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THE ANATOMY OF KNOWLEDGE:

Quantitative and Qualitative Analysis of the Evolution of Ideas in Space Syntax Conference Articles (1997-2017).

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ABSTRACT

Since its inception in the 1970s, space syntax has matured into a theory and a method comprising a set of recurring theoretical and analytical concepts, as well as new ones emerging through the years. How can we trace the evolution of the field through language? How can we analyse the development of ideas in space syntax research? What can we learn from this evolution about knowledge creation in this area? Recognising that language is central to the development of ideas in any field, this paper uses automated text-analyses, focusing more specifically on all papers published in the space syntax symposia proceedings from 1997 to 2017. The purpose is to trace the trajectory of ideas as they were elaborated, used and perhaps changed in the collective work of authors researching within this field in different parts of the world. Firstly, we identify concepts and technical terminology in the field through a combined quantitative and qualitative text analysis. Secondly, we statistically assess the use of these terms, revealing patterns and trends in the evolution of knowledge in space syntax. Thirdly, we compare patterns between established concepts and categories that stabilise over time with concepts emerging more recently. The results from our analysis of networks of concept relationships suggest that: (i) concepts and terms evolve in dependent trajectories; (ii) ideas have evolutionary developments, with some emerging and gaining growing attention, while others showing clear signs of stability, and others losing centrality over time, including networks of what can be termed as 'canonical' concepts. We have also identified (iii) an overall decline in the use of early space syntax concepts rooted in social theory and anthropology; (iv) a trend of decreasing conceptual novelty over time; (v) traces of increasing influence by other fields; and finally (vi) signs of a clear 'technological turn' in the field.

KEYWORDS

Space Syntax, Quantitative Text Analysis, Qualitative Text Analysis, Concept Identification, Concept Trajectories

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1. INTRODUCTION

Since its inception in the 1970s, space syntax has matured into a theory and a method comprising a set of recurring theoretical and analytical concepts and terminologies emerging through the years. Up to the present, this research field has involved the production of over 1,000 conference papers – texts that register the collective contribution made by more than 1,000 researchers working within what came to be a consolidated field of scientific inquiry into socio-spatial systems, buildings, cities, urban spaces and even regions. Considering such an increasing pool of texts registering the emergence, consolidation and continuing production of space syntax theory and methodological approach, can we now observe the conceptual paths taken within the field? Can we trace the evolution of space syntax through the use of the specific language developed in the field? What can such an analysis reveal of the development of ideas in space syntax research? And what can we learn from this evolution about knowledge creation in this field?

Philosophers of science like Thomas Kuhn (1962) made us aware that every scientific field or paradigm encompasses their own sets of concepts, terminologies and techniques, which compose the specific vocabulary and language used to approach and understand their object domain. Research directions and outputs go hand in hand with the evolution of languages (discursive or otherwise) employed in the work of researching and writing. Recognising that language is central to the development of ideas in any field, this paper analyses the body of words that compose the language developed and used in Space Syntax. For that, it uses automated and analogical text-analyses, focusing specifically on all papers published in the space syntax symposia proceedings from 1997 to 2017 – more precisely, 1,089 articles.

The purpose is to *map the trajectory of ideas* as they were developed, used and changed in the collective work of authors researching in space syntax in different parts of the world. Space syntax symposia papers are particularly interesting for the linguistic anatomy of the field. This is because these symposia attract researchers engaging with ideas and terminology that are widely shared within the field. Furthermore, conference publications are likely to bring fresh applications, attempts at further developments, and new insights. Authors are more likely to test ideas in conferences in ways they hardly could in a journal submission. As journals generally have high standards regarding robustness in empirical samples and findings, conferences seem interesting platforms to test novelty. Moreover, space syntax symposia can provide consistent temporal insights into the development of the field, due to their regular two-year interval. In short, symposia papers seem to be a proper field of written registers to prospect novelty, tentative uses and potential innovations in terminology, concepts and methods. Such papers might reveal trends before authors become self-conscious about them.

The method deployed in this analysis involves the following steps. First, we identify concepts in the field through a combined qualitative and quantitative text analysis that processes large amounts of texts and identifies scientific concepts and terminologies. These terminologies encompass theoretical concepts (such as ‘solidarity’ or ‘visibility’), methodological concepts (such as ‘integration’ or ‘choice’) and technical concepts (such as ‘choice value’ or ‘angular analysis’). Second, we statistically analyse the frequencies of the occurrence of these concepts and terms, and assess their evolution in time. Third, we identify the changing networks of relationships created among these notions, and compare patterns between established concepts that stabilise over time with concepts emerging more recently. Precisely, we are constructing a network of concepts and terms through their contextual relationships and investigate the structure and morphology of this network. This process reveals patterns and trends in the evolution of knowledge in space syntax. Such comparisons might enable an understanding of the relationship between what can be termed the ‘canonical’ (stable) structure of ideas with concepts occurring less persistently in the body of papers.

