innenstadt
40. Downtown Seattle
41. Downtown Los Angeles
42. Barcelona Ciutat Vella
43. Teheran Velenjak
44. Seoul Hankuk University
45. St Petersburg Admiralteysky District
46. Philadelphia Center City
47. Chicago Loop
48. Los Angeles West Addams
49. Chandigarh Sector 59 East
50. Venice Castello
51. Merida Old Center
52. Paris 9 Arrondissement
53. Qazvin Navvab Safavi
54. Indianapolis Mile Square
55. Washington Downtown
56. St Louis Downtown
57. Manhattan Williams Bridge
58. Toronto Old Toronto
59. Munich Marienplatz
60. Bangkok Panthiya Village
61. Cairo Ezzbet Al Haggana
62. Durban Central
63. Prague Prague
64. Kyoto Nakagyo Ward
65. Richmond Downtown
66. Calgary Downtown Commercial
67. Paris Gagny
68. Saint-PBurg Vasileostrovsky District
69. Pavia Old Center
70. Abu Dhabi AL Danah
71. Manhattan StuyTown
72. Oslo Sentrum
73. London Westminster
74. Kansas Downtown
75. Charlottesville Belmont
76. Madrid Moratalaz
77. Budapest Inner City
78. Harare Avenues
79. Ferrara Doro

80. Reston Commercial Area
81. Melbourne Central Business District
82. Minsk City Center
83. Teheran Eslamshahr
84. Johannesburg Robin Acres
85. Brussels Molenbeek
86. Nagoya Naka Ward
87. Sao Paulo Centro
88. Amsterdam Jordaan
89. Munich Arabella park
90. San Francisco South Of Market
91. Detroit Downtown
92. Cleveland Downtown
93. Chicago Central Business District
94. Charlotte City Center
95. Munich Maxvorstadt
96. Edinburgh West End
97. Suloszowa Linear City
98. Pavia Via Umberto Olevano
99. Ljubljana Center District
100. Ottawa Downtown
101. Paris Clamart
102. Oslo Frogner
103. Sydney Padstow
104. Downtown Atlanta
105. Nagoya Arakocho
106. Cairo Imbaba
107. Historic Centre of Mexico City
108. Auckland Central Business District
109. Tokyo Minamimagome
110. Munich Harlaching
111. Edinburgh Trinity
112. North Philadelphia
113. Edinburgh Old Town
114. Edinburgh The Grange
115. Dublin Temple Bar
116. Dar es Salaam Mikoroshoni (West)
117. Paris Adamville
118. London Tower Hamlet
119. Moscow Tverskoy District
120. Lusaka Misisi
121. Delhi Greater Kailash
122. Rabat Administrative Sector
123. Kiev Pechers'kyi
124. Calcutta Lake Market
125. Warsaw Srodmiescie
126. Bishkek Park
127. Berlin Kreuzberg
128. Trier Hauptmarkt
129. Teheran Tadschrisch
130. Bern Innere Stadt
131. Cairo Garden City
132. Bogota Polo Club
133. Athens Agios Panteleimonas
134. Ho Chi Minh Binh Tho
135. Brussels Anneessens
136. Tokyo Chiyoda
137. Hyderabad Boudha Naga
138. Pretoria Central
139. New York Bronx
140. Sydney Central Business District
141. Bucharest Sector 2
142. Seoul Mangwon-dong
143. Cape Town Silver Town
144. Denver North Capitol Hill
145. Ferrara Via Comacchio
146. Bratislava Old Town
147. Trier Im Falschen Biewertal
148. Lisbon Alfama
149. Saint-Petersburgh Smolninskoye
150. Edinburgh Craiglockhart
151. Oslo Nordberg
152. Sienna San Prospero
153. Santiago De Chile Lo Prado
154. Reston Town Center
155. Rio De Janeiro Centro
156. Charlottesville North Downtown
157. Venice Castello West
158. Cairo Manshiet Nasser
159. Sarcelles HLM

160. Paris Belleville
161. Bucharest Tei Toboc
162. Toulouse Le Mirail
163. Al Zaatari Refugee Camp
164. Berlin Europa City
165. Bristol Redcliffe
166. Porto Alegre Menino Deus
167. Dar es Salaam Keko
168. Afgooye Lafoole Refugee Camp
169. Munich Bogenhausen Nord
170. Istanbul Gulsuyu Gulensu
171. Bairut Hamra
172. Kyoto West
173. Edinburgh East Craigs
174. Tokyo Sumida
175. Tokyo Shinbashi
176. Perth Center
177. Columbia Maryland Owen Brown
178. Hyderabad Gandhinagar
179. Brasilia North Wing
180. Mumbai Santosh Nagar
181. Reston North West
182. Dar es Salaam Kiwalani
183. Wellington Te Aro
184. Ho Chi Minh Khu pho2
185. Kyoto Yamashina Ward
186. Madrid Canada Real
187. Phnom Penh Sangkat Srah Chak
188. Paris 6 Arrondissement
189. Venice San Polo
190. Delhi Meena Bagh
191. Sienna Old Center
192. Beijing Dashilanr
193. Dar es Salaam Kigamboni
194. Edinburgh Greenbank
195. Brisbane Central Business District
196. Delhi Karol Bagh
197. Rio de Janeiro Morro Do Valongo
198. Nairobi Central
199. Greenbelt Greenbelt
200. Munich Obermenzing
201. Ferrara University District
202. Dar es Salaam Tandika
203. Pavia Parco Leopardi
204. Dar es Salaam Lugalo Golf
205. Calcutta Lake Garden
206. Naarden Naarden
207. Delhi Laxmi Bai Nagar
208. Mumbai Dharavi
209. Charlottesville Fry's Spring
210. Reston South West
211. Lima Comas
212. Trier Petrisberg
213. Glendale Glendale
214. Venice Giudecca
215. Tokyo Shimokitazawa
216. Mexico City Magdalena Contreras
217. Ulan Bator North
218. Shanghai Tianping Res District
219. Boston North End
220. Manila North Cemetery
221. Budpest Gellerthegy
222. Katmandu Anamnagar
223. Evry Evry-Courcouronnes
224. Dar es Salaam Masaki
225. Izmir Kadifekale
226. Ferrara Ippodromo
227. Madrid La Finca
228. Brie Comte Robert
229. Cape Town Mandela Park
230. Columbia Maryland Town Center
231. Dhaka Islambagh
232. Caracas Petare
233. Nairobi Kibera
234. Cape Town Victoria Merge
235. Colombo Fort
236. Manila Tondo
237. Lisbon Cova

