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Assuming it is all about conditions. Framing a simulation model for complex, adaptive urban space

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Abstract

In this paper, we explore the route beyond the conventional, linear attitude within planning and its rationality debate. We combine our theoretical reasoning with a multiscale approach and with fractal-like argumentation which results in a *frame of conditions* which is supported by the outline of a *theoretical conceptual simulation model* which would also allow non-linear, iterative simulations of the urban space. The understanding of autonomous non-linear spatial development has a direct impact on planning. Addressing the underlying thinking behind Haken's synergetics we develop a framework within which the interdependencies between different levels of scale are key. We are aware that bottom-up and top-down processes often have a mutual influence on one another. We therefore propose a conceptual simulation model for planning where conditions have an impact at various levels of scale. In coherence with the idea of the 'dynamic behaviour of the system after a planning decision was made', this feedback gives us information on the surviving and non-surviving planning scenarios and decisions and is reminiscent of systems which are open to self-organizing pattern formation. Our reasoning with regard to planning and decision-making and their multilevel consequences is strongly influenced by the arguments presented in complexity studies.

Keywords

Adaptive planning, complex systems, non-linearity, spatial modelling

Introduction

For a long time now, scholars have tried to imagine urban futures (Blowers et al., 1974; Hancock, 1976; Rodwin, 1960). Obviously these futures are helpful in debating the decisions

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and choices to be made now. However, imagining futures by extrapolating facts from the past and the here and in the present has its limits. Thinking along linear Newtonian cause–effect lines seems dubious from the perspective of a world considered to be in a continuous process of discontinuous change. Futures are affected by the contextual interference and non-linear iterative processes (cf. complex systems, e.g. Portugali, 2005; Waldrop, 1992; Wolfram, 2002) and the self-referential processes of individuals (Stacey, 2003). These processes are responsible for what Rittel (1972) considers to be ‘wicked’ problems: problems which cannot be brought to a definite end as fundamentally uncertain (Rittel and Webber, 1973). Within the urban space these ‘wicked’ problems are many and are poorly understood. In this paper, we want to explore alternative routes to tackling ‘wicked problems’. We do this not by emphasizing the content and process of the issue in question, but by identifying and substantiating conditions under which content and processes evolve and contribute to discontinuous urban change. A multilevel approach will be introduced for modelling urban space using Haken’s synergetic logic combined with a frame of conditions which allows the issue in question to transform internally (self-organizing) as well as externally (being adaptive). This approach will shed light on processes of discontinuous, non-linear urban change, on wicked problems within the urban space and on our understanding of adaptive and self-organizing systems, which will help planning practitioners deal with uncertain, incremental processes of urban change. Our approach is primarily conceptual, as we are outlining a framework for tackling the idea of complex, adaptive modelling for wicked spatial problems.

Evolutionary thinking: Planning in the light of a complex emerging order

The discipline of spatial planning has long favoured a direct causal understanding and hence Newtonian worldview of urban growth. This technical paradigm addresses the idea of a factual reality, a certainty within reach and a linear route into the future. Since the 1990s remote causalities have also been acknowledged in spatial planning. The so-called communicative paradigm (Healey, 1992) was embraced, prescribing a collective, agreed reality and consensus among the actors involved (De Roo and Rauws, 2012). Thus, aside from a factual reality an agreed reality is also considered to respond to the complex built environment. Both paradigms have as their main interest the decision made in the ‘here and now’ about spatial interventions. There was (and still is) hardly any interest beyond the moment of the decision made (De Roo, 2012). Contemporary planning theory is more or less ‘a-temporal’ (De Roo, 2010; Hillier, 2007) which is peculiar, to say the least. The world is fixed, static or frozen in the theoretical planning discourse which means that traditional and contemporary planning has no eye for evolutionary behaviour. This kind of thinking went on for decades, and as in the days of Rittel, we are again witnessing a growing number of planners’ showing a desire to relate planning theory to other perspectives on the world. Of course the world is not a fixed state – discontinuous change is probably the only constant factor. Kropf (2001) notes that urban form and the social and economic life of cities are underlain by descriptions of *inter alia* transformation, cycles, growth and decay, catastrophes, shifting centres of activity, dynamics and influence.

There are various biological, Darwinist metaphors (e.g. for environmental design see Alexander, 1964; Fontana and Buss, 1996; Steadman, 1979) and concepts through which we can obtain a better understanding of evolving spaces. Here we continue this line of reasoning by employing a fractal approach as the logic of nature (e.g. Batty and Kim,

1992; Batty and Longley, 1994; Frankhauser, 1994; Frankhauser and Pumain, 2007; Qin and Liu, 2004; Salingaros, 2005; Shen, 2002; or White and Engelen, 1993 for a synthesis), introducing planners to a multilevel evolutionary perspective on the spatial organization of the urban fabric. Another evolutionary perspective relates to the complex adaptive system (CAS) (Gell-Mann, 1994; Holland, 1992, 1999; Solvit, 2012), which defines spatial systems on the basis of internal interactions between dynamics and robustness while interacting with and floating in an external environment between order (uniformity) and chaos (diversity). This idea of a CAS introduces notions such as dynamics, self-organization, emergence and adaptivity, all relevant with regard to evolving space, complexity and planning. In reality, we can identify most systems as multilevel, floating between sub- and super-systems (cf. multilevel interactions; Pumain, 2006). These notions are somewhat counter-intuitive to a traditional planner, used as he or she is to the dominance of linearity and functionality (Alexander, 1984). In this context, an excellent example is the 'shared space' concept associated with the late Hans Monderman in the early 1990s, promoting spaces free from traffic rules and thus based on a self-organizing logic among individual space users (Stalman and Wiersma, 2001). Shared space is meant to give people back their responsibility in using public space such as roads, which should result in fewer rather than more accidents because of an increase in spatial awareness and self-regulation mechanism. It relies on a strong dynamic non-linearity and multiple interactions.