We maintain that an automated text-analysis cannot replace a close reading of a text. What this method offers is amplification and augmentation of careful reading and analysis. Although our research is essentially inductive, i.e. a search for an understanding of the problem at hand driven by the empirical data, as opposed to an investigation of empirical situations driven by a theoretical proposition, a series of questions are motivating the project: What are the changes in substantive focus regarding the use of theoretical and methodological concepts? What is the weight of theoretical, methodological and technical work currently in the field? How are early concepts and the architectural, social and anthropological framework (e.g. Hillier et al. 1976; Hillier and Hanson, 1984), which established space syntax in the 1970s and 1980s holding in relation to new interests, technical innovations, analytical and computational power, developed through the years?

The analysis shows that concepts and terms are deeply relational: they can be understood through their network structure of their relationships. In such a network concepts and terms appear in groups, and find different positions and centralities in the topology of words used in the field. These centralities change in time, and these distributions are quite revealing about the evolution of the field. The results from analyses of concept frequencies, temporal trajectories and the network of concept relationships found in these works suggest that: (i) concepts and terms evolve in dependent trajectories; (ii) ideas have evolutionary developments, with some emerging and gaining growing attention, others showing clear signs of stability, while others declining. This includes networks of 'canonical' concepts, which may lose centrality over time. We have also identified (iii) an overall decline in the use of early concepts rooted in social theory and anthropology, like 'social solidarity' and 'encounter'; (iv) an apparent trend of decreasing conceptual novelty over time; (v) traces of increasing influence by other fields, like network science; and finally (v) strong signs of a 'technological turn', which describes a shift of the field's focus influenced by and towards technology i.e. the development of techniques, tools and knowledge that is based on technological progress.

2. TEXT-ANALYSIS: METHODS

From the outset of the posed research questions: '(a) how to understand the evolution of a scientific field through its language', (b) 'how to trace the linguistic development of terminology and concepts' and (c) 'how to gain insights into the evolution of knowledge creation', we have organised our approach into three main steps, 'identifying concepts, 'tracing concepts over time', and 'identifying conceptual systems', that are based on methods of textual data analysis.

2.1 LINGUISTIC IDENTIFICATION

A concept can be defined as an abstract representation or definition of an entity or phenomenon, generally in the form of a generic idea which has been generalised from particular instances (Merriam-Webster 2019; Saitta and Zucker 2013); it is through the formulation of concepts that we create generalised theoretical understanding. The identification of concepts through quantitative methods is a challenging endeavour. What particularly constitutes a concept depends highly on the theoretical framework or field a concept is embedded into (Blumer 1931); this makes the formulation of a positive definition, i.e. based on the existence of actual properties or components, difficult to be achieved. While machines outperform humans in tasks such as processing large amounts of texts, they are still weak with more complex tasks such as the extraction of meaning from texts. Extracting the generality of meaning from individual words and sentences for a research field, however, is a fundamental component for the identification of concepts. For this research, we propose a mixed approach of quantitative and qualitative methods to identify theoretical and methodological concepts along with technical terminology. For the quantitative part, a 'bag-of-words' model (Harris 1954) is employed to establish a list of words ranked according to their frequency across the database of conference articles.

The bag-of-words model is a simplified representation, where texts and documents are stripped from word order and grammatical information and are instead combined into a 'bag' of all words maintaining the number of a words occurrence. This model is commonly used in natural language processing and information retrieval, and builds on the core assumption that a word's frequency relates to its importance within a text. Word frequency distributions have been the core interest in the field of statistical linguistics for the past 85 years, grounded in linguist Georg Zipf's empirical identification of an inherent Pareto like distribution in natural languages. The so called Zipf's law states that if a set of elements – for example, the words of a text – are ordered by their frequency, the probability p of their occurrence is inversely proportional to the position n within the order of rank: $p(n) \sim \frac{1}{n}$ (Zipf 1932). This implies that some words occur substantially more often than others, allowing the identification and interpretation of their role within a language. In this research, word frequencies are computed for single words (unigrams) and word combination of two words (bigrams) with the use of the R package *quanteda*: for quantitative analysis of textual data (Benoit et al. 2018; R Development Core Team 2018). The general aim is to identify concepts and terminologies that are used frequently rather than those used only once.