238. Dar es Salaam Mikoroshoni
239. Brasilia Lago Sul
240. Oslo Ulvoya
241. Saint-Petersburgh Moskovskaya Zastava
242. Oslo Holmenkollen
243. Antananarivo Central Station
244. Kyoto Minamieganosho
245. Calcutta Sector 1 Block CC
246. Antananarivo Lake Anosy
247. Seoul Bupyeong 1
248. Nakatsugawa Ochiai
249. Sienna Ravacciano
250. Dhaka Motijheel
251. Teheran Ekbatan Phase 2
252. Teheran Ekbatan South East
253. Teheran Zaferanieh
254. Katmandu Bagbazar
255. Tokyo Shinjuku Center
256. Katmandu Kalopul-Ratopul Rd
257. Lusaka Bauleni
258. Lusaka Luburma Central
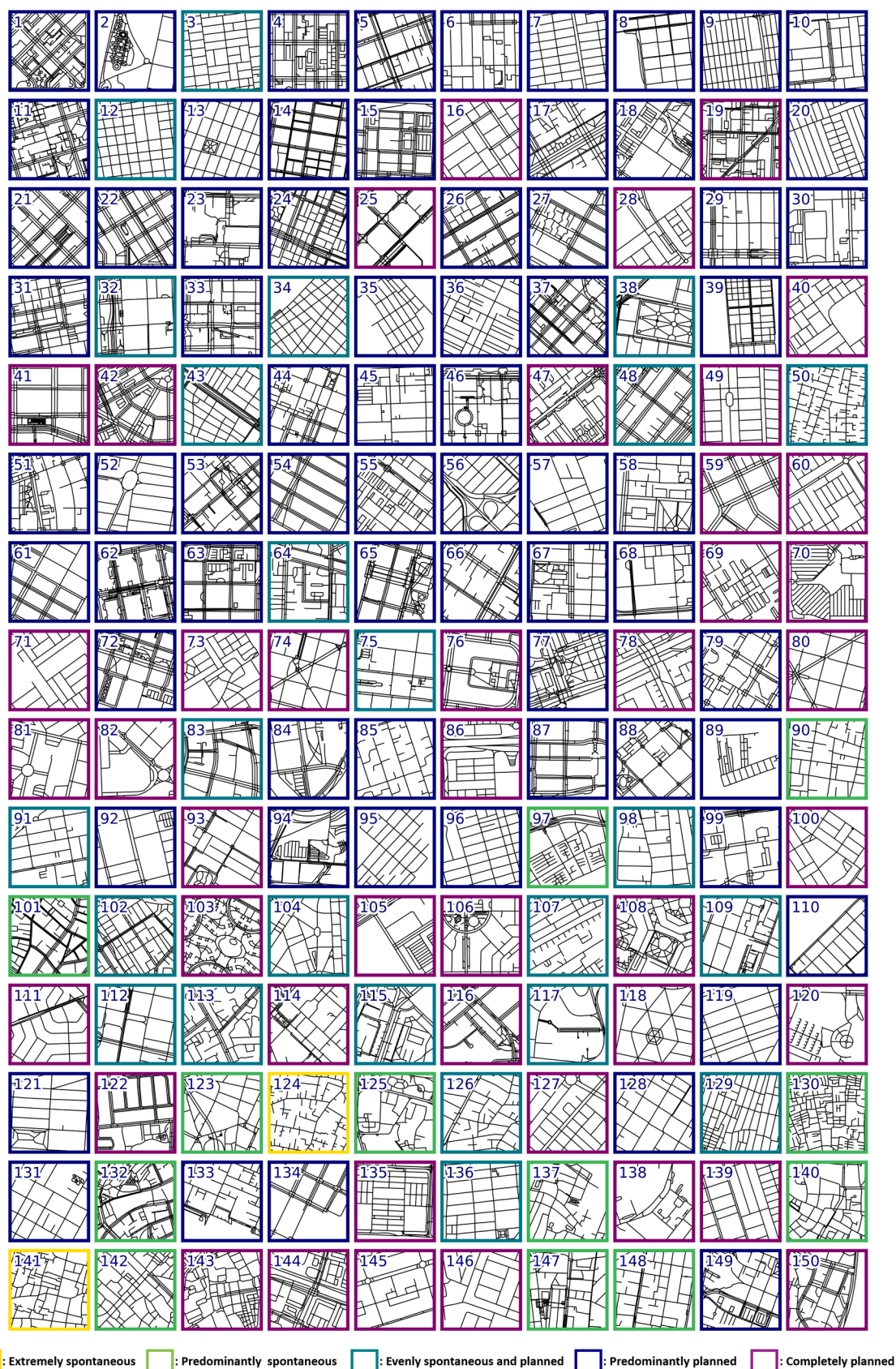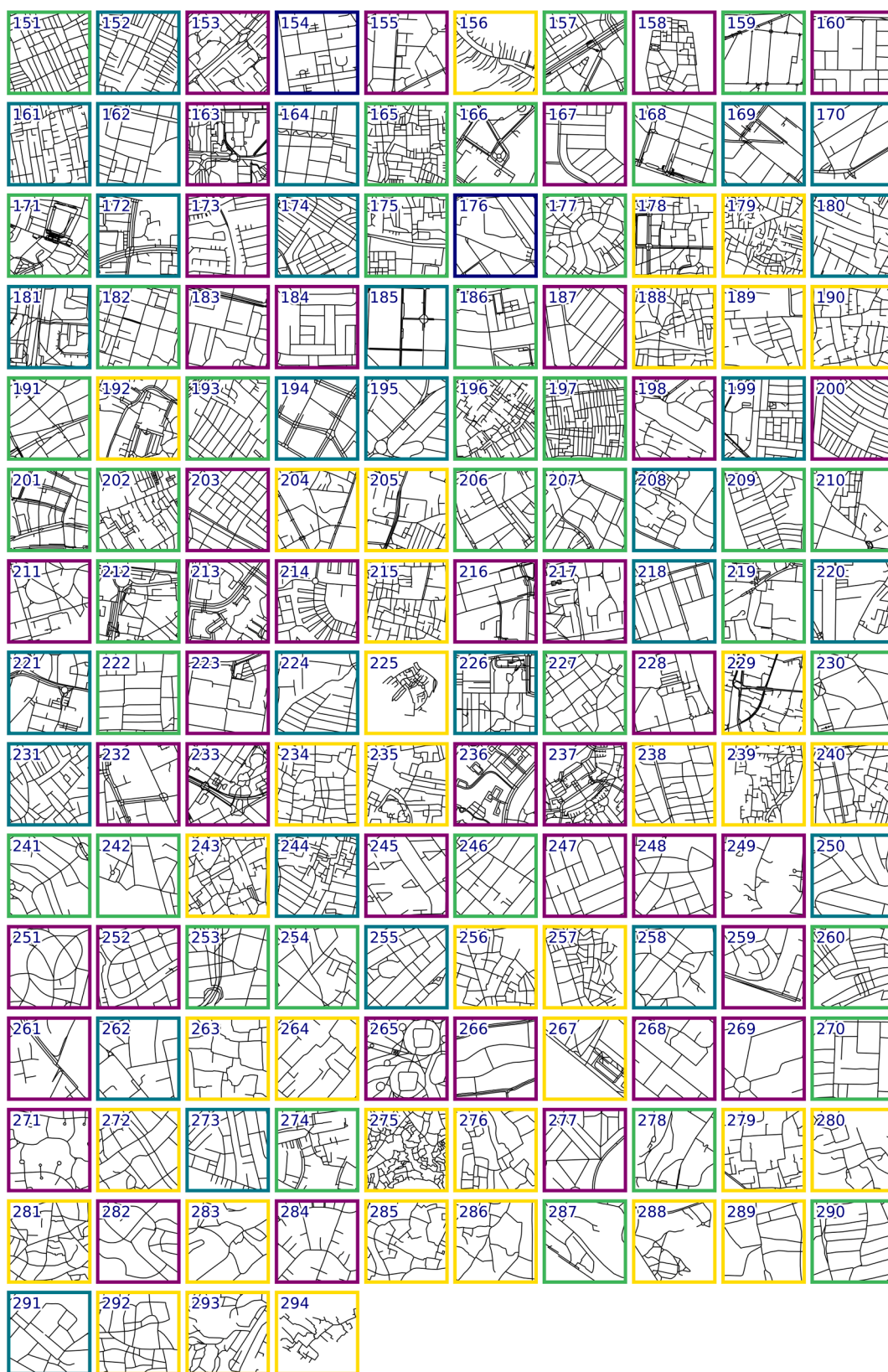259. Fes Ave du Pakistan
260. Shenzhen Baishizhou

