Towards a socio-ecological spatial morphology: a joint network approach to urban form and landscape ecology

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Abstract. *Interest in the green infrastructure of cities has rapidly increased in recent years. The reasons are several but generally relate to the great increase of research and policy on sustainable urban development. Of particular importance here is the more recent shift in this field towards greater emphasis on biodiversity and urban ecosystems and not only climate change and environmental engineering. This shift brings new demands for a deeper understanding of the morphology of green infrastructures in cities, understood as ecological environments and not only as areas for human use, as has been the general case in urban morphology. In an earlier paper (Marcus et al., 2019), we discussed how descriptions of landscape patterns of both urban and natural kinds, as developed in urban morphology and landscape ecology respectively, could be integrated into a joint socio-ecological spatial morphology. That paper outlined a framework for such a morphology where green (and blue) as well as built-up areas in cities can be jointly described as configurations of patches. However, the discussion in that paper does not address how to capture the relation between such configurations and the processes that they structure, or how such processes over time may alter such configurations, which is the aim of the present paper. It does so by extending the theory of generic function (Hillier, 1996) to other species than humans, and by applying the theory of affordances (Gibson, 1986) as a means to develop distance measures specific for different species. The origin of the discussion in both papers is the need for progress in sustainable urban development for which this relation is vital, since if we are to address the function of both urban and ecological systems through spatial form, we need to develop an understanding of how such patterns underpin and structure urban and ecological systems.*

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Introduction: linking spatial form to temporal process

Against the background of the urgent need to set cities on to more sustainable trajectories, this and an earlier paper (Marcus *et al*., 2019) propose principles for a joint description of the spatial form of cities that integrates descriptions in urban morphology with descriptions in landscape ecology. The approach presented here is taken in several steps. First, the main unit of analysis we propose to be 'configurations of patches', which subsumes the central descriptive elements in urban morphology – streets, plots and buildings – with the central elements in landscape ecology – patches, corridors and the matrix under the term 'patches' – described in geometric terms as polygons. Secondly, we made use of the notion 'generic function' identifying fundamental uses of urban space with a direct relation to spatial form, such as movement and occupation. This helps us to see how the generic function of occupation is directly related to the concepts of land use in urban morphology and biotopes in landscape ecology, which is what is captured and described by our configurations of patches. The generic function of movement, on the other hand, is related to the connections between these patches, which facilitates interaction and exchange, which is vital for the functioning and dynamics of both social and ecological systems. Thirdly, we suggest that these connections should be described, measured and analysed, using network analysis, where these networks, as in space syntax research, are made to represent the movement affordances of particular cities or urban areas from the point of view of the moving agents driving particular urban sub-systems, whether social or ecological.

In an earlier paper (Marcus *et al*., 2019), we address how descriptions of landscape patterns of both urban and natural kinds, as developed in urban morphology and landscape ecology respectively, can be integrated into a joint socio-ecological spatial morphology. That paper outlined a framework for such a morphology where green (and blue) as well as built-up areas (in urban ecology often referred to as grey infrastructure) in cities can be jointly described as configurations of patches. It based this on the argument that central descriptive elements in urban morphology, such as streets, plots and buildings (Conzen, 1960), just as central descriptive elements in landscape ecology, such as patches, corridors and the matrix (Forman and Godron, 1986), are all polygons in geometric terms, and one could borrow from landscape ecology the term patches as used above (as the most generic) as a common term for all these descriptive elements. This is in line with recent debate in *Urban Morphology* (Scheer, 2018). Hence, patches in this context would capture both patterns of built support for human land use as in urban morphology, and biotopes as parts of ecosystems as in landscape ecology, or combinations of the two, under the single concept configurations of patches, somewhat echoing the notion of the town plan, as introduced by Conzen (1960).

However, the discussion in the earlier paper is limited to the description of landscape patterns and does not address how to capture the relation between such configurations and the processes that they structure, or how such processes over time may alter such configurations. The origin of the discussion in both papers, moreover, is the need for progress in sustainable urban development for which this relation is vital, since if we are to address the function of both urban and ecological systems through spatial form, we need to move beyond descriptions of landscape patterns in themselves and develop an understanding of how such patterns underpin and structure urban and ecological processes – the ultimate

aim being to understand how spatial form supports cities as socio-ecological systems. The aim of this paper is to prepare a principal idea about how this vital step can be taken, by building on the earlier paper.