The basis of this analysis forms a database of all papers published in the space syntax symposia proceedings from 1997 to 2017[4]. The database differentiates each paper by a unique ID, a combination

[4] Short papers have not been included in the analysis, due to inconsistent information, quality and format.

of the conference number, the sequential proceeding number, the first author, the university location and country (e.g. 01_001_Hillier_London_GB, for the first space syntax paper by Hillier and Hanson 'The Reasoning Art: or, The Need for an Analytical Theory of Architecture' (1997)). All publications are converted into a TXT document type and manually cleaned from page numbers, author and affiliation information, as well as the list of references at the end of each paper. Moreover, the database has been further cleaned through automated methods (i.e. regular expressions and *quanteda* based stop-word removals). More specifically, we removed from the database words with little lexical meaning, and those that primarily express grammatical relationships among other words (i.e. function words and stop-words). Specifically, these words are: English stop-words (these refers to the most common words in English language, e.g. 'I', 'you', 'to', etc.), conjunctive adverbs (e.g. 'accordingly', 'furthermore', 'moreover', etc.), subordinating conjunctions (e.g. 'after', 'although', 'whenever', etc.), auxiliary verbs (e.g. 'could', 'should', 'would', etc.), most common verbs (e.g. 'do', 'know', 'like', etc.), and most common adverbs (e.g. 'accidentally', 'actually', 'afterwards', etc.), as well as a small number of scientific jargon (e.g. 'et al', 'proceeding', 'fig', etc.). The result of this process will be referred to from now on as *corpus*. A corpus can be subdivided into: *documents*, in our case conference papers; their *tokens*, the collection of all words within a document; as well as *types*, the collection of unique words within a document.

The number of publications in the corpus is 1089 with a total of 46601 unique selected words. Through the ratio of types to tokens, i.e. *token-type ratio* (TTR) we can gain insights into the complexity of a language or body of text (Ure 1971). TTR is the ordinary between the number of types (unique words) and the number of tokens (total words)[5]. The summary statistics of the cleaned corpus of conference proceedings shows a decrease of the token-type ratio (TTR) from 0.076 to 0.044 during the period of observation (Table 1). This means an increase in publications over time does not relate to an increase in linguistic complexity and instead points to an increase in linguistic reproduction in the field.

Table 1: Database summary statistics of the cleaned corpus

Year	1997	1999	2001	2003	2005	2007	2009	2012	2013	2015	2017
Conference	01	02	03	04	05	06	07	08	09	10	11
Publications	39	47	67	79	101	110	115	91	111	152	177
Tokens	98823	80902	147542	199432	225414	263682	268982	255864	286035	373929	435898
Types	7465	7606	10797	11841	13513	13678	14234	13376	14165	16674	19282
TTR	0.076	0.094	0.073	0.059	0.060	0.052	0.053	0.052	0.050	0.045	0.044

The authors computed word frequencies for all types within the corpus and compiled a list of the 6,000 most frequent words. This list of 6,000 unigrams and bigrams was shown to three independent researchers active in the field of space syntax with the request to mark/code all words that are or could be characterised as concepts within the field. Figure 1 shows the frequency distribution of the 50 most frequent unigrams and bigrams, with 'space' being the most frequent unigram (occurring 42,867 times and in 1084 papers) and 'space syntax' the most frequent bigram (occurring 8,723 times and in 980 papers). For comparison, the 3,000th unigram is 'organizing' (occurring 105 times and in 71 papers) and the 3,000th bigram is 'drunken behaviour' (occurring 31 times and in 4 papers). We acknowledge that starting from the 6,000 most frequent unigrams and bigrams can form a limitation for the identification of very new concepts, as their frequency is inevitably too low to be in the top 3,000 tokens. However, this is not seen as problematic, as it is not the aim to identify all potential concepts, but rather to arrive with a bottom-up list of concepts whose development is frequent enough to be traced over time.

[5] TTR is calculated through the following formula, where *V* refers to the total number of types and *N* refers to the total number of tokens: $TTR = \frac{V}{N}$.