.

Fig. E1. Figure-ground diagram snippets of a 500m × 500m subset of each study site used for the analysis of the structural element streets. The snippets are ordered by increasing structural complexity and framed in color with respect to their IoP. List of the study sites below

: Extremely spontaneous   : Predominantly spontaneous   : Evenly spontaneous and planned   : Predominantly planned   : Completely planned

(caption on next page)

Fig. E2. Figure-ground diagram snippets of a 500m × 500m subset of each study site used for the analysis of the structural element streets. The snippets are ordered by increasing structural complexity and framed in color with respect to their IoP. List of the study sites below

1. Denver Five Points
2. Rosario Del Abasto
3. El Obeid 2
4. Denver North Capitol Hill
5. Melbourne CBD
6. Riverside North Lawndale
7. Khartoum Al-Sahafa
8. Johannesburg Center Business District
9. Addis Ababa Addis Ketema
10. Obihiro Jominami
11. Toronto Old Toronto
12. El Obeid 1
13. Lima_Boca Del Diabolo
14. Philadelphia Center City
15. Kansas Downtown
16. Riyadh Al Rawabi
17. Saint-PBurg Vasileostrovsky District
18. Houston CBD
19. Indianapolis Mile Square
20. Brasilia Del Lago ||
21. San Francisco South Of Market
22. Downtown Seattle
23. Vancouver Fairview
24. Tokyo Shinbashi
25. Barcelona Eixample
26. Ottawa Downtown
27. Manhattan East Village
28. Chandigarh Sector 60-61
29. Kyoto Nakagyo Ward
30. Miami Little Havana
31. Chicago CBD
32. Budpest Monserrat
33. Phoenix Central City
34. Guatemala Zona 8
35. Merida San Juan
36. Forest Hill Forest Hill
37. Cape Town Central Business District
38. Historic Centre of Mexico City
39. Tokyo Sumida
40. Chandigarh Sector 38-40
41. Washington Downtown
42. Detroit Downtown
43. Bogota Los Martires
44. Downtown Portland
45. Miami Allapattah
46. Chicago Loop
47. Abu Dhabi AL Danah
48. Downtown Los Angeles
49. Qazvin Navvab Safavi
50. Teheran Tehran Bazaar
51. Downtown San Diego
52. Teheran District 4
53. Brisbane CBD
54. Manhattan Midtown
55. Richmond Downtown
56. Tokyo Urayasu
57. Johannesburg Bezuidenhout Valley
58. Bishkek Park
59. Canberra Reid
60. Calcutta Sector 1
61. Manhattan Washington Heights
62. Tokyo Shinjuku Center
63. Downtown Atlanta
64. St Petersburg Admiralteysky District
65. Tokyo Chiyoda
66. Saint-Petersburgh Smolninskoye
67. Calgary Downtown Commercial
68. Pretoria Central
69. Islamabad Blue Area
70. Columbia Maryland Town Center
71. Chandigarh Sector 59 East
72. St Louis Downtown
73. Islamabad G10 Markaz
74. Belo Horizonte Piratininga
75. Porto Alegre Menino Deus
76. Canberra Ainslie
77. Warsaw Srodmiescie
78. Saint-Petersburgh Municipal Okrug
79. Minneapolis Downtown West
80. Belo Horizonte Santo Agostinho
81. Islamabad I-8
82. Abu Dhabi Mohamed Bin Zayed City
83. Munich Maxvorstadt
84. Columbus Franklinton
85. Johannesburg Alexandra
86. Abu Dhabi Mussafah
87. Reston Town Center
88. Charlotte City Center
89. Venice Castello
90. Bairut Hamra
91. Durban Central
92. Harare Avenues
93. Charlottesville Belmont
94. Perth Center
95. Rawalpindi Askari 10
96. Accra Adabraka
97. Shanghai East Nanjing Road
98. TeheranDistrict 6
99. Cleveland Downtown
100. Bogota La Esmeralda
101. Boston North End
102. Seoul Mangwon-dong
103. Manhattan StuyTown
104. Fes Place de Florence
105. Abuja Central Business District
106. General Santos City Center
107. Bangkok Bueng Kum
108. Minsk Kamennaya Gorka
109. Paris Central Arrondissements
110. Dallas Junius Heights
111. Johannesburg Soweto Orlando East
112. Caracas Centro-Sur
113. Moscow Tverskoy District
114. Ho Chi Minh Ben Nghe
115. Minsk City Center
116. Sydney Bazaar
117. Panama City Obarrio
118. Rosario Parque Casado
119. Amsterdam Jordaan
120. Edinburgh West End
121. Rio de Janeiro Morro do Cantagalo
122. Sydney Jordan Springs
123. Sao Paulo Centro
124. Teheran Emamzadeh Yahya
125. Ad Doha Najma
126. Qazvin Aref
127. Rabat Hay Riad
128. Bogota La Canderlaria
129. Hyderabad Boudha Naga
130. Shanghai Yuyuan
131. Ho Chi Minh Binh Tho
132. Bratislava Old Town
133. Wellington Te Aro