The line of argument pursued here goes something like this. By capturing and understanding the ties between spatial form and socio-ecological urban processes, we will be able to use spatial form in the professional practices of urban planning and design to direct such processes into more sustainable trajectories – just as the general aim of urban planning and design already is to use spatial form to support processes underlying human needs in cities. However, to expand this professional aim so that it also comprises ecosystems, which by definition are complex systems, a vital step is to understand how spatial form supports and structures flows and interaction between individual spaces (Batty, 2013); that is, capture how spatial form creates limitations and potentials for dynamic urban processes and not only describe the static structure of spatial form itself. To achieve this, we need descriptions that capture the systemic dimensions of spatial form; that is, descriptions that capture the connections between the constituent parts of spatial patterns, since this will reveal the potential for flows and interactions in such patterns. A form of description that has proven most successful in such efforts is network analysis (Newman, 2010), not only when it comes to urban systems but systems in general. The leading approach to network analysis in urban morphology is space syntax (Hillier, 1996), which here will be used as our point of departure. However, network analysis is common also in landscape ecology (for example Estrada and Bodin, 2008; Pascual-Hortal and Saura, 2006), hence in network descriptions we sense a common language that may bridge between the two disciplines.

Before continuing this argument, however, we need a short ontological discussion on how to comprehend cities in this context. Today it is generally acknowledged that cities are prime examples of what is called complex systems – something first pointed out by Jane Jacobs (1961). A characteristic of complex systems is that their constituent parts are not independent but interdependent so that, under certain conditions, they self-organise and give rise to unexpected behaviour (for example Levin, 1998). These parts often take the form of systems in themselves so that a complex system often is composed of several nested sub-systems (Levin, 1998); where some of these, moreover, may be complex and others not. The example of the city is here an illustrative case of such a multi-system. In this case, the system of spatial urban form is only part of a complex system when connected to the city as a social system. However, these different sub-systems change over time at different speeds and, in cities, one of the systems slowest to change is the system of spatial form, a process that often stretches into centuries. In comparison, species dispersal or daily commuting are far more rapid processes, as is the process of retail clustering, albeit that the latter is relatively slower than the other two. Even slower are processes such as gentrification, which even so are far more rapid than changes in the system of spatial form. The important point here is that in a complex system, the slower sub-systems tend to frame and constrain the faster sub-systems (Weidlich, 1999) – they, so to speak, become the structures that channel the processes. The slow systems thereby create the property characteristic for complex systems of resilience (Walker *et al*., 2012), and bring a rather high degree of predictability to these otherwise highly unpredictable systems. In summary, herein we view spatial form as a critical slowly-changing sub-system within urban socio-ecological systems.

It is easy to see how commuting, for instance, which is a rapid process with a daily pulse, due to the spatial form of cities, recreates similar spatial patterns every day (Hillier *et al*., 1993). Similarly, we may observe how retail clusters may come and go, but also how their locations are dependent, albeit to varying degrees, on the spatial form of the city, just as processes of gentrification do not start anywhere but, again, are dependent on the urban system of spatial form. In our current

context it is important to underline how this is central also for the understanding of ecosystems. Such systems typically have their base in a natural environment that, in urban landscapes, is often embedded in a human-shaped landscape, consisting of a particular configuration of biotopes that function as a kind of spatial memory that structure more rapid processes in the ecosystem, such as processes related to species migrations and interactions (Andersson and Barthel, 2016; Bengtsson *et al*., 2003).

Hence we here see how the possibility to structure and shape the spatial form of cities through urban planning and design is also a central tool to structure and shape social, economic and ecological processes in cities and, furthermore, how spatial form can embed these in a resilient framework. The tricky part here is to identify the spatial attributes of such processes that makes it possible for spatial form to connect to these processes and, in extension, direct them. To begin with there may seem to be a myriad of such attributes, but most of these simply reflect the fact that most things happen in space, which is not the same as to say that all of these things are dependent on what we here understand as spatial form. If someone parks a truck in a street to sell street food over lunch, this clearly has spatial attributes; it occupies a particular location over a certain period of time, and probably also generates some particular movement patterns around it. But the parking of the truck does not create any particular demands on the spatial form of the city, only the very general demand of being able to park; which, in turn, can be expressed in even more general terms as a demand to be able to occupy space. If anything, we here sense the scaffolding behind a common trap in much contemporary urban design: the tendency to shape our cities according to too-specific uses. If instead we look for attributes of urban processes with a more direct and consistent relation to spatial form, they are of a far more general kind and are actually not that numerous. To find them, we need to search for the more generic processes hidden within the more explicit processes that are generally addressed in policy and practice.