~~Often, we can consider these to be CASs.~~ 'Being in balance' becomes an important idea when adopting a temporal and non-linear, evolutionary perspective, with 'being in balance' meaning 'temporarily stable' or 'persistently dynamic'. Cities are good examples of CASs which change over time in structural and functional senses. CASs have the potential to co-evolve during a transition process due to a mutual influence between different systems or – between a system and its environment. With co-evolution, the system undergoing a transition could fundamentally transform in terms of its structure (in the case of, e.g. Bénard convection cells or lasers). This process of co-evolution is the result of the system adapting to a new context, with a better fit between the system and its environment. During the process of co-evolution, stability decreases while the system's dynamics increases. As soon as the system connects with a new contextual environment, stability increases again (Figure 1) and the system's identity is likely to have changed radically due to the co-evolution of its structure and function. We can illustrate the co-evolutionary process with the introduction of the railways and its effect on car use and road traffic. Railways replaced horse-drawn carriages and thus became the general means of transport. At an urban level the appearance of tramways had the same effect. Structurally, a rail system restricted individual freedom of movement to some extent, while emphasizing the importance of routes which were supported by the rail network. Functionally, individuals did not need a privately owned mode of transportation. Some decades later, motorization led to a decline in railway use and many towns abandoned or reduced tramway use in order to privilege individual transportation by car. With the transformation of urban space (e.g. highways, petrol stations and car-friendly street surfaces) the infrastructure system adapted spatially and technically to enabling technological conditions. Today, sustainable development is again generating the opposite effect.

In evolutionary systems we find both a slow deformation and a sudden metamorphosis changing the underlying structure and pattern of a system (see Figure 1). For example, many changes in urban evolution have been conditioned by technical innovation and fundamental changes in society. The agricultural and industrial revolution profoundly altered how society and the economy work and changed urban systems fundamentally within a few decades. In

Figure 1. The (co)evolutionary process of systems (Yamu, 2014).

this respect, we have to consider about planning in the light of an unpredictable future (Boelens and De Roo, 2015; Hillier, 2013; Popper, 1957). Thus, planning has to be responsive to a world being adaptive, as proposed by complexity studies (e.g. Alexander et al., 1977; Batty and Longley, 1994; Batty and Marshall, 2012; Frankhauser, 2008; Haken, 1982; Nicolis and Prigogine, 1977; Portugali et al., 2012; or Yamu, 2014 for a synthesis). Non-linearity tackles urban situations (structural and functional indicators) as something stable at a particular moment while they can become unstable at the very next moment, and vice versa. This occurs because, for example, contextual driving forces (in society these could be riots or an economic crash) emerge suddenly and the existing system is no longer properly connected (a good fit) with its changing context. We consider a system's adaptation successful if the new (socio-spatial) spatial situation again achieves a high level of stability (good contextual fit with its environment) and the system is both robust and competitive. In addition, we have to consider that through the process of adaptation the system also undergoes an identity change which is reflected in new features and potentialities compared to the preceding system's condition. The more the system progresses towards it 'new' condition, the more the initial robustness and the flexibility it cope with surprises decreases.

'Changes' refer to instabilities of a system, triggered, for example, by external pressuring influences or conditions such as the impact of technology, a political revolution or sociocultural changes. This is reminiscent of synergetics, which is an attempt to find principles that govern the behaviour of complex systems (Haken, 2012). It explains the formation and self-organization of structures away and even far away from equilibrium. In synergetics, such qualitative changes are described using the concept of control parameters and order parameters. Control parameters describe external pressuring influences acting on the structure and behaviour of the system (stable, unstable), whereas the newly emerged structure of a spatial organization refers to a new order and is therefore affected by order parameters. The order parameter equals 0 in less ordered states of phases and tends to progress to 1 when an internal self-organized order appears. It provides information about how far the system is from the state of equilibrium. Batty (2005) rightly points out that cities respond flexibly to external pressuring influences such as new technologies, economic change, the changes described above in transport modes, and so on while responding to these changes from the bottom up or from the 'inside out' due to the dissipative structures in the internal mechanisms which activate the system. Each city

contains numerous subsystems which we also consider ‘urban’ too, and which influence each other while coping with contextual changes and while transforming internally as a response to these changes. What we observe are dynamic interactions within the urban and the rural at various levels of scale and different-sized systems. Thus, we need to frame models which work across scales in a multiscale manner.

