unit, a descriptive and explanatory framework that considers both the stocks and flows – of energy, information and materials – of the city. The second paper offers MUSE as a model to measure the patterns of energy consumption driven not only by the characteristics of transport and buildings but also by a number of features of specific urban microclimates. The third paper proposes a model to measure energy consumption considering not only the characteristics of urban form but also the renewable energy potential of cities. An additional step is taken by Ratti *et al*. (2005) and Salat (2009). Drawing on a quantitative morphological approach promoted by Lionel March back in the 1960s, Ratti *et al*. (2005) use digital elevation models and the lighting and thermal simulation tool to analyse the effects of urban texture on building energy consumption. Ratti and his colleagues consider the following parameters in their analysis: built volume and built surface, passive and non-passive zones, orientation of façade, urban horizon angle, and obstruction of sky view. Following a similar line of research, Salat (2009) uses a number of environmental metrics – such as building shape and passive volume – to explore energy consumption in different parts of the city. Both papers present applications of their methodological proposals in large European cities.

The development of new approaches, theories, concepts and methods should offer greater understanding of the interrelationships between urban form and the level of energy being used to maintain contemporary urban systems (considering both the quantity and the quality of the energy sources). It should also inform the debate on current urban development strategies, promoting the sustainable use of resources, land and energy as key ingredients for long-term prosperity. Finally, it should enable communication between hitherto rarely linked research communities, and generate insights into how to promote new research outputs for planning practice.

Among the different issues under discussion in contemporary debate on cities, energy is certainly one of the most important. Rising energy prices, the urgent need to reduce emissions and mitigate climatic change, and the large investments that will be needed to make installations and infrastructures fit for the future, make urban energy a key challenge for the present decade. The inclusion of a morphological dimension in this debate is essential.

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Morphological complexity: a response

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Ley (2012, p.79) categorizes fractal morphology as one of 'the more exact methods of the natural sciences' and, while criticizing geometrical methods, calls for the use of 'methods from both the humanities and life sciences'. He stresses the limitations of the sciences that study urban form, arguing that there is a need to consider the people and processes shaping urban form to provide 'full understanding'. I suggest that both physical form and the processes shaping it should be studied without either of these aspects in any sense detracting from the other. Urban morphology has been defined as 'the study of the physical (or built) fabric of urban form, and the people and processes shaping it' (Larkham and Jones, 1991, p. 55). While one urban morphologist may focus on the forces that shape urban forms, another may analyse or classify the resultant pattern, size, length, proportion, orientation of the urban elements, and the complexity appearing in the physical fabric of urban form. There are, of course, some urban scientists whose approach simultaneously covers both physical form and the processes underlying it (for example, Conzen, 1969, 1988; Larkham, 1988, 2009; Whitehand, 1981, 2001).

The fractal approach to urban form has the potential of contributing to both physical and functional analysis. For instance, some of the earlier work by Batty and Longley on measuring the complexity of urban boundaries of cities, such as Cardiff, London and Berlin, is purely geometrical (Batty and Longley, 1994). However, some more recent work, particularly that using cellular automata models to simulate the processes of urban change and growth, is based on the fractal nature of urban development and inevitably uses numerical and mathematical methods to program the models (Batty, 2005; Batty and Howes, 2001). Such interdisciplinary methods attempt to merge the natural sciences (physics, mathematics and geometry) with the human and life sciences. Here, we can suggest that the researchers succeed in transcending their specific academic disciplinary backgrounds. There is also some research that is taking a socio-economic perspective on measurement and city complexity with no direct focus on the physical structure of urban form (Byrne, 1998, 2005). These attempts not only have no 'disastrous consequences in urban planning or civic policy' as Ley (2012, p. 79) claims, but the advocates of complexity theory currently believe that this is the most realistic approach towards which our future planning should move (Byrne, 2001; Innes and Booher, 2010; Roo *et al.*, 2012).

In questioning the use of numerical values for studying the complexity of urban layouts, Ley (2012, p. 79) suggests that even a combination of various arithmetic or statistical parameters will not reflect the complexity of urban form. He assumes that urban form will 'be reduced to numbers' in this way. None of the urban scientists who have applied geometrical and mathematical descriptions to architectural and urban forms, from the Renaissance to the post-war periods (Lynch, 1960; Marshall, 2005; Stamps, 2002), intended to reduce forms to numbers. Nevertheless, measurement and geometric analysis have been fundamental to aspects of urban morphology, especially in the metrological analysis of plots and settlement forms (Lafrenz, 1988; Sheppard, 1974; Slater, 1981). Geometry as a science is a fundamental part of urban morphology, and mathematical measurement associated with numbers is an intrinsic part of geometry. Quantitative methods provide useful means of understanding the arithmetic order underlying physical fabric, but not necessarily the processes or life shaping it.