Theoretical framework: the generic function of spatial form

Hillier (1996) has proposed a concept that we deem most useful for the challenge to tie spatial form to temporal process in cities outlined above, that is, the notion of 'generic function'. The aim here is exactly to identify functions, or rather uses, of urban space, among the great many uses we encounter in urban landscapes, that truly carry consequences for spatial form. A central use of this kind, highlighted by Hillier as decisive for urban processes, is human movement (Hillier, 1996). This is consistent with a systemic approach to any entity, since the point of looking at things as systems is to capture the pattern of possible flows between its parts and the potential for interaction due to this (Batty, 2013). In cities the most important flow undoubtedly is the movement of people which, in extension, generates co-presences of people of different sizes and constitutions (the number and categorical mix of the people making up co-presences) in different locations in the city. This, in turn, has a fundamental impact on social and economic processes in cities. In social terms, the size and constitution of these co-presences generate situations of encounter with very particular characteristics that have direct relevance for urban issues such as social integration (for example Legeby *et al*., 2015; Vaughan and Arbaci, 2011). In economic terms, this variety of co-presences throughout the city constitutes local markets of distinct character, which, for instance, have direct impacts on retail distribution and the levels of rent. Even so, essential for all these specific processes is the generic process of movement, which in turn is highly conditioned by spatial form. Hence we find a link between spatial form and urban processes through the intermediate process (or generic function) of movement.

In a similar manner, in landscape ecology we see how the interest in connectivity between patches does not concern the potential for movement of animals or other types of flows *per se*, but that such flows allow for interaction and potential change, which in urban ecology is known as patch dynamics

(Cadenasso *et al*., 2013; Grove *et al*., 2015). For instance, from the point of view of patch dynamics, urban landscapes are often ecological sinks (more individuals die than are born) for a great proportion of animals – except for a few species of rodents, birds and insects – and are therefore dependent on migration of species from other sources (high-quality patches with stable or growing populations). Hence, to provide sources of ecological renewal, patch dynamics (and source-sink dynamics) is key and implies connectivity and flow between patches with high and low quality, where patches outside of cities also play an important role (Andersson and Barthel, 2016). So connectivity of patches allows different species to move (a generic function) between patches in such source-sink dynamics, but where the different qualities in patches may have different functions for the particular species, such as feeding, nesting, and breeding (specific functions).

On another level, this is also true for interaction or exchange on multiple spatial scales. When bumble bees feed, they also pollinate. For instance, whether bumble bees are able to move to particular patches or not will prove decisive for what plants we, in the end, will find in these patches. A constant flow of new individuals of a great variety carries novel biological information by way of genes, seeds and pollen (Andersson, 2006; Lundberg *et al*., 2008). Exchange processes, for instance seed dispersal, natural pest regulation and pollination shape patterns of habitats and communities of species and hence the biological content of patches. Hence such patch dynamics form part of structuring communities of species that can tolerate the disturbance regimes of urban landscapes, including light pollution, air pollution, noise, human density and spatial heterogeneity. In the long term, such dynamics may also change the patches themselves in their form and function as well as content; which, in extension, also changes how we need to delineate these patches for analytical purposes. In summary, there are complex dynamics of flows and exchanges going on between patches on multiple scales, where movement made possible through spatial connectivity is a generic function for large parts of these dynamics.

Hence we may understand movement as generic in the sense that it is inherent to and decisive for more explicit processes in cities, such as creating a local market demand for street food in particular locations or, as above, allow for pollination of plants by bumble bees. However, we may also understand it as generic in the sense that we may move through urban space in many ways: by car, by tram or on foot, but where all of these are varieties of the same generic function, that is, the function of human movement. Put differently, we may say that on a generic level, the spatial attributes of these modes of movement do not differ decisively, because even though they may have different spatial attributes, they are not different to the degree that they put new demands on spatial form; rather we typically find that the same urban spaces – what we colloquially call streets – can carry many of these different forms of movement. On a very detailed level, different movement modes may naturally need specific designs; but, on a general level, the same form works for most modes. In design terms, such an argument is clearly steering away from functionalism, which characteristically aimed for specific forms for specific functions – which has been called ‘tight-fit solutions’ (Venturi *et al.*, 1972); what is aimed for here is rather ‘loose-fit solutions’. The gain is a greater robustness in the face of change, for instance illustrated by how spatial forms constructed hundreds of years ago have managed to facilitate several generations of movement technologies, such as trams or cars. This may therefore also be interpreted as an important dimension of urban sustainability.

In such a loose-fit perspective, we see how the spatial attribute of movement takes the shape of some form of linearity that facilitates accessibility to urban locations; and that this attribute has been supported and structured by the spatial form we have come to call streets. With this as an example, we also see how the generic function of movement could be supplemented with other fundamental functions or uses of urban space, such as the occupation

of space (Bobkova, 2019; Marcus, 2001). Interestingly, we may note how the two uses, movement and occupation, are exclusive to each other; a space used for occupation cannot at the same time be a space used for movement. As a matter of fact, this leads us to the insight that, on the most fundamental level, cities are spatially organised to reconcile the basic conflict between stationary and mobile uses of urban space (Marcus, 2001); streets are spaces primarily designated to mobile uses, and plots – often combined into street-blocks and enhanced by buildings – are spaces primarily designated to stationary uses.