Systems in translation: Constraining and enabling conditions

Following on from Haken, and to frame our work in a conceptual model, we now want to introduce the conditions affecting a system. These internal and external influences constrain and enable a system’s development. Due to pressure from external forces, the system responds internally and adapts its structure and functions (De Roo, 2012). While external conditions are forces which exert pressure for internal adjustment, an internal set of cohesive conditions is still crucial, allowing the system to adjust while keeping the system functionally together. In our reasoning we consider it crucial that the internal set of cohesive conditions under which the system co-evolves remains the same. We argue that these internal conditions sustain a CAS. In other words, while the structure and function of a system co-evolve, and by which means the system fundamentally transforms, an acknowledged internal set of cohesive conditions provides a system with an identity over time (Figure 1). They strongly reflect the system’s transformative capabilities both internally (self-organization) and in responding to external influences (adaptivity). We believe these internal constraining and enabling conditions together also have self-regulating powers, in the sense that balanced interdependencies between these conditions support the system in best fitting its process of transformation, while preventing it from developing to radical extremes.

While CASs are internally both robust and dynamic, they co-evolve due to external influences affecting them while remaining ‘on the edge of order and chaos’ (Waldrop, 1992). Consequently, an urban system which we consider to behave as a CAS will have the capacity to transform between an ordered state (uniformity) and an environment whose state is chaotic (diverse). Between these extremes of uniformity and diversity the urban system will be able to adapt and to self-organize, to change by means of internal dynamics while building on layers of robustness, through which it will be able to survive. As cities’ functions transform, the enabling and constraining conditions which regulate and self-regulate this transformation keep the transformative process balanced and responsive.

Transformation is, *inter alia* the result of the system’s responsiveness to being part of a system environment which is ‘out of equilibrium’. This is the situation in which energy, matter and information are passed between the various layers the system is connected to. It makes a CAS susceptible to internal and external influencing forces and it allows the system to flow between two extreme points: uniformity – a position close to equilibrium which renders the system inert, and diversity – a position so far out of equilibrium that the system could collapse¹ (Figure 2). These interdependent dualities of internal dynamics and robustness and the positioning between the external extremes of uniformity and diversity generate the system’s complexity: a non-linear process of co-evolution, adaptation, self-organization and emergence. It creates the system’s potential in a state of becoming.

Let us consider a spatio-economic system (see Figure 2). Such a system is structured by its urban or regional disposes, and allocates various economic functions. While these structures and functions will transform over time, there is also an internal set of cohesive urban system conditions with self-regulating powers. These conditions will provide the system with its lasting identity as they will persist throughout its various transformations. Based on research done in the northern Netherlands (Hermanns and De Roo, 2006) we propose

Figure 2. (a) A model of a CAS, making reference to complex circumstances between order and chaos, and its internal interdependencies between a dynamic and robust state; (b) conditions of a complex adaptive spatio-economic system for urban and regional development (De Roo, 2012); (c) its four conditions connecting the two internal layers and the two external extremities which the system is positioned and (d) a neighbourhood and its social capital (Nienhuis, 2014).

competitiveness C_{com} , complementarity C_{cpl} , cohesion C_{coh} and compatibility C_{cpa} (the 4 Cs) to be the conditions of such a spatio-economic system. We arrive at such conditions based on the circumstance that urban and regional development involves spatial change and economic advantages. We therefore argue that the four conditions (the 4 Cs) are essential for a spatio-economic system to adapt and change.

We regard competitiveness as a potential driver for a region to differentiate itself from other regions. It can be turned into an advantage and a driving force enabling regions to develop and progress. It relates to internal dynamics and contextual diversity. What we can derive from a complex adaptive understanding of spatial economic regions is that a competing region will also have to identify its complementary qualities in order to relate to and benefit from its contextual environment. In other words, a region cannot be solely competitive (as well as being unique and specific); it must also relate to widely accepted qualities which it shares with and adds to neighbouring systems (De Roo, 2012; Hermanns and De Roo, 2006). Competitiveness C_{com} and complementarity C_{cpl} are linked to a certain degree to cohesion C_{coh} and compatibility C_{cpa} . The cohesion of a region is an important asset allowing dynamics to occur, as it represents a robust link between sub-systems which are influential for a region's development. Compatibility represents diversity while remaining robust. The diversity of a regional economic zone allows it to be fault tolerant/resilient if, for example, one or several specific functions disappear, avoiding disruptions to the region as other economic functions absorb the surplus labour. This is a condition for interchangeability building upon a 'plurality of potentials'.

