EVOLVING CONFIGURATIONAL PROPERTIES

Simulating multiplier effects between land use and movement patterns

Martin Bielik[1]; Reinhard König[1,2]; Ekaterina Fuchkina[1]; Sven Schneider[1]; Abdulmalik Abdulmawla[1]

ABSTRACT

In this paper, we introduce simulation framework for examining the effect of street network configuration on the evolution of the relationship between movement and land use allocation over time. The causal chain introduced in Space Syntax literature suggests that the potential generated by spatial configuration of a street network influences how people move and that these movement flows attract specific types of land uses. These land uses generate in turn additional movement creating an endless cycle of mutual interactions. In Space Syntax, this interaction between movement flow and land use is assumed to work in a positive feedback loop, multiplying the initial potentials given by a street network configuration. The practical consequence of this hypothetical assumption for the Space Syntax method is that the outcome of the feedback loop can be predicted as multiplication of the initial state and therefore doesn’t have to be simulated.

In this paper, we introduce a computational method for testing the multiplier effect hypothesis and identify the cases in which it holds true and those ones in which more detailed investigation considering feedback loops might be necessary. We demonstrate how such investigation based on the simulation of the interactions between movement and land use in time can be operationalized and conduct series of studies exploring the spatio-temporal effects of street network configuration.

We conclude that these exemplary studies show how the presented simulation model can be used to test the core assumption behind the Space Syntax method. We also offer preliminary insides about when and under which conditions it can be reliably applied and when system dynamic simulation might be necessary to predict not only the immediate, but also the long-term effects of street network configurations on centrality, movement and land use distribution.

KEYWORDS

Street network configuration, System dynamics, Centrality, Movement, Land use, Multiplier effects, Natural movement

[1] Faculty of Architecture and Urban Planning , Bauhaus-Universität Weimar Belvederer Allee 1 Weimar Germany, martin.bielik@uni-weimar.de, ekaterina.fuchkina@uni-weimar.de, sven.schneider@uni-weimar.de, abdulmawlik.abdulmawla@uni-weimar.de

[2] Smart and Resilient Cities, Austrian Institute of Technology, Giefinggasse 6, 1210 Vienna, Austria, reinhard.koenig@ait.ac.at

1. INTRODUCTION

In this paper, we introduce a methodological framework for simulation of spatio-temporal effects of street network configurations on land use allocation and movement. The conceptual foundation of this work is grounded on set of methods and theories for analysis of the spatial configuration of urban systems first introduced by Hillier & Hanson (1984) under the term Space Syntax.

Configurational studies of urban systems

The core idea behind the Space Syntax method is to consider each spatial element (represented as a visual axis, street segment or convex space) not as an individual entity with its qualities such as length or width, but rather as configuration of many elements constituting urban system. The configuration of the urban system is represented as spatial graph where the relationship between each individual element and all other elements in the system can be measured. As a consequence of Tobler's (1970) first law of geography, some elements are nearer and therefore closer related than the others. These elements play a more important role in the process of connecting everything together and can be described as more central. As result, the centrality of a spatial element (i.e. street segment) determine long lasting potentials defining the role it will play in urban life. Space Syntax scholars have repeatedly shown that two behavioural phenomena - the movement and allocation of land uses can be explained through the centralities of the spatial configuration.

Defining terms: configuration, centrality, movement and land use distribution

The theoretical foundations of the configurational effects of urban layout on movement and the allocation of human activities (i.e. land use distribution) has been established in the Hillier's (1996) seminal paper *Cities as movement economies.* The argument is further elaborated in Hillier (1999) and acknowledges the city as a dynamic system composed of the interplay between four major forces – the configuration, centrality, movement and land use allocation. The understanding of the qualitative differences between these forces and the different roles they play in the Space Syntax method is the key point of this paper.

As depicted in Figure 1, these are not merely four different variables interacting with each other, but rather a) two dependent variables, b) the context in which they interact – the independent variable and c) the analytical model representing these interactions. The movement and land use are two variables capturing different aspects of human behaviour, while the street network configuration is the underlaying structure (i.e. interface) facilitating the interaction between them. Finally, the role of centrality is to formally model these interactions and making them quantifiable. To illustrate this point, we can draw analogy between the Space Syntax method and another well-established analytical framework – the daylight analysis. Here the dependent variable could be the amount of light illuminating different surfaces, the exemplary context is the size and position of windows and finally, the model of the interaction is some type of physical simulation (e.g. radiance). The key consequence of the difference between the dependent variables, context and model is that if we want to influence one of the dependent variables (e.g. increase the amount of light in the room), we must change the context (e.g. increase the size of the windows). The role of the model is only to estimate the interaction between the variables through the context and as such, it cannot influence anything. The model can be only more, or less accurate depiction of these interactions (e.g. based on the number of rays in the radiance model).

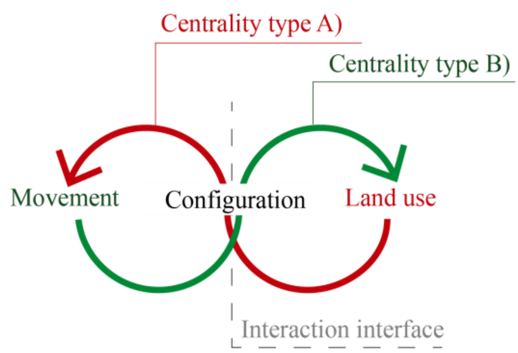


Figure 1: *Schematic representation of the relationship between configuration, centrality movement and land use. Movement and land use are interacting with each other through the configuration with centrality being the model of these interaction. Centrality of type A) is modelling the effect of land use on movement and the centrality of type B) is modelling the effect of movement on land use allocation.*

Coming back to the Space Syntax method, the context – the street network configuration influences the movement and land use allocation, while the centrality is modelling the above-mentioned influence, but does not directly affect anything. Consequently, if we want to influence the allocation of land uses, or movement flows, we must change the configuration of the urban layout which will be then depicted by the centrality measures.

However, what makes the city particularly complex is that not only movement and land use distribution are influenced by the configuration, they additionally influence each other. On the one hand Hillier (1996) argues that the movement influences the allocation of land use, with some type of land uses being attracted and other repelled by the movement. On the other hand, he recognizes that the allocation of land use generates and attract additional movement creating the "essential urban dynamic by which grid structure, movement, land use patterns and densities become interrelated" (Hillier, 1999b, p9).

To sum it up, in Space Syntax the city is understood as dynamic system of continuous interactions between movement and land use via street network configuration.

Multiplier effect hypothesis

This is what Hillier calls the 'essential urban dynamic' of the 'feedback cycle' adding that "centrality, then, is clearly not simply a state, but a process with both spatial and functional aspects"(Hillier, 1999a, p.3). At this point it must be noted that even though in the Space Syntax theory it is assumed that the city is a dynamic system based on a continuous feedback loop between movement and land use via underlying street network configuration, the Space Syntax method follows a different, much simpler and completely liner model. The actual implementation of how to quantify the impact of spatial configuration on movement and land use is a conceptual shortcut to break the cycle at its first iteration. This shortcut is formally defined under the term 'Multiplier effect' (Hillier, 1996) and is based on the hypothesis that the effect of each subsequent iteration of the feedback loop is the multiplication of the previous state. Consequently, if the hypothesis holds true, it is enough to know the results of the first iteration since any later cycle would only strengthen, but not disturb the already existing land use and movement patterns. As result, central locations with a high density of movement flows and land use are expected to stay the same or get even more central, dense and frequented.

There are no doubts about the usefulness of the multiplier effect hypothesis as it allows to reduce the spatio-temporal complexity of the relationship between centrality, movement and land use into a purely spatial problem. This makes the practical implementation of the analysis not only conceptually, but also computationally easier to carry out.