134. Oslo Sentrum
135. Kuala Lumpur Kota Damansara
136. Nagoya Naka Ward
137. Ferrara Doro
138. Brasilia Lago Sul
139. Rawalpindi Bahria Town Phase 2
140. Rome Municipio I
141. Calcutta College Square
142. Barcelona Ciutat Vella
143. Kuwait City Center Salmiya
144. Reston Commercial Area
145. Edinburgh New Town
146. Gaborone 8/10/11/12 Extensions
147. Sydney Central Business District
148. Bogota Polo Club
149. Charlottesville North Downtown
150. Manhattan Williams Bridge
151. Tunis Cite Ettadhamen
152. Ho Chi Minh Binh Hung Hoa A
153. Brasilia SHCS/ASA Sul
154. Phnom Penh Sangkat Srah Chak
155. Delhi Meena Bagh
156. Suloszowa Linear City
157. Munich Harlaching
158. Venice Castello West
159. Paris 9 Arrondissement
160. Ad Doha Fereej Al Ali
161. Bangkok Sikharin Village
162. Pavia Via Umberto Olevano
163. Toulouse Le Mirail
164. Ferrara University District
165. Hyderabad Gandhinagar
166. Kiev Pechers'kyi
167. Rawalpindi Askari 14
168. Vienna Innenstadt
169. Sydney Point Piper
170. Paris Clamart
171. Munich Marienplatz
172. Munich Bogenhausen Nord
173. Johannesburg Far East Bank
174. Nairobi Central
175. Hyderabad Anna Nagar
176. Sydney Hurstville
177. Sienna Old Center
178. Kyoto Yamashina Ward
179. Cairo Bab Ash Shariyah
180. Bangkok Dusit District
181. Minsk Kastrycnicki Raion North
182. Pavia Old Center
183. Sarcelles HLM
184. Dar es Salaam Kiwalani
185. Paris Adamville
186. Dublin Temple Bar
187. Ferrara Ippodromo
188. Nicosia Walled Old City
189. Teheran Tadschrisch
190. Qazvin Jameh Mosque
191. Budapest Inner City
192. Trier Hauptmarkt
193. Ho Chi Minh Khu pho2
194. Oslo Frogner
195. Rio de Janeiro Vila da Penha
196. Venice San Polo
197. Delhi Shahdara
198. Johannesburg Craigavon
199. Brasilia Paranoa
200. Delhi Greater Kailash
201. Bern Innere Stadt
202. Edinburgh Old Town
203. Lusaka Kamwala
204. Addis Ababa Sengatera
205. Hyderabad Gruhkalpa
206. Berlin Europa City
207. Sienna San Prospero
208. Budpest Gellerthegy
209. Tunis Intercommunale Sud
210. Brussels Anneessens
211. Edinburgh Trinity
212. Bristol Redcliffe
213. Reston North West
214. Delhi Laxmi Bai Nagar
215. Calcutta Lake Market
216. Charlottesville Fry's Spring
217. Brasilia North Wing
218. Pavia Parco Leopardi
219. London Westminster
220. Paris Gagny
221. Ferrara Via Comacchio
222. Munich Obermenzing
223. Sydney Sylvania Waters
224. Herat East Area/Echo Park
225. Fes Medina
226. Munich Arabella park
227. Merida Old Center
228. Sydney Epping
229. Antananarivo Andavamamba
230. Bucharest Sector 2
231. Brasilia SH Sol Nascente
232. Edinburgh The Grange
233. Madrid Moratalaz
234. Nagoya Arakocho
235. Kyoto West
236. Columbia Maryland Owen Brown
237. Greenbelt Greenbelt
238. Fes Oulad Tayeb
239. Kyoto Minamieganosho
240. Tokyo Minamimagome
241. Algiers Parc D'Hydra
242. Paris 6 Arrondissement
243. Tunis El Hafsia
244. Calcutta Lake Garden
245. Teheran Ekbatan South East
246. Teheran Zaferanieh
247. Accra Osu
248. Rabat Administrative Sector
249. Glendale Glendale
250. Johannesburg Westcliff
251. Cairo Garden City
252. Edinburgh Greenbank
253. Belo Horizonte Colegio Batista
254. Baghdad horjah
255. Naarden Naarden
256. Tokyo Shimokitazawa
257. Bogota Barrio San Cristobal
258. Dar es Salaam Kigamboni
259. Brie Comte Robert
260. Delhi Mandawali
261. Reston South West
262. Dar es Salaam Masaki
263. Herat Citadel
264. Herat Bagh Nazargah
265. Minsk Syerabranka
266. Madrid La Finca
267. Minsk Vialiki Trascianiec
268. Sydney Georges Hall
269. Madrid Ciudalcampo
270. Lusaka J7VC+Q3H
271. Columbia Maryland Arrowhead
272. Nakatsugawa Honmachi
273. Lusaka Garden
274. Venice Giudecca
275. Dar es Salaam Keko
276. Abuja Lugbe Organic
277. Oslo Nordberg
278. Sydney Mosman
279. Dhaka Motijheel
280. Dar es Salaam Lugalo Golf
281. Dar es Salaam Tandika
282. Charlottesville Fontana
283. Trier Im Falschen Biewertal
284. Oslo Ulvoya
285. Katmandu Anamnagar
286. Lusaka Misisi
287. Oslo Holmenkollen
288. Islamabad Al-Meher Colony
289. Nakatsugawa Ochiai
290. Ulan Bator North
291. El Obeid 3
292. El Obeid 4
293. Seoul Area 1
294. Fes Mausolee Moulay Abd