In addition, we introduce a condition at the neighbourhood level, social capital S_{cap} (Figure 2(d)). Strong social capital (Bourdieu, 1972; Jacobs, 1961) is a condition ensuring the neighbourhood is able to maintain its spatial and social quality, is willing to invest and to

renovate, and is willing to be an attractive place to live (cooperation level and social networks) (Nienhuis, 2014). Based on his study of resilient communities in the city of Arnhem, Nienhuis (2014) presents us with four conditions for social capital in a neighbourhood in need of revitalization (Figure 2). It relates to the degree to which a neighbourhood community participates in communal life. It suggests people are sympathetic to explicit and implicit behaviour rules within the neighbourhood. To connect the neighbourhood to society and its encompassing sociocultural attitude, avoiding a strong internal orientation which could result in ignorance, an important condition is to transcend cultural values in a neighbourhood. Tolerance is a condition for the neighbourhood community to allow space for dissent. A community which is not too inwardly focused is able to maintain a workable balance between keeping distance and showing willingness to support its members if there is a need to do so. The attractiveness of a neighbourhood within a wider hierarchy of places within the urban area is another condition. We frame this condition here as ‘branding’. ‘Branding’-related criteria could be the position a neighbourhood has in the housing market, the perceived quality of the public space available, a neighbourhood market, a neighbourhood’s reputation for safety, its historical values, and so on. Nienhuis argues that these conditions are important with respect to the resilience of the neighbourhood’s community and its willingness to take responsibility for the neighbourhood’s qualities. If so, this would make these conditions essential to neighbourhood policy and planning (De Roo, 2015).²

Framing a conceptual simulation model for planning

We use the theoretical framework of CASs and conditions as the underlying logic for formulating a conceptual model for planning. In order to make the model operational, we combine a functional normative model based on the conditions (the 4 Cs, see Figure 2) with a spatial model across scales. This multiscale spatial model has the advantage of being usable in a top-down and bottom-up manner with interactions at various levels (region to neighbourhood) relevant to the system. Using the Hakenian logic for the framed model we first need to understand a system’s predominant order parameters over time. We thus identify an indicator using the logic of fractals, whose rationale corresponds to that of the order parameter in synergetics. This ‘fractal-based’ indicator is logically linked to a hierarchical principle. We should recall that hierarchy itself is a discrete gradient, as it represents levels of interactions (Pumain, 2006) linked to self-organization and is part of complex systems.

Once identified, the order parameters (e.g. economic parameters such as an automobile factory influencing the morphological structure by triggering the development of many workers’ homes around the factory) will feed into the normative functional model developed according to the previously described constraining and enabling conditions. This functional model in turn is linked to a multiscale spatial model in order to address conditions bottom-up and top-down across scales. In the following, we propose a conceptual model which allows us to understand how different spatial and functional scenarios can be evaluated.

Identifying Haken’s control parameters due to spatial transformation: Measuring empirical structures over time

The analysis of city complexity includes the analysis of the morphology of the city’s components (Thomas and Frankhauser, 2013). Empirical spatial structures, the urban morphology of cities, follow an irregular and inordinate morphology. Many investigations

have shown that spatial organization of built-up space can be described using a fractal distribution law (e.g. Batty, 2005; Batty and Xie, 1996, 1999; Frankhauser, 1994; Shen, 2002; or Thomas et al., 2010 for a synthesis). To measure empirical structures we assume that the same type of law holds for empirical structures as it does for theoretical ones. Accordingly, we can interpret spatial structures as random fractals (Mandelbrot, 1982). Moreover, it is possible to introduce a fractal-based indicator characterizing that extent to which the spatial distribution of built-up space follows a fractal distribution law (Frankhauser, 2000). This indicator corresponds in logical terms to that of order parameters in synergetics. To identify the fractal-based indicator we use *radial analysis*. Using a rasterized black and white image of a spatial agglomeration where the black pixels represent a built-up surface we can count built-up mass around a freely chosen starting point (Figure 3). The radial analysis applies iteration logic to an increasing radius ε . The number of elements $N(\varepsilon_i)$ (built-up 'black' pixels) within the radius ε and the distance i (measured in pixels) is estimated by means of a power law.

Thus, for fractal patterns we observe a scaling law linking the number of black pixels $N(\varepsilon_i)$ corresponding to the distance ε_i from the counting centre. This relation reads as

$$N(\varepsilon_i) = a\varepsilon_i^D \quad (1)$$

where D is the *fractal dimension* and a a *prefactor of shape*. The procedure is repeated with an increasing distance from the chosen counting centre. From the logarithmic representation, we obtain a linear relationship between $\log N(\varepsilon_i)$ and $\log \varepsilon_i$ which reads as

$$\log N(\varepsilon_i) = D \log \varepsilon_i + \log a \quad (2)$$

We can expect that the observed relationship in real-world urban structures does not really follow a strict scaling law. The parameters D and a would then depend on the distance

$$\log N(\varepsilon_i) = D(\varepsilon_i) \log \varepsilon_i + \log a(\varepsilon_i) \quad (3)$$

Figure 3. The logic of radial analysis.

Therefore, to explore any eventual deviations from this law when moving from distance ε_i to the next distance ε_{i+1} , the local variation of the empirically observed relationship is considered (Frankhauser, 1998)

$$\alpha = \frac{\log N(\varepsilon_{i+1}) - \log N(\varepsilon_i)}{\log \varepsilon_{i+1} - \log \varepsilon_i} \quad (4)$$

This function is called the ‘*scaling behaviour curve*’. The scaling behaviour curve’s fluctuations allow us to identify different characteristics of urbanization according to the change in fractal behavioural logic (Frankhauser, 2008) shown in Figure 4. We can distinguish two phenomena through the curve’s shape: first, high local fluctuations due to large undeveloped areas (e.g. public squares, urban open space, highways, etc.) and second, variations over larger distance ranges indicating changes in scaling behaviour (e.g. block sizes) and thus a change in the urban morphological pattern or on the fringe of settlements. We therefore use Gaussian smoothing to eliminate local fluctuations and highlight structural, long-range changes. We obtain a curve of smoothed values $\tilde{\alpha}(\varepsilon_i)$. This is shown in Figure 4, which we use as a reference to identify order parameters.