Natural movement hypothesis

Additional to the *multiplier effect* hypothesis, there is one more concept further reducing the real-world complexity of the Space Syntax method. The configurational effect of the street network on movement is calculated based on equally distributed land uses (origins and destinations). This equally loaded model represents the 'natural' movement potential of the street network which is then assumed to be the driving force shaping the distribution of land uses. As consequence, even though in real cities the land uses are not distributed equally, these disruptions are expected to get corrected through time and the *"relation between grid structure and movement is retained"* (Hillier, 1999, p.9).

Research questions and scope of the paper

Acknowledging the importance of the multiplier effect and natural movement hypothesis for the Space Syntax method, we argue that these need to be carefully tested to not only empirically prove their validity, but also to identify their limitations and so strengthen both, the Space Syntax theory and its methodological implementation. With this in mind, we present a methodological framework for simulating the spatio-temporal effect of urban configuration and demonstrate how this can be used to address the core hypothesis of the space syntax method regarding the natural movement and multiplier effect of street network centralities. The main aim of this paper is not to prove or falsify these hypotheses, but rather introduce the method and computational model for testing it. In particular, we conduct series of experiments to show how the following two research questions might be addressed by the method presented in this paper:

Multiplier effect research question:

Q.1: Under which conditions is the result of the feedback loop between movement and land use distribution predictable as a function of the multiplier effect? In other words, we want to know if and when the configurational properties of the street network reveal directly after the first iteration of the feedback loop, or if they evolve in time and are completely visible only through simulation.

Natural movement research question:

Q.2: Under which conditions does the *natural movement potential* of the network configuration correct the effect of unequal distribution of land uses (disruptions) throughout the feedback cycle?

2. METHOD

In the following section, we translate the previously described Space Syntax method, its theoretical assumptions as well as our research questions into a computational model able to quantify the effect of spatio-temporal configurations on movement and land use distribution. Conceptually, the feedback loop between the movement and land use can be seen as an iterative process going on within a given street network. The street network configuration is the context which stays unchanged, but the movement flows and land use distribution evolve through time. This process can be characterized by its initial state (i.e. how is the land use distributed before the evolution starts) and the iteration steps. The iterations and the consequent evolution can be imagined as a set of two consecutive steps starting with centrality model of the land use distribution on the movement flows. Next, we apply the second centrality model estimating the effect of previously calculated movement flows on the land use distribution. This sequence of two mutual interactions between movement and land use is considered as one iteration. In the next iteration loop, the movement is calculated based on the newly re-allocated land uses. This results into new movement flows and the land uses will again adjust their position in the urban system. As result, the proposed computational model required the definition of two centrality functions (i.e. one for modelling affect of land use on movement and one for modelling the effect of movement on land use).

The basic spatial units of the simulation are street segments[3] as well established representation of urban structure used in the Space Syntax literature (Turner, 2001). These are defined as visual axes divided at their intersections and can be approximated as road-centre lines (Turner, 2007), a widely used representation in transportation and urban planning. The three key variables explored in this paper – movement and land use can be aggregated and mapped to each street segment. In the following, we define the mathematical operationalization of each variable as well as their mutual interaction and implementation of the above described feedback loop.

Operationalizing effect of land use on movement

The methodological framework for operationalizing the Space Syntax theory offers a multitude of methods for quantifying the impact of land use on movement in terms of graph centrality. For purposes of this paper we term this type of centrality measure modelling movement based on land use distribution as the *movement potential centralities*[4]. In general, these movement centralities are based on quantifying the relationships between land uses (origins and destinations of movement) via shortest paths. This is done by representing the urban system as a graph where some spatial elements serve as connectors (graph edges) and others as potential origins and destinations of movement (graph nodes)[5]. When calculating centrality, edges can differ in their length as well as nodes can differ in their weight. The former indicates the distance between neighbours (e.g. metric distance, travel time, cognitive distance) and the latter express the importance of node in terms of being origin and destination of movement (e.g.

[3] Other representations such as axial lines are commonly used through out the Space Syntax literature. These are however limited to topological distance and less common in other fields (e.g. transportation planning) for which the presented methodology and experimental results might be relevant.

[4] Since the street network centrality has only partial influence on the real movement flows with other factors such as individual preferences, aesthetic or culture playing significant role, it is common in the Space Syntax literature to talk about influence of network centrality on movement through movement potential of the street network. This movement potential can be seen as intermediate agent and in context of this paper is used interchangeably with the term movement.

[5] Planar graphs usually use streets as edges and intersections or individual buildings as nodes. In Space Syntax, the inverse graph was adopted which use the streets as nodes (origins and destinations of movement) and connections between streets are modelled as edges. Even though, this difference is crucial for the Space Syntax method it doesn't create any constrains for application of the presented simulation framework and is therefore not further discussed.

nodes containing a train station produce different out- and income traffic rates than those located in residential areas or a public park). The resulting centrality is influenced by both, the edge (Figure 2a) and node weights (Figure 2b). Here, it is important to realize that two sets of elements with the same configuration (i.e. same structure of connections – edges) might produce different movement potential centralities if the elements them self are of different weight. For example, one can imagine three cities with the same street network, but different distribution and of land uses as exemplary depicted in Figure 2b. In such case, the movement potential centrality of given location will differ for each case not because of the configuration, but due to the allocation of land uses[6].

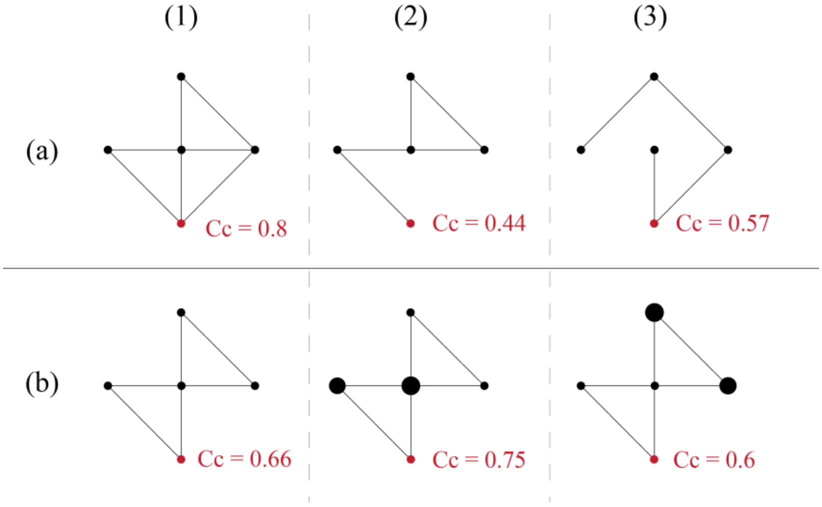


Figure 2: *Exemplary spatial graphs consisting of edges (lines) and nodes (circles) showing the impact of a) different edge configurations and b) node weights on the centrality of given red node. We exemplary calculate closeness centrality Cc (Equation 4) for each red node (for details see the Method section) based on the node and edge weights* (Node weight = 1 for small dots or 2 for large dots, Edge weights ≈ 1).

From this point of view, we can define the movement potential centrality MPC as a function of a) the network configuration SNC (i.e. edges and their connections) and b) the weights (i.e. network loadings) w given by the land use distribution.

$$MPC = f(SNC, w); \tag{1}$$

From the vast opportunities offered by Space Syntax' analytical framework to implement such MP_C, one specific model introduced by Turner (2001) as an *angular segment map* seems to be particularly useful in predicting pedestrian movement flows in the urban context (Hillier & Iida, 2005; Turner & Dalton, 2005; Varoudis, Law, Karimi, Hillier, & Penn, 2013). The distances, or the shortest paths between the street segments are minimizing the angular turns along a path. The angular distance as opposed to the traditional metric distance has been repeatedly confirmed to be a better approximation of human movement and consequently as being a better predictor of pedestrian and vehicular movement flow compared to its metric counterpart (Hillier & Iida, 2005; Lerman, Rofé, & Omer, 2014).