So far, the discussion has primarily concerned human uses of urban space but, as we could see in the discussion about patch dynamics above, the concept of *generic function* and the idea that the uses 'movement' and 'occupation' are inherent to other uses and processes in cities, may also prove useful when we want to address the relation between spatial form and ecological processes. However, we here need to be careful before tying these to the same spatial forms as human uses. As discussed in the earlier paper (Marcus *et al*., 2019), animals in cities may, for instance, not use streets as the primary space for movement; moreover, different animals such as birds and squirrels have different movement abilities. There are also other processes that are vital for ecosystems, movement of water, soil and energy for instance (Cadensso *et al*., 2013), which is why we can make a differentiation between dispersal-based meta-ecosystems and resource-flow based meta-ecosystems here (Gounand *et al*., 2018), where we focus first. This is also true for human uses of urban space, where movement of both water and energy are equally important. However, we will here limit ourselves to the movement of other animals in urban ecosystems just as we limit ourselves to the movement of humans in urban morphology. The spatial form used for movement by a particular animal may be a patch or a set of patches of a certain kind, but for another species it may prove to be a different set of patches. Hence, due to the fact that we here have several moving agents, we do not see the same distinct separation between movement and occupation in the spatial form of ecosystems as for urban processes, which all relate to one species – humans.

An important insight here is the fact that a configuration of patches is perceived and used differently by different species, depending on their sensory equipment, their size and their main means of movement – crawling, walking, running, jumping or flying (Andersson, 2006). To further illustrate this, we use a patch of wetland in an urban landscape as an example. Inside this patch lives a population of an amphibian species. Hence the generic function of this patch is mainly occupation for that particular species, since it affords feeding, dwelling and mating within the same patch. However, the very same patch may afford the generic function of movement for another species, for instance, as part of a network of patches forming an ecological corridor; alternatively, a bird species that mainly nests and feeds in a forest patch may use it as a stepping-stone in a corridor connecting forest patches of occupation located several kilometers apart. Patches without vegetation in this case define what in landscape ecology is called the matrix. The bird species in question may only reluctantly fly over such a matrix since it makes it vulnerable to predatory birds, whilst the wetland vegetation affords shelter and the possibility of moving under cover. The same patch, but with a transformed land use (for example horticultural garden instead of wetland), would still be perceived to hold the generic function movement for this particular bird species, but it would no longer hold the generic function of occupation for the amphibian species, since it would lack the moisture needed (cf. Andersson, 2006). Such ecological insights make the picture complex, but also enable possibilities of analyzing conflicts and synergies in overlapping patterns based on how different species (including humans) move and occupy the landscape.

Moreover, just as it has repeatedly been demonstrated that the configuration of spatial form directs the movement of people to certain spaces more than to others due to the pattern of varying centrality that it creates (Hillier *et al*., 1993; Stavroulaki *et al*., 2019), in a

similar way we know that the configuration of patches in natural landscapes influences the flow of animals, pollen, water and many other entities that make up ecosystems on a larger scale (Andersson and Barthel, 2016). Hence we can conclude that spatial form has the ability to strongly influence the generic function of movement, or flows more generally, both in natural and urban landscapes; and also that in doing so it does not discriminate in an exacting manner between different forms of movement. So when we talk about exploring the spatial form of cities in the aim of integrating ecosystems into urban planning and design, we here see how the concept of generic function proves useful. It presents the theoretical foundations for an approach where, rather than aiming for a complete catalogue of the different spatial demands introduced by the many species we find in urban ecosystems, we may instead attempt to identify the far fewer spatial demands that relate to generic functions, such as the set of diverse modes of movement typical for local species or species groups.

If this resolves the task of tying spatial form to ecological process on a theoretical level, the next challenge concerns how to develop a methodology whereby spatial form can be represented so that the capability of affording and structuring generic functions, especially movement, or flows more generally, is captured. We may then say that what we have called configurations of patches provides a concept and method for describing occupation or stationary uses in cities, where each patch in ecological terms describes a biotope or group of biotopes, and in social terms the built elements of human habitats. What we need to add is a form whereby we can represent the connections or, rather, the connectivity between the individual patches in such configurations of patches, since this is what ultimately facilitates movements or flows between the patches and, by extension, potential interaction. This is essential, since it constitutes the difference between a description of a static landscape pattern and a representation, albeit highly simplified, of a living ecosystem. Hence, what we aim for, from an ecological perspective, are descriptions that capture a set of patches in an urban landscape that represents biotopes of natural, semi-natural and artificial origins, as well as their internal connectivity constructed from the point of view of a particular species or species group.