.

$$\sum_{i,j,k} P\Big(\{\alpha,\beta,\gamma\}_{i,j,k}\Big) = 1$$

Where A is the given settlement where the structural complexity is measured; *elementX* is a structural element among *buildings*, *morphological units* or *streets*; *n* is the number of objects of this structural element; $\{\alpha,\beta,\gamma\}_{i,j,k}$ is the set of three parameters falling into their respective bins i,j,k; and $P(\{\alpha,\beta,\gamma\}_{i,j,k})$ represents the frequency this triplet is occurring in the particular settlement.

The joint entropy mathematically represents the individual entropies of its variables reduced by their mutual information (Cover & Thomas, 2005). In our case, we understand it as the specific diversity, for a structural element in a settlement, of the combined triplet of morphological parameters. The normalization term $-\log_2 n$ is added to make the computation of the ***structural complexity*** independent of the size of the structural element sample in the settlement.

Appendix D

Appendix E

Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104711.

References

Akbar, J. A. (1988). *Crisis in the built environment: The case of the Muslim city*. Concept Media ; E.J. Brill (U.S.A.) [Distributor].

Alexander, C. (1965). A city is not a tree. *Architectural Forum, 122*(1), 58–62.

Alexander, C. (1979). *The timeless way of building*. Oxford University Press.

Angel, S. (2010). Ten compactness properties of circles: Measuring shape in geography. 4. 21.

Ankerst, M., Breunig, M. M., Kriegel, H.-P., & Sander, J. (1999). OPTICS: Ordering points to identify the clustering structure. *ACM SIGMOD Record, 28*(2), 49–60. https://doi.org/10.1145/304181.304187

Batty, M. (1974). Spatial Entropy. *Geographical Analysis, 6*(1), 1–31. https://doi.org/10.1111/j.1538-4632.1974.tb01014.x

Batty, M. (2005). *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*. MIT Press.

Batty, M. (2009). Cities as Complex Systems: Scaling, Interaction, Networks, Dynamics and Urban Morphologies. In R. A. Meyers (Ed.), *Encyclopedia of Complexity and Systems Science* (pp. 1041–1071). New York: Springer. https://doi.org/10.1007/978-0-387-30440-3_69.

Batty, M. (2016). Complexity, Cognition, Urban Planning and Design, Chapter 2: Evolving a Plan: Design and Planning with Complexity. In *Complexity, Cognition, Urban Planning and Design* (pp. 46–67). Springer International Publishing. https://doi.org/10.1007/978-3-319-32653-5.

Batty, M., & Marshall, S. (2009). Centenary paper: *The evolution of cities: Geddes, Abercrombie and the new physicalism. Town Planning Review, 80*(6), 551–574. https://doi.org/10.3828/tpr.2009.12

Batty, M., & Marshall, S. (2012). The Origins of Complexity Theory in Cities and Planning. In J. Portugali, H. Meyer, E. Stolk, & E. Tan (Eds.), *Complexity Theories of Cities Have Come of Age: An Overview with Implications to Urban Planning and Design* (pp. 21–45). Springer. https://doi.org/10.1007/978-3-642-24544-2_3.

Berghauser Pont, M., Haupt, P., Berg, P., Alstäde, V., & Heyman, A. (2021). Systematic review and comparison of densification effects and planning motivations. *Buildings and Cities, 2*(1), 378. https://doi.org/10.5334/bc.125

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(17), 7301–7306. 10.1073/pnas.0610172104.