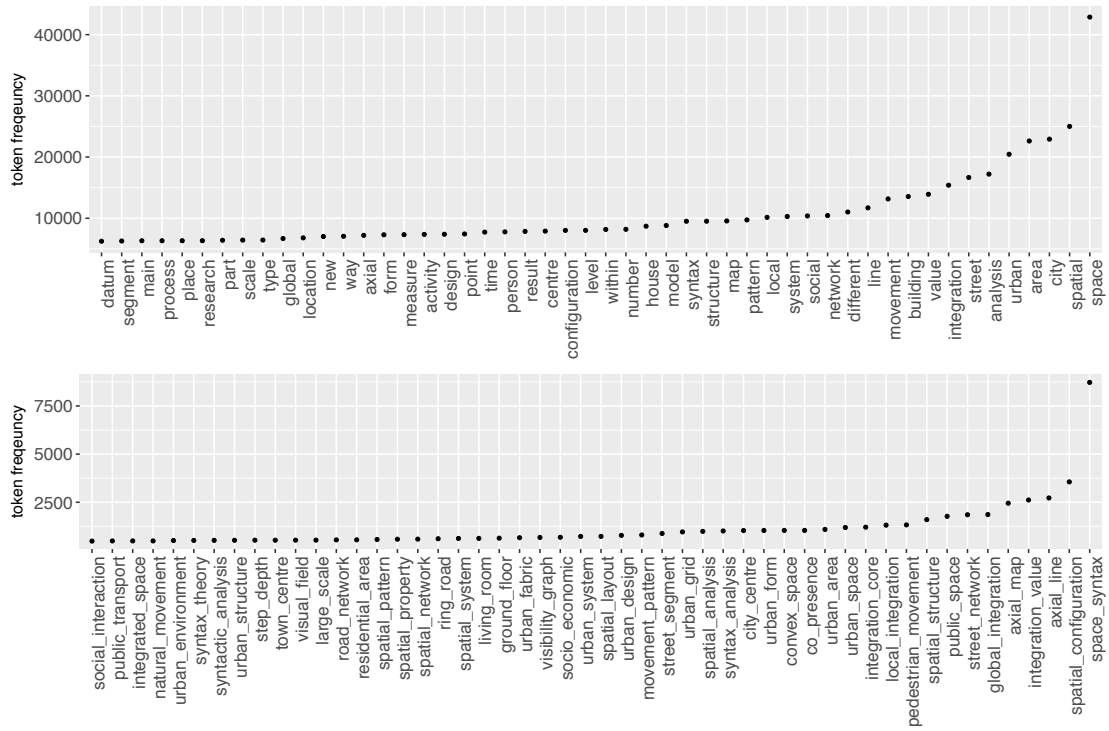

Figure 1: The 50 most frequent unigrams and bigrams across all conferences.

2.2 TRACING CONCEPTS OVER TIME

Based on the list of identified concepts by the three researchers, trajectories of these are traced over time. This is done by computing frequencies for each of the concepts per conference year, providing a quantification of their respective usage over time. Temporal frequency distributions can provide insights into the development of concepts, as they give indicators on consistent, decreasing or increasing usage. We differentiate between three fundamental stages: namely, the *emergence* (the coming into existence of a concept over time), *consistency* (the state of sustained usage of a concept over time), and *decline* of a concept over time. For instance, if a concept is not present in early conferences, but occurs at some point and is increasingly used over time, it is classified as an emerging concept. If a concept is frequently used in early years, but less so in later conferences, is categorised as a declining concept, and likewise if there is no significant change in frequency, a concept is classified as a consistent concept. This classification should not be seen as ordinal but rather as a continuous number of increasing or decreasing degree. Furthermore, we standardize the computed frequency to allow comparisons of trajectories across years and differing frequencies (henceforth 'scaled word frequency'). Firstly, frequencies are divided by the total number of tokens per conference year in order to be able to compare frequencies between different years, and secondly, frequencies are standardized by subtracting the mean and dividing by the standard deviation of the entire vector of words frequencies. Finally, the data trend for each word is calculated and their slope compared across all concepts. Based on this comparison, concepts are grouped into the proposed categories.

2.3 IDENTIFYING CONCEPTUAL SYSTEMS

In addition to the concepts' trajectory, it is of particular interest to identify the relationship among different concepts. Do some concepts form conceptual clusters? Do related concepts exhibit co-dependent trajectories, or do some concepts relate to each other in an inverse relationship where over time one concept replaces another? In order to address these questions, we computed the co-occurrence for each word in relation to all other words to investigate the relationship between different concepts. This is done by counting how often a concept occurs in each paper for all concepts and the entire corpus; the resulting vectors of occurrences are then correlated with each other and form a word co-occurrence matrix. This matrix can be visualized as a *network of relationships*. Within this network, edges are undirected and weighted by the respective correlation value. Formal descriptions of network properties and morphology provide insights into how and to which extent concepts relate to each other.