Methodological approach I: network analysis in landscape ecology

As is suggested in the Introduction, an entity of interlinked parts of the kind discussed above is what is typically being described in network analysis (e.g. Newman, 2010), a field that specifically addresses the relations between things rather than the things themselves. Despite sounding reductive, this has proved extraordinarily successful and is today applied in a wide range of research fields in both the social and the natural sciences. It has also been applied in urban modelling (Batty, 2013) as well as in studies of spatial form, where space syntax research has taken a lead (Hillier, 1996). Similarly, network analysis has long been applied in landscape ecology to describe connectivity between biotopes (for example Pascual-Hortal and Saura 2006). In network analysis, entities of interlinked parts are typically represented using graph theory, which makes use of a very simple geometric language consisting of only two elements: vertices (or nodes) representing the parts, and edges (or links) representing the links. This, because of rather than despite its simplicity, has proved to be an extremely powerful language of representation. We may see the potential when we realise that more or less anything in the world may be conceived of as interrelated parts, from the internet to biological food-chains. Our configurations of patches above is then a rather typical example that also can be represented as graphs by letting each patch be a node and each connection a link. This is also exactly how network analysis has been applied in landscape ecology (Figure 1) (see Zetterberg, 2011). Fundamentally, this is also the approach in space syntax, but as we realise, given the highly reductive language of graphs, what you choose to represent as

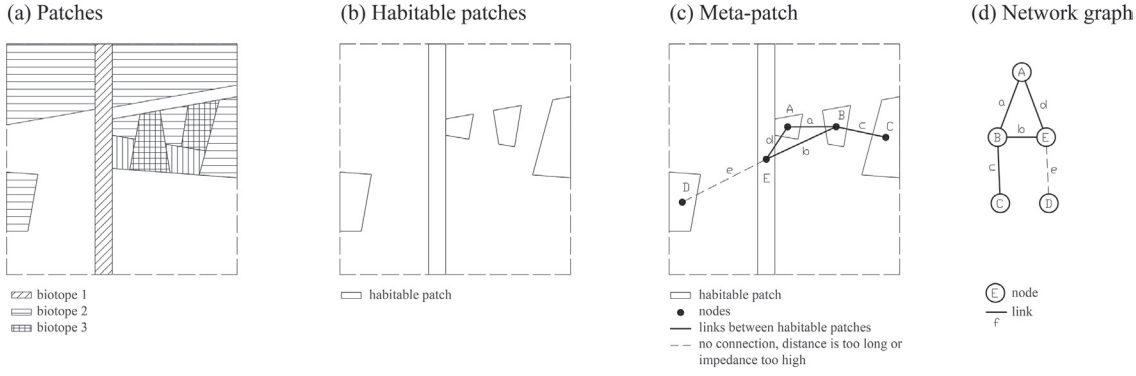

Figure 1. Patches, corridors and the matrix are composed of biotopes which, depending on their geometry and the species being studied, are categorized as patch, corridor and matrix (a). For mobile animals, most habitats are made up by a variety of complementing biotopes, that is, habitable patches (b) that can be spatially connected or not, depending on the distance and other forms of impedances such as buildings and roads and so forming meta-patches (c) that can also be represented as a network graph (d).

a node and what you choose to represent as a link, becomes extremely important and, as we shall see, space syntax has here introduced some original ideas of high relevance for the modelling of cities.

If we begin with the application of network analysis in landscape ecology, it is important to keep in mind that network representations in this field are typically made from the point of view of a particular species or species group, where each patch of relevance for this species (which together constitute the habitat of the species) is represented as a node and each connection between these patches, defined as an accessibility for the particular species, is represented as a link. As discussed above in relation to patch dynamics, depending on the size and distribution of the patches in a particular landscape, patches may in practice not always represent individual biotopes, but also groups of connected biotopes, termed a meta-patch. Either way, such descriptions can then be analysed using the many different measures and analytical techniques developed in network analysis, such as calculating different varieties of centrality in the network. Several GIS-based digital tools have been developed for this kind of description and analysis, for instance the MatrixGreen (Bodin and Zetterberg, 2010).