Boeing, G. (2017). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems, 65*, 126–139. https://doi.org/10.1016/j.compenvurbsys.2017.05.004

Boeing, G. (2019). Urban spatial order: Street network orientation, configuration, and entropy. *Applied Network Science, 4*(1), 67. https://doi.org/10.1007/s41109-019-0189-1

Cataldi, G., Maffei, G. L., & Vaccaro, P. (n.d.). *Saverio Muratori and the Italian school of planning typology*. 10.

Conzen, M. R. G. (1960). Alnwick, Northumberland: A Study in Town-Plan Analysis. *Transactions and Papers (Institute of British Geographers), 27*, iii. https://doi.org/10.2307/621094

Conzen, M. P. (1980). The Morphology of Nineteenth-Century Cities in the United States. *Urban History Review, 119–141*. https://doi.org/10.7202/1020702ar

Conzen, M. G. (1988). Morphogenesis, morphological regions and secular human agency in the historic townscape, as exemplified by Ludlow. In *Urban Historical Geography. Recent progress in Britain and Germany* (pp. 253–272).

Cover, T. M., & Thomas, J. A. (2005). *Elements of Information Theory* (1st ed.). Wiley. 10.1002/047174882X.

Cozzolino, S. (2020). The (anti) adaptive neighbourhoods. Embracing complexity and distribution of design control in the ordinary built environment. *Environment and Planning B: Urban Analytics and City. Science, 47*(2), 203–219. https://doi.org/10.1177/2399808319857451

Cozzolino, S. (2021). On the spontaneous beauty of cities: Neither design nor chaos. *URBAN DESIGN International*. https://doi.org/10.1057/s41289-021-00170-w

Cozzolino, S., & Moroni, S. (2021). Multiple agents and self-organisation in complex cities: The crucial role of several property. *Land Use Policy, 103*, Article 105297. https://doi.org/10.1016/j.landusepol.2021.105297

Cozzolino, S., & Moroni, S. (2022). Structural preconditions for adaptive urban areas: Framework rules, several property and the range of possible actions. *Cities, 130*, Article 103978. https://doi.org/10.1016/j.cities.2022.103978

Cozzolino, S. (2018). Reconsidering Urban Spontaneity and Flexibility after Jane Jacobs: How do they work under different kinds of planning conditions? 5(3), 11.

Dibble, J., Prelorendjos, A., Romice, O., Zanella, M., Strano, E., Pagel, M., & Porta, S. (2019). On the origin of spaces: Morphometric foundations of urban form evolution. *Environment and Planning B: Urban Analytics and City Science, 46*(4), 707–730. https://doi.org/10.1177/2399808317725075

Dovey, K. (2020). Towards a morphogenesis of informal settlements. *Habitat International, 14*.

Dovey, K., & Kamalipour, H. (2017). Informal/Formal Morphologies. In *Mapping Urbanities*. Routledge.

Fisher, R. A. (1925). *Statistical Methods for Research Workers*. Oliver and Boyd.

Fleischmann, M., Feliciotti, A., & Kerr, W. (2021). Evolution of Urban Patterns: Urban Morphology as an Open Reproducible Data Science. *Geographical Analysis, n/a*(n/a). 10.1111/gean.12302.

Fleischmann, M., Feliciotti, A., Romice, O., & Porta, S. (2020). Morphological tessellation as a way of partitioning space: Improving consistency in urban morphology at the plot scale. *Computers, Environment and Urban Systems, 80*, Article 101441. https://doi.org/10.1016/j.compenvurbsys.2019.101441

Fleischmann, M. (2019). momepy: Urban Morphology Measuring Toolkit. *Journal of Open Source Software, 4*(43), 1807. 10.21105/joss.01807.

Frank, L. D., & Engelke, P. O. (2001). The Built Environment and Human Activity Patterns: Exploring the Impacts of Urban Form on Public Health. *Journal of Planning Literature, 16*(2), 202–218. https://doi.org/10.1177/08854120122093339

Glantz, S. A. (2012). *Primer of biostatistics* (7 Ed.). McGraw-Hill.

Gu, K. (2019). Urban Morphological Regions: Development of an Idea. In V. Oliveira (Ed.), *J.W.R. Whitehand and the Historico-geographical Approach to Urban Morphology* (pp. 33–46). Springer International Publishing. 10.1007/978-3-030-00620-4_2.

Habraken, N. J. (1987). The Control of Complexity. *Places, 4*(2), 3–15.

Habraken, N. J. (1998). *The structure of the ordinary: Form and control in the built environment*. MIT Press.

Habraken, N. J. (Ed.). (2016). Complexity, Cognition, Urban Planning and Design, Chapter 4: Cultivating Complexity: The Need for a Shift in Cognition. In *Complexity, Cognition, Urban Planning and Design* (pp. 79–98). Springer International Publishing. 10.1007/978-3-319-32653-5.

Hajrasoulih, A., del Rio, V., Francis, J., & Edmondson, J. (2018). Urban form and mental wellbeing—Scoping a theoretical framework for action. *Journal of Urban Form and*

Mental Health, 5(10). https://www.urbandesignmentalhealth.com/journal-5--urban-form-and-mental-wellbeing.html.

Hakim, B. S. (2014). *Mediterranean urbanism: Historic urban*. Springer.

Herfort, B., Lautenbach, S., Porto de Albuquerque, J., Anderson, J., & Zipf, A. (2021). The evolution of humanitarian mapping within the OpenStreetMap community. *Scientific Reports, 11*(1), 1. https://doi.org/10.1038/s41598-021-82404-z

Higueras, E., Román, E., & Fariña, J. (2021). Guidelines for Healthier Public Spaces for the Elderly Population: Recommendations in the Spanish Context. In J. Martinez, C. A. Mikkelsen, & R. Phillips (Eds.), *Handbook of Quality of Life and Sustainability* (pp. 35–51). Springer International Publishing. https://doi.org/10.1007/978-3-030-50540-0_3.

Ikeda, S. (2017). *A City Cannot be a Work of Art. 4*(2). 8.