Based on the angular segment map we calculate closeness and betweenness centrality as two distinct measures capturing the importance of a street segment in terms of its movement potential. The closeness centrality (in Space Syntax literature also termed as *"integration"*) captures how close (or integrated) any location i relative to all other locations in the network is (Equation 2). The formal definition of the closeness centrality used in this paper comes from Sabidussi (1966) and can be interpreted as the number of segments in the network N divided by the total sum of distances d_{ik} from segment i.

$$Closeness[i] = \frac{\mathrm{N}}{\sum_k d_{ik}} \tag{2}$$

The betweenness centrality (*"choice"* in Space Syntax) was introduced by Freeman (1977) as a measure of the information flow in social networks. This was adopted by geographers and *Space Syntax* scholars

[6] This conceptual distinction between centrality and configuration gets little attention in the Space Syntax method as the node weights are assumed to be equally distributed (Hillier, 1999) with the consequence of both terms being used interchangeably.

as a potential of street networks to facilitate the traffic flow. The *Betweenness* centrality of a segment i in a street network is defined as the sum of all possible shortest paths that traverse through i. Formally, *betweenness* of a node is expressed as:

$$Betweenness[i] = \sum_N^i \frac{n_{jk}[i]}{n_{jk}} \quad (3)$$

where N is the number of segments in the system, n_{jk} is the number of shortest paths between nodes j and k, and $n_{jk}[i]$ is the number of these shortest paths that pass through the segment i.

Both, the closeness and betweenness centrality can be measured at different radii, with the radius r being the maximum distance of shortest paths considered in the calculation. The definition of travel radius is crucial, since it reflects the maximum travel distance and therefore could be used to model movement flows based on different modes of travel.

Finally, we need to define how loading of the street network by origins and destinations (i.e. land use allocation) affects the calculation of the street network centralities. For the purpose of this paper we consider a simplistic land use model considering only differences in intensity but not function. As a result, land use weighting of a segment with value of zero means that no destinations and origins can be found at this location. Land use weighting of a value of ten means that ten times more origins and destinations can be found at this segment as compared with a segment weighted by the value one. The land use weighted closeness and betweenness centrality is mathematically expressed by the following equations, where W_i represent the weighting at segment i:

$$MPC_{(Closeness\ [i])} = \frac{\sum_N \mathrm{W}_k}{\sum_k d_{ik}.W_k} \quad (4)$$

$$MPC_{(Betweenness\ [i])} = \sum_N^i \frac{n_{jk}[i]}{n_{jk}}.W_j.W_k \quad (5)$$

Additionally, it must be noted that no limit is set for how much land use weighting can be assigned to any segment. Even tough, this *"naive"* implementation of land use weighting might not represent the real-world distribution of land uses, we argue that it is still useful and sufficient for the purpose of demonstrating the potential of the spatio-temporal model for measuring the effects of street network configuration presented in this paper.

Operationalizing effect of movement on land use

As next, we define centrality model of how movement influences the land use. This centrality is termed here as the *land use potential centrality* LC. In general, the of movement flows on land use can be expressed in terms of utility function representing the benefits for given land use gained from accessibility to people staying or moving around. Based on the type of the land use, this function can take many different forms as in detail discussed in the urban economy literature (Sevtsuk & Kalvo, 2017). In the experimental study presented here, we adopt simplistic linear utility function for the *land use potential centrality model* considering only the movement flows at given location and directly translating these into land use intensity. This centrality measure can be also expressed as special case of weighted and normalized closeness centrality with radius equal to zero. In other words, the relative increase in *movement potential centrality* MPC of street network will cause proportional relative increase in *land use potential centrality* LPC. This increase, will however remain relative to all other locations in the system so that the overall amount of land uses in the system remains constant throughout the simulation. For this reason, the land use is only going to be redistributed, its total sum doesn't grow or shrink.

$$LPC_{(Closeness\ [i])} = \frac{MPC_{(Closeness\ [i])}}{\sum_{j=0}^{n} MPC_{(Closeness\ [j])}} \quad (7)$$

We want to point out, that the equality condition for land use as well as the simple function translating centrality directly to movement can be in future altered by more complex ones, capturing the additional morphological, social, economical and environmental constrains. Nevertheless, we argue that for the purpose of this demonstration, these simple functions are preferable as they improve the interpretability of the simulation model and its results.

Operationalizing the feedback loop, multiplier effect and natural movement hypothesis

As described above, the leading question of this paper is how we can test the multiplier effect and the natural movement hypothesis by means of dynamic simulation. We operationalize both hypotheses by using the unified modelling language (UML) to a) visualize the relationship between movement and land use and b) translate the feedback loop between these variables into a computational algorithm. The presented UML diagrams show how data is being processed in the run time of the algorithm. It consists of a start feeding the initial street network (black dot), series of functions (rectangles) which process the data in sequence depicted by arrows and the conditional statement (diamond) deciding when to interrupt the feedback loop and return the result. Henceforth, in Figure 2a we present the UML diagram of the full feedback loop, while in Figure 2b we show its simplification as implemented in the Space Syntax model based on the multiplier effect hypothesis.

The computational dynamic model of the feedback loop is composed of three functions representing the interaction between the movement potential expressed by *movement potential centrality* MPC and distribution of land use expressed by *land use potential centrality* LPC. Additionally, in each iteration the cycle interruption condition A is tested to decide whether the simulation is finished or should be continued.

Each simulation is initiated by a street network configuration SNC and the initial weightings w given by the initial land use distribution. From this distribution, we can compute the movement potential MPC_i in the street network. At this point, the condition A will be evaluated. In our implementation, if two consequent loops of the feedback cycle produce the same *movement potential centrality* and the minimum number of iterations N_{min} has been reached, then the cycle will break and return the final *movement potential centrality* MPC_N.

$$A(MPC_i \neq MPC_{i-1} \lor i < N_{min}) \tag{8}$$

Otherwise, the condition is evaluated as *true* and the cycle continues by feeding the *movement potential centrality* MPC_i into the *land use potential centrality* function LPC_i. Here, the sum of all land uses is kept constant over all iterations. This updated land use distribution turn creates feedback for the *movement potential centrality* function MPC_{i+1} and the complete cycle is closed.

The multiplier effect hypothesis (Figure 3b) assumes that there is a multiplier function m (Equation 11) which predicts the final movement potential distribution MPC_N from the initially calculated movement potential distribution MPC_1, without further iterating through the feedback cycle (Figure 3a). In other words, the Space Syntax model as implemented based on the multiplier effect hypothesis immediately breaks the feedback loop after the first iteration.

$$MPC_N = m(MPC_1); \tag{9}$$

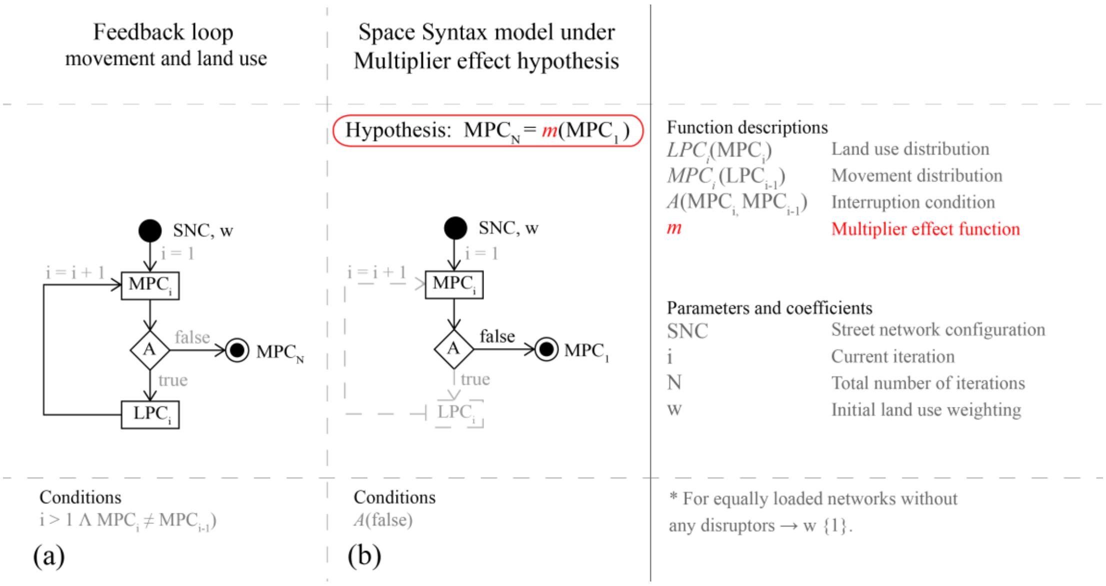


***Figure 3**: UML diagram of the Space Syntax underlying urban dynamics model. a) current model of the feedback loop between movement and land use. b) displays the "multiplier effect" hypothesis.*

In Figure 4 we illustrate the evolution of the movement MPC_i and land use LPC_N potential of the street small exemplary network configuration.