Naturally, these methodologies and tools are developed from a theoretical framework originating in ecology and are specifically constructed to analyse and understand ecosystems. They therefore do not concern themselves much with the built form of cities. Hence they are limited when it comes to specifically describing urban ecosystems and are far from satisfactory if we want to understand cities as socio-ecological systems. In particular, we identify two issues related to how connections are represented in these tools and where the absence of built form descriptions clearly creates deficits if we are to create a joint socio-ecological morphology. First, these tools typically describe connections between patches by way of shortest distance, which in simple terms means that a connection between two patches is represented by a straight line. If we reflect on the fact that these connections in real life need to be realised by particular agents, most often animals of different kinds, we realise that they only rarely describe a shortest-distance path – not even in the case of birds – but most of the time describe rather crooked geometries. Significantly, in cities this crookedness is most often a result of the built form and infrastructure around or between which these animals need to navigate. This is why we realise how descriptions developed in

urban morphology could be useful here, both to achieve more accurate analyses in landscape ecology but, especially, given our current purposes, to achieve a joint description of socio-ecological spatial form. In simple terms we could substitute crooked geometries for straight-line geometries by letting built form structure connections between patches in a more life-like manner. Importantly, however, we need to keep in mind that the resultant description from such an approach would allow for movement in different ways for different animals (humans being one of them), depending on their particular movement abilities. We would, therefore, need to create different network representations of the same spatial structure, depending on the particular species that we are analysing.

A second issue is how the distances of these connections are measured. In tools such as MatrixGreen, distance is measured in part as the metric distance of the straight lines connecting patches, and in part by the impedance of these connections. The impedance is dependent on the characteristics of the patches it crosses, for instance, variations in the substrate of the ground, such as hard and dry or soft and wet substrates, which naturally influences whether different species can move across them (Urban *et al*., 2009). However, the impedance of a connection can also be due to obstacles which, in cities, as pointed out above, often relate to the built form, such as variations in the height or the pattern of buildings. In the tools discussed above, such variations in impedance due to substrates or built form are based on estimations expressed in numbers. For instance, depending on the species under analysis, substrates that are soft and wet may be estimated as having a higher impedance than those that are hard and dry; perimeter street-blocks may be estimated to have a higher impedance than isolated high-rise buildings; and five-storey buildings a higher impedance than two-storey buildings. This means that distance is, to an important degree, measured by numerical estimations of the impedance of built form. This may, in many cases, be sufficient, but in relation to urban morphology and urban design, it remains problematic. Not only do such estimations seem difficult to make, they also translate the variable of greatest concern in both of these fields – built form – from geometry to numbers, which in the case of urban design, moreover, needs to be translated back to geometry when applied in practice. Hence we see the obvious risk of substantial loss of information in these translations. This naturally raises the question whether there are other forms of representation that may improve these tools.

Methodological approach II: network analysis in urban morphology

We now turn to network analysis in urban morphology, where space syntax research has developed a comprehensive and innovative methodology which, furthermore, is theoretically supported in a manner that makes it possible to explicate the rationale behind its representations. While there may still be different interpretations (cf Stavroulaki *et al*., 2017), one recurrent theoretical grounding for these representations is the theory of affordances (cf Marcus, 2018)**,** introduced by the American ecological psychologist James Gibson (1979). Gibson defines affordances as the entities that emerge in the meeting between properties of the physical environment and the abilities of a particular species, for instance humans. It can then be argued that what is represented in the typical descriptions developed in space syntax, of which the axial map is the most well-known (cf Stavroulaki *et al*., 2017), is exactly affordances related to generic functions such as, in particular, human movement (Marcus, 2018). Taking the example of the axial map, it constitutes a representation of the spatial system of a city or an urban area, as structured by built form and accessible for a moving human, by the means of the least number of straight (axial) lines covering the whole system. The axial line can be directly linked to Gibson's affordances, in that it is defined to represent a space possible for a human to physically access and visually overlook. This fits Gibson's definition closely in that both accessibility and visibility are here

to equal degree an effect of both the structure of the built environment and the abilities of mobility and perception particular to humans.

For a representation of a city or an urban area one may, of course, need many axial lines of this kind, which together make up an axial map. Such a map is then constituted by a distinct set of lines, where each line may be conceived of as a node in a network and each crossing of lines as a link between such nodes. Based on such a network representation one can then, as in the tools developed in landscape ecology, perform all the typical analytical procedures developed in network analysis and thereby reveal vital relational properties in systems of urban space. This has proved revealing not least when it comes to human movement patterns (for example Stavroulaki *et al*., 2019). However, the important thing here is to keep in mind that what is mapped in the axial map, as well as its derivations (cf Stavroulaki *et al*., 2017), is neither the physical environment nor human movement abilities, but what emerges between the two; that is, what the built environment affords human movement.

If this concerns human movement, which we have argued to be critical for several vital social and economic processes in cities, such as social integration and the creation of local markets, we now ask how this may be applied to the movement of other animals, since we know that the movement of animals to equal degree is a prime driver in patch dynamics. Based on the discussion above we may conclude that what we need are similar but other representations of the movement affordances given by particular environments, now related to the movement abilities of species or species groups other than humans.