Inostroza, L. (2017). Informal urban development in Latin American urban peripheries. Spatial assessment in Bogotá, Lima and Santiago de Chile. *Landscape and Urban Planning, 165*, 267–279. https://doi.org/10.1016/j.landurbplan.2016.03.021

Jacobs, J. (1961). *The death and life of great American cities (Modern Library ed)*. Modern Library.

Kelso, J. A. S., Portugali, J., & Stolk, E. (2016). Complexity, Cognition, Urban Planning and Design, Chapter 3: Self-organization and Design as a Complementary Pair. In *Complexity, Cognition, Urban Planning and Design* (pp. 68–78). Springer International Publishing. 10.1007/978-3-319-32653-5.

Kohli, D., Sliuzas, R., Kerle, N., & Stein, A. (2012). An ontology of slums for image-based classification. *Computers, Environment and Urban Systems, 36*(2), 154–163. https://doi.org/10.1016/j.compenvurbsys.2011.11.001

Kostof, S. (1982). Urbanism and Polity: Medieval Siena in Context. In *International Laboratory for Architecture and Urban Design Yearbook* (pp. 62–73).

Kostof, S. (1991a). *Lectures from Architecture 170 class, University of California, Berkeley*. https://digicoll.lib.berkeley.edu/search?ln=en&p=collection%3A%27Architecture+170+Lectures%27&f=&rm=&ln=en&sf=latest+first&so=d&rg=10&c=Digital+Collections&of=hb&fti=0&fti=0.

Kostof, S. (1991b). *The city shaped: Urban patterns and meanings through history* (1. paperback ed). Thames & Hudson.

Kostof, S. (1992). *The city assembled: The elements of urban form through history* (1st North American ed). Little, Brown.

Kraff, N. J., Wurm, M., & Taubenbock, H. (2020a). Uncertainties of Human Perception in Visual Image Interpretation in Complex Urban Environments. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 13*, 4229–4241. https://doi.org/10.1109/JSTARS.2020.3011543

Kraff, N. J., Wurm, M., & Taubenböck, H. (2020b). The dynamics of poor urban areas—Analyzing morphologic transformations across the globe using Earth observation data. *Cities, 107*, Article 102905. https://doi.org/10.1016/j.cities.2020.102905

Krefis, A., Augustin, M., Schlünzen, K., Oßenbrügge, J., & Augustin, J. (2018). How Does the Urban Environment Affect Health and Well-Being? *A Systematic Review. Urban Science, 2*(1), 21. https://doi.org/10.3390/urbansci2010021

Kropf, K. (2009). Aspects of urban form. *Urban Morphology, 13*(2), 105–120.

Kropf, K. (1993). *The definition of built form in urban morphology.*

Kruskal, W. H., & Wallis, W. A. (1952). Use of Ranks in One-Criterion Variance Analysis. *Journal of the American Statistical Association, 47*(260), 583–621. https://doi.org/10.1080/01621459.1952.10483441

Kuffer, M., Barros, J., & Sliuzas, R. V. (2014). The development of a morphological unplanned settlement index using very-high-resolution (VHR) imagery. *Computers, Environment and Urban Systems, 48*, 138–152. https://doi.org/10.1016/j.compenvurbsys.2014.07.012

Kuffer, M., Van Maarseveen, M. F. A. M., Sliuzas, R. V., & Pfeffer, K. (2017). *Spatial patterns of deprivation in cities of the global south in very high resolution imagery.*

Larkham, P. (1992). *Organic Thought in Urban Geography: 'The 'Evolution' of towns*. 10.1111/J.1467-8470.1992.TB00728.X.

Lefebvre, H. (1974). *La production de l'espace* (4. éd). Éd. Anthropos.

Legeby, A., Berghauser Pont, M., & Marcus, L. (2015). Streets for co--presence? Mapping potentials. *Proceedings of the 10th International Space Syntax Symposium, 108*:1-108:17.

Lynch, K. (1984). *Good city form*. MIT Press.

Mangin, D., & Panerai, P. (1999). *Projet urbain*. Parenthèses.

Mann, H. B., & Whitney, D. R. (1947). On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. *The Annals of Mathematical Statistics, 18*(1), 50–60. https://doi.org/10.1214/aoms/1177730491

McDonald, J., Wise, M., & Harris, P. (2008). *The Health Impacts of the Urban Form: A Review of Reviews* [Research reports]. Centre for Health Equity Training, Research and Evaluation, part of the Research Centre for Primary Health Care and Equity, University of New South Wales. https://cphce.unsw.edu.au/health-impacts-urban-form-review-reviews-centre-health-equity-training-research-and-evaluation-unsw.

Microsoft. (2020). *Building Footprints—Bing Maps*. https://www.microsoft.com/en-us/maps/building-footprints.

Moroni, S., & Cozzolino, S. (2019). Action and the city. Emergence, complexity, planning. *Cities, 90*, 42–51. https://doi.org/10.1016/j.cities.2019.01.039

Mouratidis, K. (2018). Built environment and social well-being: How does urban form affect social life and personal relationships? *Cities, 74*, 7–20. https://doi.org/10.1016/j.cities.2017.10.020

Mouratidis, K., & Poortinga, W. (2020). Built environment, urban vitality and social cohesion: Do vibrant neighborhoods foster strong communities? *Landscape and Urban Planning, 204*, Article 103951. https://doi.org/10.1016/j.landurbplan.2020.103951

Noizet, H., & Clémençon, A.-S. (2020). *Faire ville: Entre planifié et impensé, la fabrique ordinaire des formes urbaines*. Presses universitaires de Vincennes.

Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press.

Panerai, P., Demorgon, M., & Depaule, J.-C. (1999). *Analyse urbaine*. Parenthèses.

Pont, M. B., & Olsson, J. (2018, May 15). Typology based on three density variables central to Spacematrix using cluster analysis. *24th ISUF 2017 - City and Territory in the Globalization Age*. 24th ISUF 2017 - City and Territory in the Globalization Age. http://ocs.editorial.upv.es/index.php/ISUF/ISUF2017/paper/view/5319.