In addition, we also refer to the arithmetic mean $\bar{\alpha}$ of all empirical values α_i (Figure 4). We interpret the arithmetic mean $\bar{\alpha}$ as the fractal dimension D of our system under scrutiny. This value corresponds to a unifractal without any deviation. We then introduced two kinds of variances. For the first we computed for each distance ε_i the square deviations of all real data with respect to the smoothed value $\tilde{\alpha}(\varepsilon_i)$. This local variance for each distance (radius) ε_i reads as (Frankhauser, 2000)

$$\sigma(\varepsilon_i) = \frac{1}{m} \sum_{j=1}^m (\alpha(\varepsilon_i) - \tilde{\alpha}(\varepsilon_i))^2 \quad (5)$$

Figure 4. ‘Raw’ scaling behaviour curve versus Gaussian smoothing to identify control parameters.

If we compute a mean value for all local variances for each distance ε_i , we obtain a global variance measure for local fluctuations with respect to the smoothed values – the *residual variance* σ_{res} :

$$\sigma_{res} = \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m (\alpha(\varepsilon_j) - \tilde{\alpha}(\varepsilon_i))^2 = \frac{1}{n} \sum_{i=1}^n \sigma(\varepsilon_i) \quad (6)$$

Second, we compute the square deviations from the global mean $\bar{\alpha}$ for each distance ε_i and then compute their mean value σ_{tot} . This is the variance of empirical data with respect to the mean fractal dimension over the range of distances:

$$\sigma_{tot} = \frac{1}{n} \sum_{i=1}^n (\alpha(\varepsilon_i) - \bar{\alpha})^2 \quad (7)$$

Combining both these variance measures allows the introduction of an *order parameter* η , the definition of which is based on the correlation ratio:

$$\eta = 1 - \frac{\sigma_{res}}{\sigma_{tot}} \quad (8)$$

From a synergetic perspective, this parameter can be interpreted as the ‘order parameter’. It informs us about a spatial pattern’s degree of order (no order/rather ordered) and thus its degree of organization at a certain level. If the smoothed curve $\tilde{\alpha}$ is close to a theoretical fractal then the order parameter becomes more sensitive with respect to local deviations.

Fractal order can increase or decrease over time, meaning the change in the order parameter over time informs us about changes in spatial organization due to social, political or economic circumstances, for example. Figure 5 provides an example of the evolution of the order parameter for a number of metropolitan areas in France and Germany. To generate the necessary data ~~we used~~ a series of maps of various development phases for Montbéliard, Lons, Audincourt, Berlin and Munich. Montbéliard’s development over time is of particular interest. This agglomeration is a conurbation, the dynamics of which were crucially influenced by the establishment and location of a Peugeot automobile factory after the Second World War. By choosing different centre points for a series of analyses, we were able to prove that the Peugeot enterprise was the dominant driving force for urbanization in post-war Montbéliard. New communities have developed near the factory and we can thus depict a direct interaction and interdependence between socio-economic factors and spatial dynamics. Accordingly, we argue that the emergence of the Peugeot factory acts with a long-range dynamic coherent to a slaving principle, where a rapid reaction by local decision-makers can be observed as manifested in the development of new housing estates in the factory’s vicinity. A new spatial order for the conurbation thus emerges.

By means of fractal analyses the spatial fractal order parameter can be identified and socio-economic influences derived (control parameters). This is essential for understanding the dominant influencing control parameters in evolving systems. From the fractal analysis we derive an evaluation of morphological changes over time. This supports an insight into spatial reorganization and transformation, considering an emerging order which prioritizes a bottom-up approach. This information is used to develop scenarios, as we can for instance, identify shifts in socio-economic centrality. This empirical knowledge can thus be used in developing planning scenarios within the framework of the spatial and functional model.

Figure 5. The evolution of the fractal order parameter (Frankhauser, 2008).

Using iterative logic: The spatial model

For the spatial multiscale model we use a logic reminiscent of fractals. We should recall that fractals represent the idea of a hierarchical system consisting of quasi-independent sub-systems which are tenuously linked to higher level systems (e.g. the hierarchy of city, town, village and hamlet). Biological systems also show that fractality allows highly efficient interpenetration of different ~~attributes of space~~. Trees, for example absorb as much light as possible through their leaves. In our spatial model, fractality permits the linking of open space and built-up space with a greater efficiency across scales. A case study of Walloon municipalities in Belgium (Thomas et al., 2008) proved that households were mainly dissatisfied with their residential environment when the fractal dimension D was close to 2, whereas a high percentage of satisfaction was observed when the fractal dimension D was in the range between 0.5 and 1.8, representing a variety of ‘spatial offers’. We hence deduce that an emerging fractal order in growing cities corresponds to a certain degree to an underlying optimization principle.