We here realise that many species have movement and visibility abilities that dramatically differ from those of humans. We may take the example of bees, which are essential for pollination in urban ecosystems, but which both see and move in ways foreign to humans. This may demand radically different forms of representation from those we have addressed so far; the axial map, for instance, is unlikely to correctly capture the movement affordances for a bee in an urban setting. Interestingly, there are alternative representations developed in space syntax that may prove useful here, for instance the visibility graph (Turner *et al*., 2001). In this form of representation, all accessible space is divided into cells rather than lines, as in the axial map, whereby the inter-visibility and inter-accessibility between these cells can be calculated and represented as visual fields (Figure 3). The broader point here, however, is that through the notion of affordances we can with precision identify

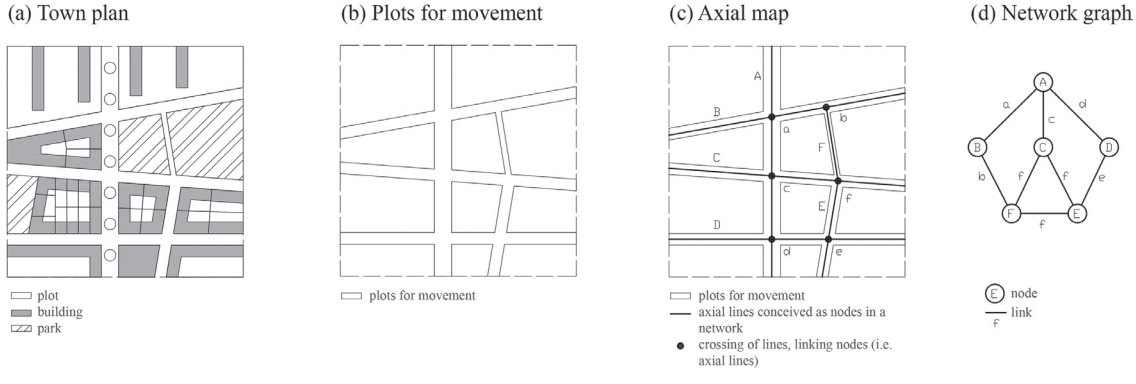

Figure 2. Town plans (a) are composed of plots, which depending on their generic function, can be categorized as plot for movement, that is, street (b). These can be represented as axial lines where each line may be conceived of as a node in a network and each crossing of lines as a link between such nodes (c) that, in turn, can be represented as a network graph (d).

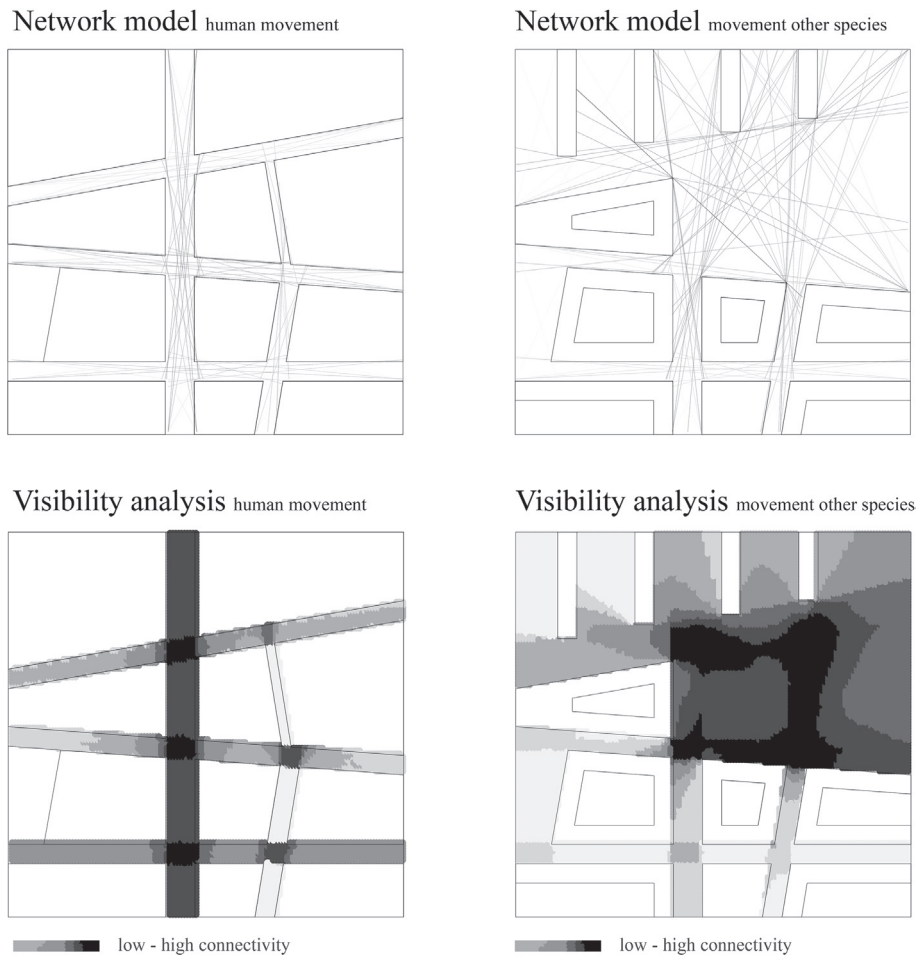

Figure 3. Intervisibility and inter-accessibility represented as axial lines (top) and visual fields (bottom).