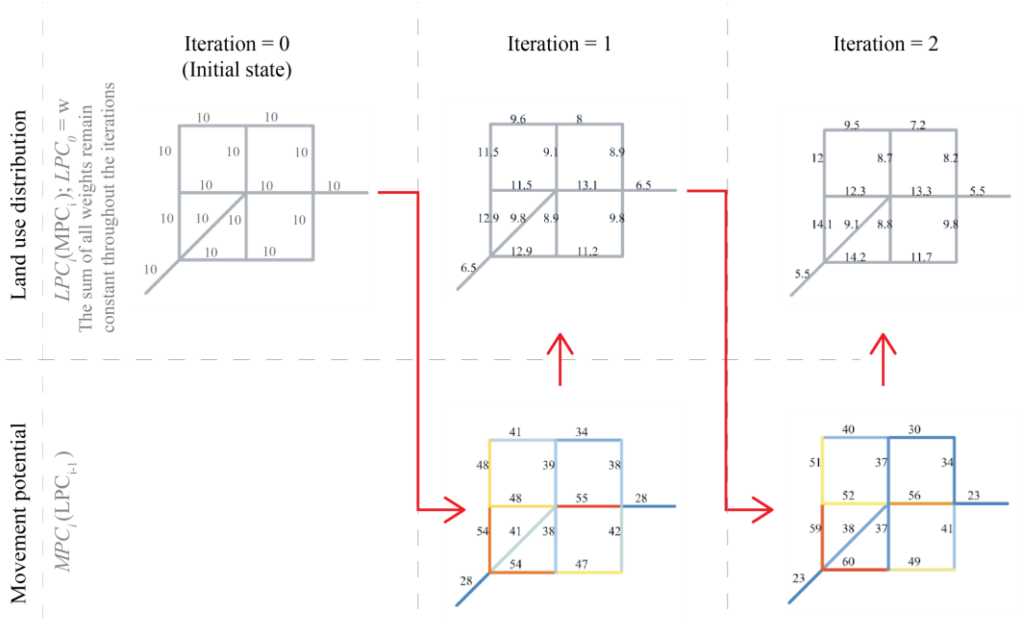


Figure 4: *Exemplary illustration of two iterations of our dynamic simulation. The numbers show the values of variables LMCi, MPCi, per iteration i in the street network configuration. The initial state is an equally loaded network. The centrality values show the angular betweenness centrality with radius Rn (global radius). Value range: high movement potential = red, low movement potential = blue.*

Based on the algorithmic operationalization of the Space Syntax theory, we can now specify our research question Q.1 and Q.2 in mathematical terms so that they can be quantitatively tested in form of the following hypotheses H.1 and H.2:

H.1: There is a *multiplier effect* function m that express the relationship between the initially calculated movement pattern MPC_1 and the final movement pattern MPC_N resulting from the iterative interaction between land use and movement. Such *multiplier effect* function allow to predict the final movement pattern MPC_N from the initial movement MPC_1 pattern with no need for simulation.

For testing H.1, the initial network loads w can be either equal for all street segments in the network (equally loaded) or a sequence of numerical values higher than zero (disrupted). Hypothetically, the multiplier function m can take many different forms (e.g. constant factor, linear, polynomial, or exponential function), however in this paper we exemplary test its linear form with intercept α and multiplier coefficient β:

$$MPC_N = m(MPC_1) \tag{10}$$

$$m = f(a + \beta . MPC_1) \tag{11}$$

H.2: There is a *natural movement* effect function n that express the relationship between the initially calculated movement pattern of **equally loaded network** $MPC_{(equal)1}$ and the final movement pattern resulting from the iterative interaction between land use and movement of **disrupted network** $MPC_{(disrupted)N}$. Both $MPC_{(equal)1}$ and $MPC_{(disrupted)N}$ are based on the same configuration but differ in the initial weighting. Such *natural effect* function can be seen as special case of *multiplier effect* function and allow to predict the final movement pattern MPC_N from the initial movement MPC_1 pattern with no need to consider both a) the simulation and b) the network loads (weighting).

$$MPC_{(disrupted)N} = n(MPC_{(equal)1}) \tag{12}$$

$$n = f(a + \beta . MPC_{(equal)1}) \tag{13}$$

Computational implementation

The above mathematical operationalization of Space Syntax theory in form of angular betweenness and closeness centralities was computationally implemented with the DeCodingSpaces-Toolbox. DeCodingSpaces-Toolbox[7] is open source analytical and generative plugin for visual programming environment Grasshopper (Rhino3D) developed and published by the Computational Planning Group[8]. The DeCodingSpaces-Toolbox for street network analysis represents a street network as an inverse graph with the possibility to weight both, its vertices (i.e. origins and destinations) and edges (i.e. connections). Using this graph, we can calculate shortest paths between all pairs of vertices based on metric, angular or a custom user-defined measure for distances and can calculate a wide range of centrality measures for each node (closeness, betweenness, gravity, degree, etc.). These can afterwards be integrated in a dynamic urban simulation as demonstrated in Koenig, Bielik & Schneider (2018). Finally, the spatial distribution of the resulting centralities can be directly visualized in Rhino3D.

Using Grasshopper makes it possible to provide a basic dynamic spatio-temporal simulation based on the analysis of street network configurations that can be easily controlled, flexibly extended by additional analysis, and adapted to new urban analyses use cases. The main drawback of using Grasshopper is its relatively slow data processing capacity and the limitations for file sizes. To speed up the graph analysis, the DeCodingSpaces-Toolbox has parallelized the graph calculations by running it on the GPU optionally. Within Grasshopper, the RAM of the used computer primarily defines the limit for the graph size.

3. SIMULATION EXPERIMENTS

For the following experiments, we used the street network of the inner city of Weimar as an exemplary case study area. Weimar is a medieval, mid-size German city with approximately 60.000 inhabitants. The size, historical development and the overall variety of street network patterns makes it a good candidate for testing the proposed simulation model. On the one hand, the size of the city makes it possible to relatively quickly calculate many iterations of the simulation, but on the other hand it is large and diverse enough to let non-trivial configurational patterns emerge.

Summary of simulation model parameters

As already discussed, the computational dynamic feedback loop model introduced in this section is based on four main inputs: i) ii) two main centrality models defining the interaction between movement and land use allocation in both directions (MPC, LPC), iii) the street network configuration SNC and iv) its initial land use weightings w as the interaction interface. The way how each input is defined can influence the outcome of the dynamic simulation and can be therefore understood as model parameter. For example, the initial land use weighting w can take countless different forms (e.g. equally loaded, disrupted by various number and size of disruptions) with each form presenting different model setting of the input parameter w. Since we can expect that different settings of the simulation model parameters might lead to different results, it might be meaningful to explore the complete parameter space. However, this would be beyond the scope of this paper, so for practical reasons, we limit our exploration to following input parameters:

(i) We explore the influence of different initial land use weightings w. We run the simulation on both equally loaded and disrupted network. Here, we limit our exploration to two disruptors of different sizes, however many other variations of disruptor number and size can be introduced.

(ii) We explore the influence of different definitions of movement potential centralities MPC. In specific, we use the closeness and betweenness centrality

(iii) We explore the influence of different radii at which the movement potential centralities are measure. We alter between local radius of 600m and global radius acompassing the whole network

Finally, it must be noted that we kept the model parameter defining the number of iterations N constant to 28. This number of iteration cycles has been experimentally identified as large enough for all our experiments to find the state of equilibrium when no further change in the system can be observed.