Initial reflections on the spatial multifractal model presented here were proposed by Frankhauser (2008); a further development was the cell-based multifractal spatial model produced and made operational by Yamu and Frankhauser (2013, 2015) and Yamu et al. (2015). Here we present an ongoing development to operationalize the model for the idea of adaptivity. We used a multifractal approach for the model with two different reduction factors as this ~~allowed~~ us to generate different-sized cells (representing different-sized areas) within one iteration level. Further, the advantage of using a fractal iteration logic is its scale invariance.³ For the spatial model we started with what we call ‘decomposition logic’ (a top-down process; see Figure 6) in order to ‘disassemble’ and set up the framing condition for each iteration step for the spatial system under scrutiny.

At each iteration step a number of different-sized cells are generated, allowing the coverage of different-sized systems (at a regional scale) and communities (at an urban scale). Every cell at each iteration step can be relocated and changed in its geometry when

Figure 6. Spatial model using an iterative logic. (a) Theoretical multifractal Sierpinski carpet at iteration step 1; (b) Theoretical multifractal Sierpinski carpet at iteration step 2; (c) Multifractal Sierpinski carpet cells relocated; (d) How the spatial model can be modified for each iteration step.

necessary to cover an urban agglomeration according to a ‘best-fit’ logic. In addition, extra cells can be added if needed for each iteration level. We have to be aware that a change in a cell’s geometry generates pseudo-scale invariance. The cells are represented in our example by a square (Figure 6). Every geometric form, reduction factors and number of cells generated at each iteration step can be defined a priori by means of an iterated function system. Iteration reduces the sizes of cells, which correspond to a multiscale modelling approach. Overall, the decomposition process allows the model to be adjusted to any spatial system. Decomposition is a top-down iterative process where the cells generated at each iteration step are relocated and adjusted according to the system’s individual condition (zoom in logic). We can thus work with a multiscale, fractal logic consistent across levels. The sizes of cells can be calculated for each iteration step (i_2 , i_3) according to the reduction factors and the initial figure i_1 (Figure 6):

$$i_2 = \frac{1}{r_1} i_1 \quad (9)$$

$$i_3 = \frac{1}{r_2} i_1 \quad (10)$$

The spatial model includes geo-referenced information on features including built-up areas, street network, public transportation network, amenities, green areas, natural areas and restricted zones.

Incorporating the 4 Cs: The normative functional model

A functional model is linked to the spatial model incorporating the logic of earlier described ‘conditions’. The coupling of the two models enables the development of planning scenarios and their functional evaluation. We are aware that our chosen parameters in the latter do not cover the whole parameter spectrum, but this decision was made for reasons of simplification and abstraction and to derive a conceptual model. In addition, for notations 11 to 13 and 20 a normalized value range (0–1) is used.

Using fractal analysis to understand the socio-economic influences on an urban system links us back to the idea of the four conditions of competitiveness C_{com} , complementarity C_{cpt} , cohesion C_{coh} and compatibility C_{cpa} (see Figure 2). We should recall that competitiveness is a potential driver for regions to differentiate themselves from one another. It is also related to internal dynamics and contextual diversity. Competitiveness C_{com} can be evaluated by the number of shops and services facilities and diversity. A high number of shops and services n with a low diversity δ equals high competition and low compatibility. Compatibility C_{cpa} reflects a high diversity of shops and services. Competitiveness and compatibility are covariant. The larger the value of C_{com} , the smaller the value C_{cpa} . In addition, a larger number of shops and services facilitate economic well-being. This can be evaluated across the scales for urban agglomerations, cities and neighbourhoods:

$$\mu(C_{com}) = \mu(n)(1 - \mu(\delta)) \quad (11)$$

$$\mu(C_{cpa}) = 1 - \mu(C_{com}) \quad (12)$$

Both criteria, diversity and number of evaluations are presumed to be ‘equivalent’. The product corresponds to a rather ‘pessimistic’ evaluation, since both qualities are required simultaneously. This seems realistic, since individuals seem to be equally interested in both criteria. Depending on the size of the spatial system under scrutiny, n and δ can vary. Competition is of importance at a regional, urban and intra-urban scale. The number of shops and services as well as diversity is likewise evaluated. Ongoing, cohesion C_{coh} works from a territorial level to a neighbourhood level. Cohesion includes quality of life, well-being and social coherence. Regarding the idea of well-being and quality of life, we assume that diversity of shops, services and facilities is more important than their numbers. Diversity influences the attractiveness of an area. This is reminiscent of the idea of elasticities in economics:

$$\mu(C_{coh}) = \mu(n)^{(\mu(\delta))} \quad (13)$$

At a local level we also include the social capital S_{cap} , indicating the social and spatial quality of a neighbourhood as an attractive place to live. Social capital is linked to social cohesion and is represented by the neighbourliness and socially active environment spatial aspects (Freeman, 2001; Podobnik, 2002). Its distinguished characteristics include population density, the availability of public transport and the walkability of neighbourhoods. Its indicators are therefore the numbers of bus stops, tram stops and train stations; the numbers of public places (for stationary activity) and the width of pavements, implying the assumption that most neighbourhoods have pavements. We are aware that this does not represent the whole range of social capital, but the named factors are of major importance in promoting attractive effective neighbourhoods which can also support informal exchanges between people.