Portugali, J., & Stolk, E. (Eds.). (2016). *Complexity, Cognition, Urban Planning and Design*. Springer International Publishing. 10.1007/978-3-319-32653-5.

Portugali, J. (Ed.). (2016). Complexity, Cognition, Urban Planning and Design, Chapter 1: What Makes Cities Complex? In *Complexity, Cognition, Urban Planning and Design* (pp. 28–45). Springer International Publishing. 10.1007/978-3-319-32653-5.

Purwani, S., Nahar, J., & Twining, C. (2017). Analyzing bin-width effect on the computed entropy. *AIP Conference Proceedings, 1868*(1), Article 040008. https://doi.org/10.1063/1.4995123

Python Software. (2020). *3.7.14 Documentation*. https://docs.python.org/3.7/index.html.

Rashid, M. (2017). The Geometry of Urban Layouts. *Springer International Publishing*. https://doi.org/10.1007/978-3-319-30750-3

Riofrío, G. (2003). Urban Slums Reports: The Case of Lima. *Peru. UN-Habitat Glob. Rep. Hum. Settlements.*, 195–228.

Rowe, C., & Koetter, F. (1978). *Collage city*. MIT Press.

Salat, S., & Bourdic, L. (2012). *Urban complexity, scale hierarchy, energy efficiency and economic value creation*. 97–107. 10.2495/SC120091.

Salat, S., Bourdic, L., & Labbe, F. (2014). BREAKING SYMMETRIES AND EMERGING SCALING URBAN STRUCTURES: A Morphological Tale of 3 Cities: Paris, New York and Barcelona. *International Journal of Architectural Research: ArchNet-IJAR, 8*(2), 77. 10.26687/archnet-ijar.v8i2.445.

Salat, S. (2011). *Les villes et les formes: Sur l'urbanisme durable*. Hermann [u.a.].

Sapena, M., Ruiz, L. A., & Taubenböck, H. (2020). Analyzing Links between Spatio-Temporal Metrics of Built-Up Areas and Socio-Economic Indicators on a Semi-Global Scale. *ISPRS International Journal of Geo-Information, 9*(7), 7. https://doi.org/10.3390/ijgi9070436

Sapena, M., Wurm, M., Taubenböck, H., Tuia, D., & Ruiz, L. A. (2021). Estimating quality of life dimensions from urban spatial pattern metrics. *Computers, Environment and Urban Systems, 85*, Article 101549. https://doi.org/10.1016/j.compenvurbsys.2020.101549

Seto, T., Kanasugi, H., & Nishimura, Y. (2020). Quality Verification of Volunteered Geographic Information Using OSM Notes Data in a Global Context. *ISPRS International Journal of Geo-Information, 9*(6), 6. https://doi.org/10.3390/ijgi9060372

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal, 27*(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Shapely 1.7.1 documentation. (2021, visited). https://shapely.readthedocs.io/en/stable/manual.html/.

Shipley, R., & Utz, S. (2012). Making it Count: A Review of the Value and Techniques for Public Consultation. *Journal of Planning Literature, 27*(1), 22–42. https://doi.org/10.1177/0885412211413133

Taubenböck, H., Murawski, M., & Wurm, M. (2018). Large Housing Estates—Analysing the Morphologic Similarities and Differences of a Specific Town Planning Concept. pdf. *23rd International Conference on Urban Planning, Regional Development and Information*, 275–284. http://repository.corp.at/id/eprint/433.

Taubenböck, H., & Kraff, N. J. (2014). The physical face of slums: A structural comparison of slums in Mumbai, India, based on remotely sensed data. *Journal of Housing and the Built Environment, 29*(1), 15–38. https://doi.org/10.1007/s10901-013-9333-x

Taubenböck, H., Kraff, N. J., & Wurm, M. (2018a). The morphology of the Arrival City—A global categorization based on literature surveys and remotely sensed data. *Applied Geography, 92*, 150–167. https://doi.org/10.1016/j.apgeog.2018.02.002

Thai, H., Stevens, Q., & Rogers, J. (2020, October 14). The influences of formally-planned urban morphology on home-based economic opportunities and the economically-driven self-organisation of urban form. *Proceedings of the 12th Space Syntax Symposium*. Space Syntax Symposium, Beijing.

Thai, H. M. H., Stevens, Q., & Rogers, J. (2019). The influence of organic urban morphologies on opportunities for home-based businesses within inner-city districts in Hanoi. *Vietnam. Journal of Urban Design, 24*(6), 926–946. https://doi.org/10.1080/13574809.2018.1554995

Tonkiss, F. (2013). *Cities by design: The social life of urban form*. Polity Press.

Turner, J. C. (1967). Barriers and Channels for Housing Development in Modernizing Countries. *Journal of the American Institute of Planners, 33*(3), 167–181. https://doi.org/10.1080/01944366708977912

von Szombathely, M., Albrecht, M., Antanaskovic, D., Augustin, J., Augustin, M., Bechtel, B., … Schlünzen, K. (2017). A Conceptual Modeling Approach to Health-Related Urban Well-Being. *Urban Science, 1*(2), 17. https://doi.org/10.3390/urbansci1020017

Whitehand, J. (2001). British urban morphology: The Conzenian tradition. *Undefined*. https://www.semanticscholar.org/paper/British-urban-morphology%3A-the-Conzenian-tradition-Whitehand/b9fd4ff8d85095a871183c75263de48be98e7049.

Wilcoxon, F. (1945). Individual Comparisons by Ranking Methods. *Biometrics Bulletin, 1*(6), 80–83. https://doi.org/10.2307/3001968

Zhang, M., & Zhao, P. (2018). The determinants of informal housing price in Beijing: Village power, informal institutions, and property security. *Cities, 77*, 117–129. https://doi.org/10.1016/j.cities.2018.01.018