---

[7] URL: https://toolbox.decodingspaces.net/

[8] URL: http://cplan.web-republic.de/

Experimental design and measures

Based on the methodological framework described above, we test with the following simulation experiments our two hypotheses H.1 and H.2 by exploring the effect of initial land use weighting w and the definition of movement potential centrality measure MPC on the evolution of the movement potential distribution[9]. The experiment E.1 is used to test the multiplier hypothesis for equally loaded networks (i.e. the simulation starts with every street segment having the same amount of land use attached to it). The experiment E.2 is used to test the multiplier hypothesis for disrupted networks (i.e. the simulation starts with some street segments having higher land use intensity than others). For both experiments E.1 and E.2 we test the influence of the centrality measure type and its radius on the multiplier effect hypothesis. In other words, we look if the strength of the multiplier effect on movement potential depends on how we measure centrality (i.e. betweenness or closeness and local (600m) or global radius). As a result, we run both experiments four times as depicted in Figure 5 and Figure 8, where each line is showing the evolution of the movement potential based on the used centrality measure and its radius.

This experimental design allows us to test a wide range of conditions under which the multiplier hypothesis holds true. This can be accomplished by simply comparing the initial and final state of the simulation. The degree to which these two movement potentials are similar expresses the strength of the multiplier effect. Additionally, we measure the natural movement hypothesis by comparing the equally loaded and disrupted network. Here, we measure how effective is the natural movement potential in removing the disruptions from the street network and bringing the land use loads back to its natural state. This is achieved by measuring the similarity between the initial state of the equally loaded network and final state of the disrupted network.

All experiments follow the same scheme, as it is described in the UML diagram in Figure 3a. To visualize and quantify the results of both simulation experiments, we present the following figures and measures.

Figures:

(i) Figures 5 and 8 capturing the spatial distribution of movement potential centrality MPC_i. This figure shows five states at i=1, i=7, i=14, i=21 and i=28 from the series of 28 iterations of the simulation.

(ii) Figures 6 and 9 with diagrams quantifying the evolution of the multiplier effect and the change in movement potential between two subsequent iterations,

(iii) Figures 7 and 10 explain in detail the multiplier effects m between MPC_1 and MPC_N. It offers deeper inside into understanding the multiplier effect between the first and the last iteration of the simulation by showing the resulting scatter plot. In this way we can construct hypotheses about the nature of the multiplier function and visually identify other than linear types of relationship. To measure the strength of the multiplier effect and to estimate the intercept α and coefficient β of the multiplier function m, we use the linear regression between MPC_1 and MPC_N as depicted in Equation 11 and 15.

(iv) Figure 11 explains the effect of natural movement potential on disrupted networks.

Measures:

(i) Measure of the **System change** ***Ch*** presented in Figures 6a and 9a. the system change is the inverse of linear correlation between movement potential of subsequent simulation iterations. For this we first calculate the similarity index S and then its inverse. The system change measure in range from 0 to 1. If the movement potentials of two subsequent iterations do not correlate at all, the index of change will be equal to 1. On the contrary, if two subsequent movement potential remain unchanged will equal to 0.

$$S = R^2 \rightarrow lm(MPC_{i-1} \sim MPC_i) \qquad (14)$$
$$Ch = 1 - S$$

(ii) Measure of the **Multiplier effect** ***Me*** presented in Figures 6b, 7, 9b and 10 is calculated as linear regression between the movement potential at the first and the last iteration of

[9] Movement potential is the outcome of the simulation model as depicted in Figure 2.

the simulation. In this case the result of 0 means that no linear multiplier effect could be observed and the result of 1 means that the current state of the simulation can be completely explained by linear multiplier function. When plotting these multiplier effect for all iterations of the simulation, we can observe how this effect evolves (see Figures 6b and 9b).

$$Me = R^2 \rightarrow lm(MPC_N \sim MPC_1) \tag{15}$$

(iii) Measure of the **Natural movement effect *Ne*** presented in Figure 11 captures the degree to which the movement potential of disrupted network gets corrected towards its natural movement potential at the end of the simulation process. This is calculated as a linear regression between movement potential at initial state of the equally loaded network and movement potential at the final simulation state of the disrupted network. If the natural movement effect is equal to *1* means that the disrupted network was completely corrected to resemble its natural – equally loaded state.

$$Ne = R^2 \rightarrow lm(MPC_{(disrupted)N} \sim MPC_{(equall)1}) \tag{16}$$

Testing multiplier effect hypothesis

Simulation Experiment E.1

For E.1 we initialize all four networks with equally loaded street segments $(w_i = 1)$ and run it for *N=28* iterations (Figure 5 - 7). The main purpose of the simulation is to test the multiplier effect hypothesis for equally loaded networks.

The result of E.1 depends highly on the used radius R for the centrality measure. For global radius Rn the changes in movement potential during the simulation remains low and multiplier effects are high during the entire duration of the simulation (Figure 6). The high and stable values mean that there is a constant linear multiplier effect by means of which we can predict the movement pattern MPC_N that we find at the end of a simulation *(i=28)* by the movement pattern MPC_1 at the beginning of the simulation. Hence, we do not need the simulation, because we can predict very well its outcome by the multiplier function *m*. As Figure shows, for global radius Rn the multiplier effect Me = *.99* for closeness centrality and Me = *.84* for betweenness centrality.

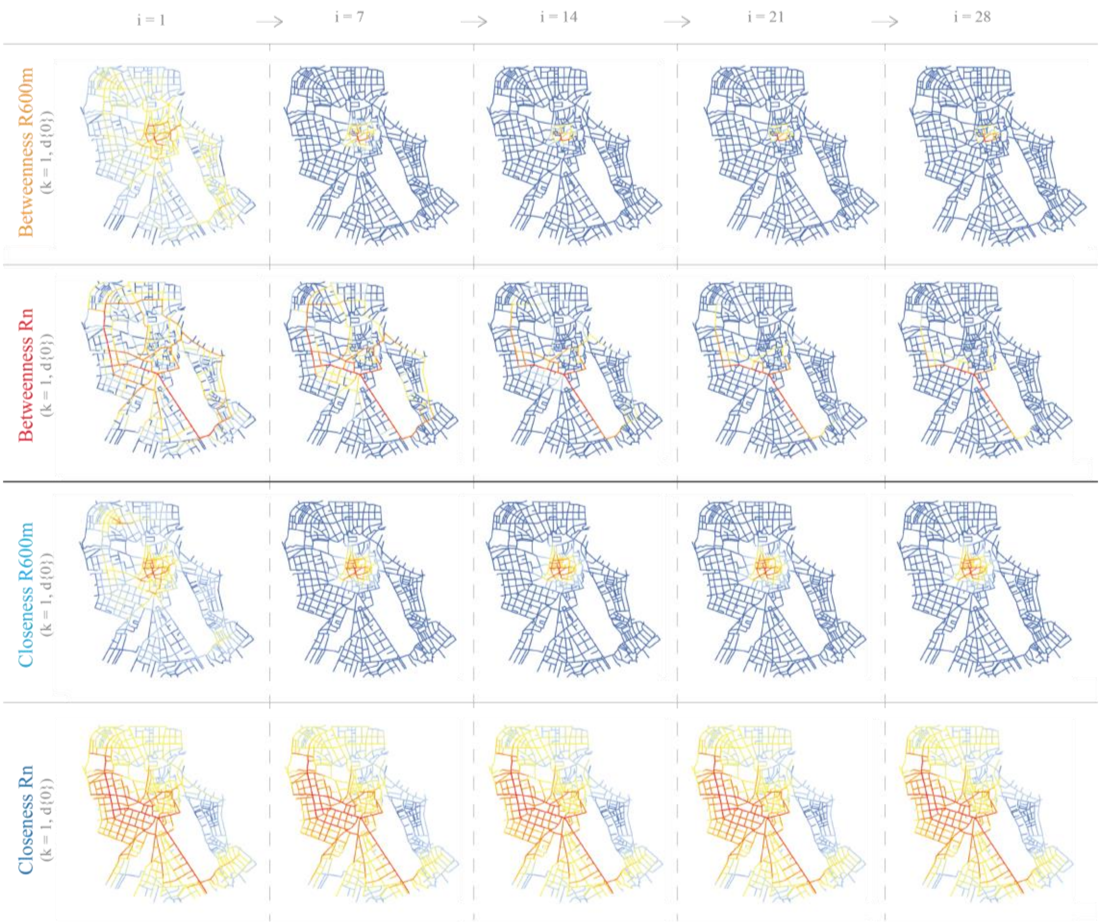
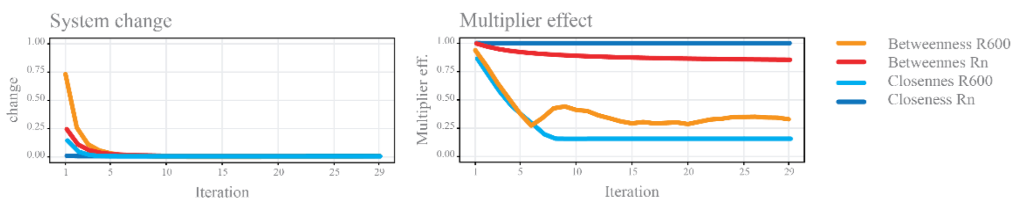