We take the availability of multiple stops pt , e.g. bus or tram stops, into account for public transport by means of a linear increase. In our example having four stops is evaluated as good, which represents a ‘saturation level’ of 1 for a neighbourhood:

$$\begin{aligned}\mu(pt) &= 0.25 n, \\ \mu(pt) &= 1 \quad \text{for } n \geq 4\end{aligned}\tag{14}$$

We use the same logic for public places with 0.02 ha as being the minimum size for a public space, for instance. In our example, the existence of two public spaces represents a ‘saturation level’ of 1 for a neighbourhood:

$$\begin{aligned}\mu(ps) &= 0.5 n, \\ \mu(ps) &= 1 \quad \text{for } n \geq 2\end{aligned}\tag{15}$$

We use Fruin standards (1971), a level-of-service concept which describes the amount of space per pedestrian needed for unimpeded movement, to define the walkability of a pavement. We introduce a pavement classification related to a maximum pedestrian flow and street hierarchy (e.g. side street versus shopping street pavement) and thus introduce a minimum width for these classifications. Fruin standards can be applied to individual street segments, defined according to intersection and change of angle. The number of pavements offering a high service level in relation to their street type – pedestrian zone versus through road – is evaluated. The saturation threshold depends on the neighbourhood size and its urban morphology in terms of block sizes. Thus, we first identify the number of ‘valid’ pavements and then we define the saturation level.

First, we assume that we have a number v of sidewalk pavement segments sw with a width w_i and length ($i = 1, 2, \dots, v$). Moreover, we distinguish different types j of sidewalks (e.g. pedestrian zone, shared space, shopping high street pavement, inner city street pavement). For each sidewalk type we introduce a minimum width $w_{crit}(j)$ and minimum length $l_{crit}(j)$ for each pavement type to be operational. This reads as:

$$\mu_i(sw) = \Theta(w_i - w_{crit}(j)) \cdot \Theta(l_i - l_{crit}(j))\tag{16}$$

Θ is a Heaviside step function with the value of 0 for values lower than w_{crit} and is 1 for all higher values. Following on from this, the total number of pavements considered for the functional model is:

$$n(sw) = \sum_{i=1}^v \mu_i(sw)\tag{17}$$

The evaluation $\mu(sw)$ progressively reaches the saturation threshold $n_{max}(sw)$, depending on the neighbourhood size and its urban morphology in terms of block sizes:

$$\mu(sw) = \frac{1}{n_{max}(sw)} n(sw)\tag{18}$$

Accordingly, for the overall evaluation of the local social capital S_{cap} we used additive logic introducing weighting, allowing the model to be adapted to neighbourhoods of any spatial layout, e.g.:

$$S_{cap} = 0.15 \mu(pt) + 0.15 \mu(ps) + 0.7 \mu(sw)\tag{19}$$

where the sum of the weighting factors must be 1, which also applies for the subsequent formulae.

Finally, we introduce the concept of complementarity C_{cpl} . Ullman (1956, 1980) refers to the concept of complementarity when one area has a deficit of a product g and another area a surplus. This surplus–deficit relationship is dominated by the concept of interaction and mostly represented by models reminiscent of gravitational spatial models. We are aware that this Newtonian approach does not hold for spatial interactions which are capable of complex or unpredictable behaviour. Dendrinis and Sonis (1990) demonstrated that there are many cases where no equilibrium can be achieved. However, for our functional model we are interested in the complementarity potential of a certain area and do not consider interactions between different defined areas. As the exchange of goods is global, we use a simplified approach to define the complementarity potential of an area by its surplus of goods g or – diversity δ for a certain area and scale:

$$\mu(C_{cpl}) = \mu(g)\mu(\delta) \quad (20)$$

Combination of criteria in the light of a bottom-up approach

The combination of criteria L allows to implement for the spatio-functional model a bottom-up approach. Thus, for the simulation it follows the idea of emergence. We apply this approach in the first instance through a weighted combination of criteria in applying a scalar logic (urban agglomeration, city, quarter and neighbourhood). The ponderation is variable in order to be adaptable to any spatial system. The weightings here assumptions but reflect their degree of influence on each level.⁴ This reads as:

- Level 1: Spatial agglomeration L_1

$$L_1 = 0.75 \mu(C_{om}) \cap 0.10 \mu(C_{oh}) \cap 0.10 \mu(C_{cpl}) \cap 0.05 S_{cap} \quad (21)$$

- Level 2: City L_2

$$L_2 = 0.65 \mu(C_{om}) \cap 0.15 \mu(C_{oh}) \cap 0.15 \mu(C_{cpl}) \cap 0.05 S_{cap} \quad (22)$$

- Level 3: Urban quarter L_3

$$L_3 = 0.3 \mu(C_{om}) \cap 0.15 \mu(C_{oh}) \cap 0.15 \mu(C_{cpl}) \cap 0.35 S_{cap} \quad (23)$$

- Level 4: Neighbourhood L_4

$$L_4 = 0.1 \mu(C_{om}) \cap 0.10 \mu(C_{oh}) \cap 0.10 \mu(C_{cpl}) \cap 0.7 S_{cap} \quad (24)$$

We then link all the spatial levels to create interdependency and implement this bottom-up approach. According to weighting logic used, the overall combination L yields, for instance:

$$L = 0.15 L_1 + 0.15 L_2 + 0.2 L_3 + 0.5 L_4 \quad (25)$$

By means of the combination of criteria, each cell for each iteration level can be evaluated. A normalized evaluation between 0 and 1 is operational and useful with a corresponding colour range for visualization purposes.