what we need to represent: for instance, the movement affordances created by a physical environment to moving agents that are drivers in their particular systems, whether social, economic or ecological. Based on this we can then develop the appropriate means for their representation. Founded on the knowledge and understanding that this can give us, we may then structure and shape the built environment to support and direct that movement and in extension, support and direct the urban sub-system for which this movement is an essential driver.

Based on the discussion above, we see the possibility to propose an improvement of network analysis of green infrastructures in cities, inspired by the kind of descriptions developed in space syntax, which we also believe can pave the way towards a network analytical tool that integrates urban morphology and landscape ecology. In contrast to tools like MatrixGreen, distance is in a space syntax model, such as the axial map, arguably represented in the geometric description itself, rather than by numbers abstracted from it. This offers a means to overcome the issues described as problematic in these tools from an urban planning and design perspective. First, we do not need to rely on shortest-distance descriptions between nodes, since the nodes in space syntax are constituted by a set of axial lines structured by the built form of the urban area analysed, hence making spatial form a central part of the geometric description. Secondly, by measuring distance as the number of such axial lines – which, in

simplified terms, means that distance is measured as the number of turns made between two nodes – we see also that distance is written into the geometric description and, moreover, that it is directly related to the abilities of a particular moving agent. The idea behind this is that the number of turns may not imply a physical distance but a cognitive distance (or impedance) that therefore reflects, not the physical effort to move the distance, but the mental effort to navigate it (Hillier, 2012). We then realise that a particular measure of physical distance, such as metric distance, remains relevant for many different animals, in that 100 metres may be a very different distance to different animals, but still indicates for each animal the necessary energy demand to move that distance. To indicate the necessary mental effort in contrast, we realise that we need particular measures dependent on the different means of navigation for different species. For species that, like humans, rely on vision, for instance bees, representations of the kind developed in space syntax can be relevant as has been discussed; but, for species that use other senses such as heat sensing and echolocation, other forms of representation need to be developed. At the same time, many of the species found in cities have proven adaptive to human environments and are often similar to humans in that visibility is central for their navigation.

In summary, we find something useful here if we look for a way of representing links between spaces of occupation both for social and ecological systems. We see that distance here is more closely linked to the agent by not simply measuring it metrically, which indicates the physical effort to overcome the distance, but also topologically, as the number of axial lines or visual fields, which arguably indicate at least part of the mental effort particular to a species to overcome the distance. It is also more closely linked to the environment in the way that the built environment is written into the distance measure in that it is inherent to the geometric representation of the environment rather than abstracted from it into numbers. Hence, we here find the principles for measuring functional distance for different species acting as agents in urban systems. By developing geometric representations of the particular affordances vital to different species for their movement, we can capture both the physical and mental distance presented by particular urban landscapes for these species, just as the axial map has proven able to do for humans. Exactly what these representations are is a task for future research, but we have indicated how a way forward for bees as central agents in systems of pollination, for instance, could be the cell-based rather than line-based representations used in VGA analysis. While the development of such representation may prove a challenge, it seems potentially practicable, since we have seen how a broad toolbox of applicable representations (for example Turner *et al*., 2001) already exists, at the same time as geometric representation of spatial perception and cognition typical for different species or species groups is a theoretically well-supported idea (Dolins and Mitchell, 2010).

Conclusion: towards network analysis in socio-ecological urban morphology

We have discussed a comparison of similarities and differences between the spatial morphologies found in landscape ecology and urban morphology, with the aim of preparing the ground for an integrated socio-ecological spatial morphology and the inclusion of ecosystems into the practice of urban planning and design. Critical for these practices is a deep understanding of spatial form as defined by buildings and landscaping in cities, since this constitutes a critical slow-changing subsystem whereby socio-ecological processes can be structured and directed by these practices. It is essential here to capture the flows or movements in both social and ecological sub-systems, since this facilitates interaction and exchange which is what generates the more specific dynamics in these systems. The physical structure and spatial form of cities can therefore play a critical role in directing such dynamics towards more sustainable trajectories, and the investigation of how to

integrate ecosystems into a joint spatial morphology of cities seems an urgent but manageable challenge.

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