The science of complexity stems from two parallel, but related, scientific developments in chaos and fractal theories. While the concern of chaotic dynamics is the behaviour of complex systems, fractal geometry provides subtle perspectives on the study of the forms and structural complexities of those systems. The applications of these new theories to urban form can be categorized into three main groups: conceptualizing city complexity (Byrne, 2003; Portugali *et al.*, 2012); simulating urban growth and change (Batty, 2012); and measuring urban physical complexities (Cooper, 2003; Cooper and Oskrochi, 2008). Fractal dimension assessment contributes to the latter application as a sensitive criterion for measuring and mapping urban physical complexity.

The fractal assessment of a range of aerial photographs can show the changes of complexity between one neighbourhood and another. As the assessed fractal dimension is unique, a fractal identification code can be formulated for each neighbourhood (Haghani, 2009). These codes can be translated into fractal maps providing a type of 'morphological fingerprint' for the area being examined (Haghani and Larkham, 2010). In terms of pattern recognition and identification, the fractal assessment method can be employed for the classification of urban patterns based on the level of the physical complexity underlying their forms. One of the advantages of the fractal classification over other methods is that it can provide a mathematical gauge for classifying urban patterns wholly independent of the eye of the examiner.

Another application of this technique is for analysing change over time. For instance, if several photographs of an urban space, an urban landscape, a street view, or an urban elevation are available from different periods, the degree of change in physical complexity over the periods between photographs can be calculated mathematically.

This can be useful, particularly when the researcher needs to assess the degree of physical impact of an urban intervention on an existing urban fabric. However, it should be noted that fractal measurement is not an evaluation tool. As Ley (2012) points out, an urban layout with a greater degree of complexity is not of necessity a better layout. Use of the fractal dimension is, in fact, a new assessment tool in the toolbox of urban designers and decision makers, facilitating measurement of the degree of change that their proposals may impose on the physical fabric of an urban environment (Haghani, 2009). Other tools are required to measure the change in socio-economic complexity of the environment or any other aspects of human life in the city.

The application of current fractal analysis methods has limitations. First, older aerial photographs are generally available in 2D and none of the currently-available software programs can measure fractal dimensions of 3D urban spatial photographs. Hence research is limited to 2D image analysis. Secondly, the software employed only performs a binary – black and white – image analysis. Therefore, some of the greyscale data may be missed during examination. Thirdly, current fractal analysis software accepts only a single layer format as its input, and therefore the program cannot distinguish the difference between layers of information in an image. Thus, the unnecessary data have to be removed manually from an image before examination, and manual data removal might be associated with mistakes. Nevertheless, future research and software development may overcome some of these limitations as soon as new technology can offer more accurate image processing tools.

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Fractal assessment: some questions and comments

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In his response to my plea for interdisciplinary collaboration among urban morphologists Haghani (this issue, pp. 60-3) focuses on my concern about employment of 'the more exact methods of the natural sciences [...] in a mistaken or misleading way' (Ley, 2012, p. 79) and gives an explanation for his method of examining morphological complexity by a fractal assessments of aerial photographs. In so doing he is evidently misunderstanding my position regarding the significance of geometry and geometrical methods for urban morphology. As an architectural historian and urban planner, geometrical methods are my primary tools for understanding, envisaging, and examining urban form (and the same is true for most of my colleagues). In stressing his point about fractal analysis Haghani is claiming a long pedigree of geometrical and mathematical descriptions in architecture and urban design 'from the Renaissance to the post-war periods'. I believe it is unnecessary to re-evaluate the quoted contributions of Lynch (1960, 1981), Marshall (2005) and Stamps (2002). They all represent commonly accepted and fruitful approaches towards urban form. But do they call for the 'mathematical gauge for classifying urban patterns' that Haghani is suggesting?

To my knowledge the use of geometry in the description of architecture and urban form was known already in the Bronze Age (see, for example, the Kassite city plan of Nippur, scratched into stone, *c*. 1500 BCE, in the Hilprecht collection in Jena, or the city of Umma real estate plan, *c*. 2200 BCE, in the Louvre in Paris). Geometrical descriptions were almost concurrent with the development of cities themselves. This early employing of geometry can be explained by a deep human desire to deal with the complexity of the city in simplifying quantitative, and sometimes also normative, ways (for example, in proving possession). However, as we know from the Ideal City of the Renaissance, the widespread attempt to reverse this by producing a 'perfect' geometrical plan to improve urban quality failed. This was despite the intellectual brilliance of authors such as Alberti, Filarete, and Leonardo da Vinci, whom we might call urban designers rather than urban scientists with respect to their urban plans.

In my Viewpoint I never intended to question the necessity of geometry in urban morphology nor the potential benefit of a chaos or fractal approach to describe urban development (as a matter of fact, chaos theory is fundamental to my theory on how we perceive and understand urban form: see Ley, 2009). I do, however, insist that the complexity of urban form, which is always related to the complexity of urban life, cannot be fully described by mere quantitative methods. The anxiety that I expressed in my Viewpoint was that some people might seek to determine the complexity of urban patterns with a complex method to obtain simple numerical values without due caution about how these numerical values might be perceived and employed by third parties. Haghani's response unfortunately adds to my anxiety. On the one hand he states that 'fractal measurement is not an evaluation tool', but on the other he advocates, in the same paragraph, that the use of the fractal