'If, then': Scenario development and its significance for planning practice

As a planning tool, the conceptual model described here enables the development of time-discrete planning scenarios. This can be made operational using an interactive GIS database where shops, services, and so forth can be manually added or retrieved and the spatial system can be adapted on demand where spatial and functional intervention is found to be needed on the basis of the evaluation outcome. This intervention in turn serves as a new input for the next evaluation. Therefore, we can simulate possible developments over time and arrive at a time-discrete tool. In addition, we can test the different 'behaviours' of a scenario and subordinated scenario fine-tuning, using the same input quantities by varying weightings for the criteria combinations, as well as changing the input thresholds, for instance the saturation threshold can be changed from four to six bus stops, as shown in our example for the local social capital. The possibility of interactive alteration of the database creates a certain causality, as the modified database becomes the new input in the next testing cycle. An advantage of the step-by-step development of scenarios is that this is closely related to team-oriented planning processes. Each change in the database can be discussed according to the experts' experience of the system under scrutiny. It allows us to explore best-fit scenarios for systems in terms of 'surviving' and 'non-surviving' systems.

Basic changes to the functional and spatial system (e.g. real estate development or additional shops) and its evaluation inform us about the best-fit scenario according to these changes. Testing the 'behaviour' (subordinated scenario) of the system informs us about which functions need to be strengthened and which weakened in the context of competitiveness, complementarity, cohesion and compatibility (Figure 7). This has a

Figure 7. Example decision tree for time discrete scenario development with a maximum of three scenario behaviour testing events using the decision path $S_1 S_{1B1}, S_{1B1} S_2, S_2 S_{2B1}, S_{2B1} S_3, S_3 S_{3B3}, S_4 S_{4'B3}, \dots$

direct impact on physical and institutional planning and diverse stakeholders, as it can provide information about the ‘balance’ between the 4 Cs.

Overall, the model enables the testing of growing and shrinking systems over time. For a growth scenario, we add functions and spatial structures where we want to enhance the evaluation of the best fit. For shrinking scenarios, we use an inverse logic. Moreover, both can be combined, ~~for instance by strengthening an infill development and revitalizing rather than deconstructing a sprawling urban fringe.~~

Discussion and conclusion

In this contribution, we consider the options for planning in a non-linear world in which structures and functions co-evolve and transform fundamentally. Our reasoning is constructed around the idea that an internal set of cohesive conditions of urban systems remains the same, while the structure and function, and content and meaning of urban CASS change over time. With this internal set of cohesive conditions, we are able to frame CASS which represents urban development.

By means of fractal analysis we can identify predominant control parameters and order parameters along the lines of Haken’s synergetics. We gain an understanding of the actual state and conditions of a spatial system based on its emergent situation. This enables us to develop scenarios according to a bottom-up logic using the conceptual model outlined herein. The model’s framework incorporates internal conditions outlined by a functional normative model combined with a spatial multiscale model. Framed by the conditions the conceptual multiscale model becomes a representation of an emergent, non-linear logic for spatial planning. Based on its internal conditions, the model supports spatial transformations. The internal set of cohesive conditions is therefore precondition for urban change. We have demonstrated that these conditions of urban change do matter, central as they are to non-linear thought. While the structure and function of urban systems fundamentally transform, giving the urban its new identity, the conditional markers of the co-evolving urban system remain. These conditions are therefore a continuous factor in the processes related to an urban system.

In conclusion, we would like to forge a link to Rittel’s ‘wicked’ problem, with which we started this paper. According to Rittel and Webber, solutions to wicked problems are not true or false, but good or bad (Rittel and Webber, 1973: 161–167). Incorporating non-linear logic into spatial issues and their related problems will not solve wicked problems in terms of their content as a Newtonian world view would suggest, but stresses the importance of conditions under which problems ~~wicked~~ or otherwise adapt, emerge, co-evolve and self-organize. Approaching wicked problems by understanding them as a path to complex systems should support of further theoretical argument in the understanding of spatial developments and possibilities for intervention.

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Notes

1. We have to be aware that according to Haken there are also systems which are far from equilibrium yet at the same time stable. As in the laser, for example, where the production of laser light is stable while at the same time far away from equilibrium.
2. In this context, Weidlich (1987) introduced a model of a city system where population is distributed uniformly while the agglomeration parameter remains at a low level. This parameter describes to what extent individuals prefer social contacts. This situation becomes progressively more unstable as the parameter's values increase. Ultimately, only one big city survives while the other cities drop to small population levels.
3. We have to be aware that scale variance may only be identical at a discrete number of points for simple fractals which have a unique scaling factor.
4. The combination of criteria was first formulated for accessibility measures by Tannier (CNRS) and later adapted, tested and verified by Yamu and Frankhauser (2013). Herein, we further developed this idea and made it operational for a simulation model for adaptive space.

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