Figure 5: *E.1. Spatio-temporal simulation of configurational effects on different centrality measures. All simulations are initiated with an* ***equally loaded*** *network (w_i=1) and run for N=30 iterations. In each row we show the development of the computed movement potential based on the type of centrality measure and its radius. The colored network images in the top row show streets with high centrality (red) to low centrality (blue) at various iterations of the simulation. Value range: high movement potential = red, low movement potential = blue.*



(a) (b)

Figure 6: *E.1. System change and multiplier effect for equally loaded networks. For each of the used centrality measures (rows in Figure 3).*

For R=600m the result is very different. The multiplier effect is much smaller than for the simulations with Rn and not stable for the betweenness centrality (Figure 6). Figure 7 shows the final multiplier effect $Me = .19$ for closeness centrality and $Me = .33$ for betweenness centrality. Hence, for R=600 we can at least predict the most central area for both centrality measures as the visual results in Figure 7 on the left indicates, but the overall multiplier effect and thus the prediction accuracy is very low. Using a simulation seems to be at least a very good supplement.

Figure 7: *E.1. Multiplier effect for equally loaded networks. The scatter plots and the correlation factors R^2 compares the movement potential at the first and the last iteration of the simulations: LogN ($MPC_N \sim MPC_1$). Value range: high movement potential = red, low movement potential = blue.*

Simulation Experiment E.2

For E.2 we use the same setup as for E.1, except that we initialize all four networks with non-equally loaded street segments. We select two locations with disruptors of different sizes for each simulation (marked by the red dots in Figure 8) and run the simulations for $N=28$ iterations (Figure 8 - Figure 10). The size of disruption thereby means how much land use acting as origins and destination of the movement can be found at the given location. We decided to vary the size of the disruptions as compared to keeping it constant in order to exemplary demonstrate the effect of this parameter on the final result of the simulation. In the process of pre-study experimentation, we found out that the same size of disruption has different effect based on the analysis radius of the centrality measure. More specific, the smaller the analysis radius the bigger was the impact a disruptor of the same size.

Additionally, it must be noted that the disruptions are set only at the beginning (the initial land use weighting) of the simulation. In all consequent simulation steps these additional land uses introduced into the system are redistributed completely by following the movement potential updated each in iteration of the feedback loop. As a result, the disruptions might either stay at their initial location or relocate to more suitable locations during the simulation. In our model, these disruptions could represent large retail stores which are often planned and located based on other criteria than the network centralities and their natural movement potential. These disruptions generate additional movement to and from their location. However, as time goes on, these activities evaluate the benefits of their initial location and can be re-allocated to new ones, allowing better access to existing movement flows (e.g. potential customers). Of course, not all disrupting land uses can be easily redistributed over time (e.g. train station), but for our simulation experiment, we are interested in the theoretical influencing force of the network configuration. Accordingly, we first examine in E.02 if we can still predict the outcome of the simulation by the multiplier function m in a disrupted network.

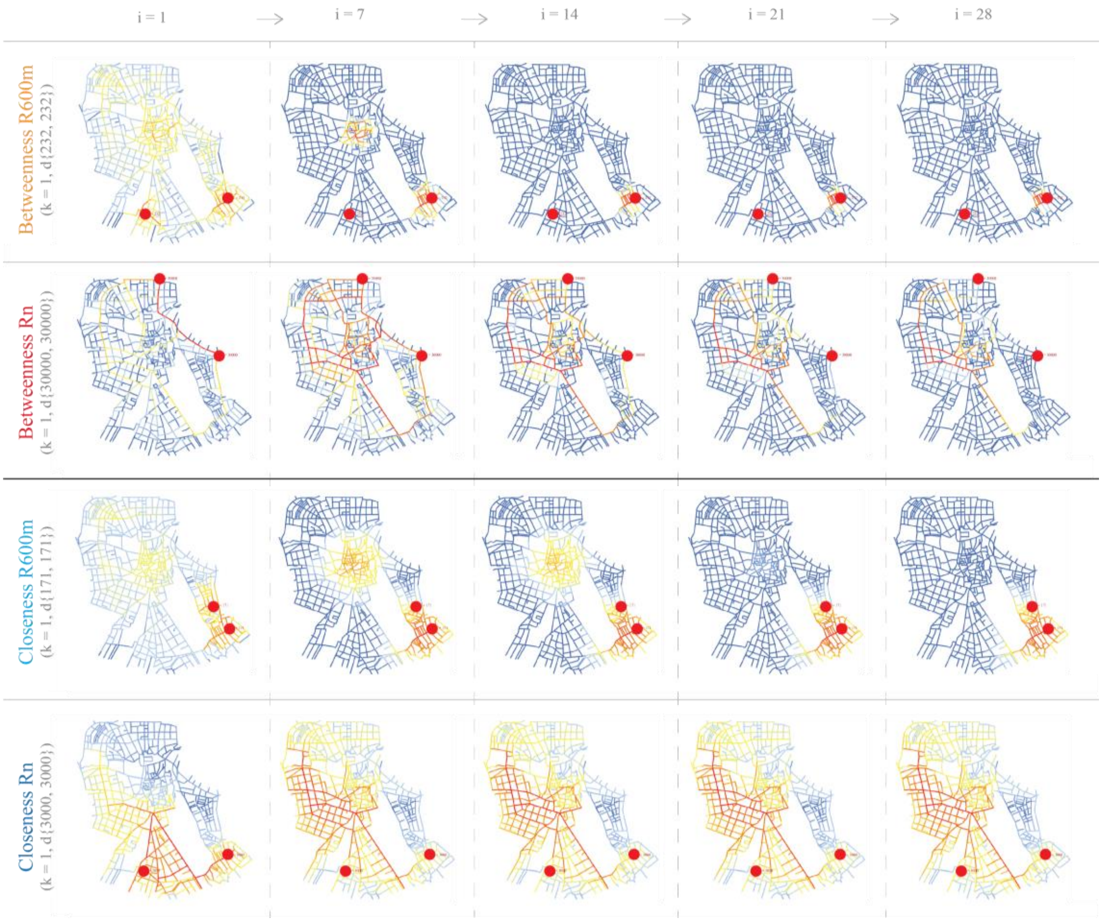


Figure 8: *E.02. Spatio-temporal simulation of configurational effects on different centrality measures. All simulations are initiated with a* ***non-equally loaded*** *network and run for N=28 iterations. In each row we show the development of the computed closeness and betweenness centrality measures with Rn and R=600m. The colored network images in the top row show streets with high centrality (red) to low centrality (blue) at various iterations of the simulation. Value range: high movement potential = red, low movement potential = blue.*

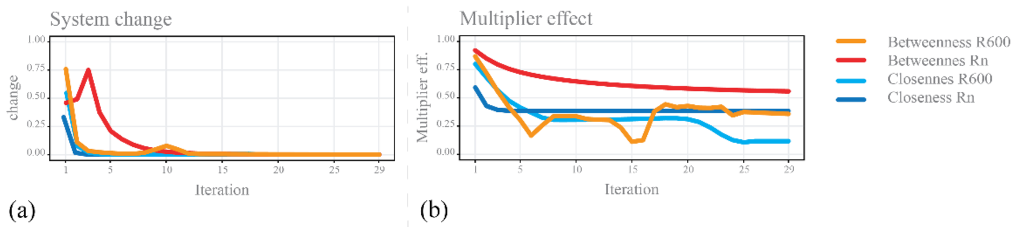


Figure 9: *E.02. System change and multiplier effect for non-equally loaded networks. For each of the used centrality measures (rows in Figure7).*

As clearly visible in Figure 7 the results of E.2 depends similarly as in E.1 on the used radius R for the centrality measure. We observe that for Rn the changes between the iterations and multiplier effects remains relatively stable during the simulation (Figure 9). Nevertheless, compared to the results from E.1 (equally loaded network), the linear multiplier effect in E.2 is much lower. As Figure 10 shows, at global radius there is a multiplier effect Me=*.42* for closeness centrality and a multiplier effect Me=*.54* for betweenness centrality. The further inspection of the scatterplot in Figure 10 that neither the distribution is normal, nor the variance of the data is constant which makes the linear model even the relatively high Me not reliable in practice. Especially in case of global betweenness centrality the segments with the highest movement potential (outliers in the scatterplot) could not be predicted by the movement pattern MPC_1 at the beginning of the simulation.

For R=600m the multiplier effect is even smaller than for the simulations global radius and shows strong fluctuations (Figure 9b). The cause of the fluctuations can be seen in the first and third row in Figure 8. In the beginning, there are at least two competing local centers, of which one disappears at the end of the simulation. Thus, all the land uses converge to one of the local centers. As Figure 10 shows, the multiplier effect for closeness centrality is Me =*.11* and for betweenness centrality Me =*.41*. Based on the small multiplier effect for both centrality measures it is not possible to predict the most central area at the end of simulation based on the initial state.

We can summarize that for networks with non-equally loaded street segments and the presence of strong disruptors, the prediction by a multiplier function m is not reliable and a simulation is needed to find the movement potential distribution resulting from the feedback loop.

Figure 10: *E.02. Multiplier effect for non-equally loaded (disrupted) networks. The scatter plots and the correlation factors R^2 compares the movement potential at the first and the last iteration of the simulations: LogN ($MPC_N \sim MPC_1$). Value range: high movement potential = red, low movement potential = blue.*

Testing natural movement hypothesis

Using the results from E.1 and E.2, we examine the hypothesis H.2 of our study. We are interested if the network configuration can force to a redistribution of the weightings and thus return to a movement pattern that correspond to a network configuration without any disruptions. Therefore, we test if we can predict the outcome of the simulation that was initialized by a non-equally loaded (disrupted) network by the analysis of an equally loaded network in its initial state (Equation 16). The results of the corresponding comparisons are shown in Figure11. We distinguish again between centrality analysis at global radius Rn and local radius R=600m.

On the global scale with Rn we observe a strong natural movement effect Ne =*.99* for closeness centrality and Ne =*.72* for betweenness centrality. These factors are comparable with the results from

E.1. This means that the movement pattern potential in a network is well preserved, even after adding disruptions and running a simulation for redistributing land uses. Thus, we do not need a) the simulation and b) the information about the land use loads because we can predict both very well as product of the multiplier effect and natural movement effect acting on the initial state of the equally loaded network.

On the local scale with R=600m the result is very different. Here we can find almost no *natural movement effect* (*Ne =.00* for closeness centrality and *Ne =.13* for betweenness centrality). Thus, a prediction based on the equally loaded network is not reliable, since even the location of the most central areas is not predictable. In this case, both the land use weighting and the simulation seems to be necessary in order to assess the movement potential of the urban system.

Figure 11: *Natural movement effect. The scatter plots and the correlation factors R² compares the natural movement potential computed at the 1st iteration of an equally loaded network and the at the last iteration of a disrupted network: LogN ($MPC_{N\,disrupted} \sim MPC_{1\,equall}$). Value range: high movement potential = red, low movement potential = blue.*

4. DISCUSSION

In this section, we summarize the results from the simulation experiments E.1 and E.2 and discuss them in context of our research hypotheses. In hypothesis H.1 we expect, that throughout the iterative relocation of trip destinations (i.e. the feedback loop between centrality, movement and land use), the movement pattern is retained because of the multiplier effect. Therefore, there is a multiplier function m that expresses the relationship between the initially calculated movement potential MPC_1 and the final and stable movement potential MPC_N resulting from the simulation.

When starting from an equally loaded street network, we found on a global scale *Rn* a very strong linear *multiplier effect*, which relates MPC_1 to MPC_N with $R^2 > 0.8$ for both movement potential centrality types (i.e. betweenness and closeness). However, the *multiplier effect* goes down to values $R^2 < 0.33$, when using a local radius $R{=}600m$. Even with this low *multiplier effect*, at least the areas with highest movement potential in the network are predictable from MPC_1.

However, in case of the disrupted networks (i.e. not equally loaded), the *multiplier effects* are smaller and more sensitive to the type of centrality measure with only global closeness confirming the *multiplier hypothesis*. The disruption in the initial weighting of the street network configuration is case of non-linear feedback effects between movement and land use, which result in a decrease of the multiplier effect. This is caused by a form of competition between the local centers for the available land uses, following the principle "the winner takes it all". Consequently, the resulting movement pattern is hard to predict without a dynamic simulation, since the development and preservation of a local center may change over time and thus a more complex and unpredictable centrality pattern might emerge.

For hypothesis H.1 this means:

1. We can fully confirm H.1 under the conditions of equally loaded street networks and a global scale Rn for the both betweenness and closeness centrality analysis.
2. We have not enough evidence to confirm H.1 for equally loaded street networks and a local scale R=600m for both the betweenness and closeness centrality analysis. A dynamic simulation would be a good supplement.
3. We have to reject H.1 for non-equally loaded (disrupted) street networks for the global (Rn) and local (R=600m) scale for the centrality analysis with the exception of global closeness centrality. Under these conditions, there is no observable linear multiplier effect. Furthermore, the scatter plots in Figure 7 and Figure 10 do not suggest presence of a more significant non-linear effect. Thus, we conclude that a dynamic simulation is needed for the analysis of movement potentials and allocation of land uses in case of disrupted networks.

In hypothesis H.2 we expect, that even when starting from a disrupted network, the resulting movement pattern resembles the natural movement pattern from an equally loaded network. This expectation can be considered as a *natural movement* effect of a street network. We tested H.2 by series of linear regressions shown in Figure11. For a global scale *Rn* there is a very strong linear *natural movement effect* for both closeness and betweenness centrality which relates $MPC_{(disrupted)N}$ to $MPC_{(equall)1}$ with $R^2 > 0.7$. However, when running a local scale analysis with radius R600m, there is almost no observable *natural movement effect* with $R^2 < 0.13$. Furthermore, the exploratory analysis does not suggest any non-linear *natural movement effect* either.

For hypothesis H.2 this means:

1. We can confirm H.2 on a global scale *Rn* for the both betweenness and closeness centrality measures.
2. We have to reject H.2 completely on the local scale R=600m for both betweenness and closeness centrality measures.

With the detailed analysis of the scatter plots in Figure 6, Figure 9, and Figure10 we looked for hints if a *"relation between grid structure and movement is retained, though not in linear form"* (Hillier, Penn, Hanson, Grajewski, & Xu, 1993; Peponis, Hadjinikolaou, Livieratos, & Fatouros, 1989), in the cases where we rejected the hypothesis. However, in our study we were not able to find other relations than the shown linear ones.

An additional difficulty needed to get addressed by the Space Syntax theory is the fact, that even if we find a high multiplier effect, the multiplier function *m* (equation 9) has different parameters α and β for each case. Thus, there is no generally valid model to predict the outcome of a simulation based on its initial stage, but the prediction function needs to be defined individually for each network, centrality measure, and radius combination. In our case, this is done by means of a simulation.

Finally, we want to mention, that especially when simulating non-equally loaded street networks, we observed that a small subset of the central locations that are present in the beginning get more central during the simulation and accumulate the land uses and movement potentials, whereas other local centers lose their movement potential completely. This effect can be described by the theory of economies of scales. Small advantages in the beginning can accumulate to bigger ones, as Krugman (1993) has demonstrated with his core-periphery model with multiple regions, which he called the racetrack economy. In this model, several cities are arranged in a circle with each city connected only to its direct neighbours. Solving the model numerically made it possible to show the effects of scaling on agglomerations of multiple cities or regions (Krugman, 1991). The same effect seems to be present in our simulations.

5. CONCLUSIONS & OUTLOOK

With the presented study, we developed a dynamic computational model for simulating the impact of street network configuration on movement potential and land use allocation. We demonstrated how this model can be applied to investigate the fundamental assumptions of the Space Syntax theory, the *"multiplier effect"* and the *"natural movement effect"* of street networks. The theory assumes that the effect of a street network configuration on movement can be analysed without considering (i) the feedback loop between centrality, movement and land use and (ii) its unequal loads (e.g. different densities of land uses, population and commercial activities). This is possible because the feedback loop is expected to only amplify the effect of the *"pure"* (equally loaded) street network configuration.

By using a dynamic simulation model, we showed that this assumption of a *multiplier effect* is only true under specific conditions, namely for model of pedestrian flow potential based on the equally loaded global centrality measures. Furthermore we conclude that there is no generally valid prediction function that can be used for all networks and measures and has to be calibrated for each case individually. For network analysis on the local scale, we were not able to find a multiplier effect. Our simulation results suggest that there is a *natural movement effect* only on global scale in case of closeness centrality, but not for any other measure or scale. This effect corrects the distortions in movement potential caused by unequal land use distributions or densities back to the state of an *"ideal"* equally loaded network.

The simulation model that we developed for this study is free accessible and can be used for further investigations of different boundary conditions and model parameters under which the *natural movement effect* and *multiplier effect* assumptions holds true. This is of great importance since both assumptions significantly simplify the computational complexity of estimation of the configurational effects on movement and land use. For instance, additional experiments could implement more complex land use allocation functions limiting the capacity of a street segment, which reflects a limit in sizes for plots and buildings to agglomerate urban functions. In the simulation, this limitation would restrict the weighting of a street segment and could lead to a more disperse distribution of central locations.

In addition, for a holistic understanding it would be important to run a complete sensitivity analysis that shows how the parameter-space (containing all possible combinations of control parameter settings of the simulation model) is connected to the solution-space (the results of a simulation model for all parameter combinations). Zünd (2016) demonstrates an analysis method using hierarchical clustering to show how probable it is that an urban simulation model ends up in a certain category or type of result. By such an analysis we could for example find out, at which size a disruption changes the movement pattern of a network configuration permanently, or what effect the initial locations of the disrupters have.

6. SUPPLEMENTARY MATERIALS

All data, algorithms and software implementation and additional graphics and videos further explaining the content of this paper can be downloaded from https://toolbox.decodingspaces.net/evolving-configurational-properties

7. ABBREVIATIONS:

i	Iteration
LPC	Land use potential centrality (type B)
m	Multiplier function
Me	Multiplier effect
MPC	Movement potential centrality (type A)
N	Total number of iterations
n	Natural movement function
Ne	Natural movement effect
SNC	Street network configuration

w Initial network weighting (loadings)

8. AUTHORS CONTRIBUTIONS

Contributor Role	Bielik	König	Fuchkina	Schneider	Abdulmawla
Conceptualization	X	X	X	X	X
Formal Analysis	X				
Investigation	X	X			
Methodology	X				
Software	X		X		
Supervision		X		X	
Visualization	X				
Writing – Original Draft Preparation	X	X			
Writing – Review & Editing	X		X	X	X

9. FUNDING

Martin Bielik was funded by Ernst-Abbe doctoral researcher program. This research was partially carried out in the course of the research project "IN^3 – Integrated Infrastructure" funded by the German Ministry for Education and Research (BMBF).

10. CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

11. REFERENCES

Bielik, M., König, R., Schneider, S., & Varoudis, T. (2018). Measuring the Impact of Street Network Configuration on the Accessibility to People and Walking Attractors. *Networks and Spatial Economics*. https://doi.org/10.1007/s11067-018-9426-x

Freeman, L. C. (1977). A set of measures of centrality based on betweenness. *Sociometry*, *40*(1), 35–41.

Hillier, B. (1996). Cities as movement economies. https://doi.org/10.1057/udi.1996.5

Hillier, B. (1999a). Centrality as a process: accounting for attraction inequalities in deformed grids. *URBAN DESIGN International*, *4*(3), 107–127. https://doi.org/10.1057/udi.1999.19

Hillier, B. (1999b). The hidden geometry of deformed grids: Or, why space syntax works, when it looks as though it shouldn't. *Environment and Planning B: Planning and Design*, *26*(2), 169–191. https://doi.org/10.1068/b260169

Hillier, B, & Hanson, J. (1984). *Hiller & Hansen.pdf*. http://dx.doi.org/10.1017/CBO9780511597237

Hillier, B, & Iida, S. (2005). Network and psychological effects in urban movement. In *Proceedings of the 5th International Symposium on Space Syntax* (Vol. 1, pp. 475–490).

Hillier, B, Penn, A., Hanson, J., Grajewski, T., & Xu, J. (1993). Natural Movement - or, Configuration and Attraction in Urban Pedestrian Movement. *Environment and Planning B: Planning and Design*, *20*(1), 29–66. https://doi.org/10.1068/b200029

Koenig, R., Bielik, M., & Schneider, S. (2018). System Dynamics for Modeling Metabolism Mechanisms for Urban Planning. In *Proceedings of SimAUD* (pp. 293–300). Delft, Netherlands.

Krugman, P. (1991). Increasing returns and economic geography. *Journal of Political Economy*, *99*(3), 483–499.

Krugman, P. R. (1993). On the number and location of cities. *European Economic Review*, *37*, 293–298.

Lerman, Y., Rofé, Y., & Omer, I. (2014). Using space syntax to model pedestrian movement in urban transportation planning. *Geographical Analysis*, *46*(4), 392–410. https://doi.org/10.1111/gean.12063

Peponis, J., Hadjinikolaou, E., Livieratos, C., & Fatouros, D. A. (1989). The spatial core of urban culture. *Ekistics*, *56*(334/335), 43–55.

Sabidussi, G. (1966). The centrality index of a graph. *Psychometrika*, *31*(4), 581–603.

Tobler, W. R. (1970). A Computer Movie Simulation Urban Growth in Detroit Region. *Economic Geography*, *46*, 234–240. https://doi.org/10.1126/science.11.277.620

Turner, A. (2001). Angular Analysis, (May), 7–11.

Turner, A. (2007). From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis. *Environment and Planning B: Planning and Design*, *34*(3), 539–555. https://doi.org/10.1068/b32067

Turner, A., & Dalton, R. C. (2005). A simplified route choice model using the shortest angular path assumption. *8th International Conference on GeoCompuation*. Retrieved from http://discovery.ucl.ac.uk/39855/

Varoudis, T., Law, S., Karimi, K., Hillier, B., & Penn, A. (2013). Space syntax angular betweenness centrality revisited. In *2013 International Space Syntax Symposium*.

Zünd, D. (2016). *A meso-scale framework to support urban planning* (PhD Thesis). ETH Zurich.