3.0 RESULTS

3.1 CONCEPTS IN THE FIELD OF SPACE SYNTAX

Based on the previously introduced list of most frequent words the three researchers independently identified 816 terms in total, of which 205 are unigrams and 611 are bigrams. For reasons of intercoder reliability, i.e. the extent to which two or more independent researchers/coders agree on the coding, we subsequently select those terms that are identified by at least two researchers. Only 287 (222 bigrams and 65 unigrams) of these terms are classified as 'concepts' and 'technical terminology' by at least two researchers. This means that three-fourths of the most frequent concepts in the field of space syntax are predominantly bigrams, i.e. two-word combinations. These bigram concepts are for example words such as (in unrelated order) 'foreground network', 'generic function' or 'isovist occlusivity'. Examples of identified unigrams are words such as 'interface', 'permeability', or 'choice'. Table 2 shows the 20 most frequent of these 287 identified terms as well as the number of papers each occurs in.

Table 2: 20 most frequent uni- and bigrams identified by researchers in the field, among a total of 287 terms.

#	unigram	frequency	No of papers	bigram	frequency	No of papers
1	integration	15401	933	space_syntax	8723	980
2	local	10147	856	spatial_configuration	3559	661
3	syntax	9510	1001	axial_line	2724	434
4	configuration	8018	923	integration_value	2619	528
5	axial	7206	668	axial_map	2452	455
6	global	6690	747	global_integration	1863	349
7	choice	4926	628	street_network	1852	319
8	accessibility	4531	607	spatial_structure	1598	458
9	depth	4470	596	local_integration	1312	258
10	core	3882	587	integration_core	1207	227
11	visibility	3665	418	co_presence	1040	215
12	path	3511	530	convex_space	1039	217
13	syntactic	3275	537	urban_grid	962	249
14	connectivity	3224	518	street_segment	881	184
15	node	3147	394	movement_pattern	803	267
16	isovist	2775	216	visibility_graph	674	158
17	centrality	2628	338	visual_field	532	158
18	visitor	2291	328	step_depth	530	100
19	configurational	2279	495	syntactic_analysis	524	219
20	angular	2169	265	natural_movement	494	191

These 287 terms can be further differentiated into categories according to their roles in the space syntax language. They include: *theoretical concepts*, not just words representing entities but interpretations of a property or a phenomenon through discursive means, rendering that property or phenomenon reasonably knowable without particular dependence on methodological descriptions (e.g. 'visibility'); *methodological concepts*, relying on analytic procedures developed for investigating empirical problems, including representation and calculation, rendering a property or phenomenon representable and quantifiable, say, through geometrical or mathematical descriptions (e.g. 'isovist', 'isovist integration'); and *technical concepts*, including words expressing methodological procedures or components, which on their own do not qualify as methodological concepts (e.g. 'nach value', a standardised value of choice). The above classification is instrumental for the purposes of our analysis.

Relationships internal to these categories should be subject for further study, as they are likely to provide more precise information on the evolution of specific classes of ideas and their role in the overall evolution of the field. At this stage, however, we shall focus on the entire system of connections among words in use in space syntax.

3.1 CONCEPT TRAJECTORIES

The established series of keywords has been used to perform a temporal analysis of word frequencies. Concepts are subsequently grouped according to their commonalities in terms of slope value in order to classify a concept into identified categories (emergence, decline and consistency). The ten most increasing, decreasing and consistent concepts are plotted in Figure 2 and Figure 3 respectively. The share of increasing concepts (trend line slope > 0.10) is with 80 of 287, twice as big as the number of decreasing concepts with 27 (trend line slope < -0.10), while the majority shows rather steady developments across the observed time period with 180.

The overall trends of each of the ten concepts with most increasing frequencies are highly comparable, with relative variation in their curve development (Figure 2). Differently to these common developments, the time of emergence of concepts is one of the key differences. However, while some terms (e.g. 'nach value' or 'angular distance') exhibit steadily increasing usage over time, others (e.g. 'betweenness' or 'background network') increase showing higher variation in their curve development.

The ten concepts with most decreasing frequencies exhibit much higher variation in their curve compared to the ten most increasing concepts (Figure 3, top). Most concepts have been used highly in early conferences, after which their use declined rapidly within the first 5 conferences. Concepts such as 'space occupancy' and 'global movement' for example where highly used in the first conference (1997), declined shortly after and almost disappeared entirely. Others, such as 'axial graph', followed the same trajectory, but experienced a sharp increase in 2007, just to disappear shortly after. Overall, one can observe that there is a series of concepts that have significantly lost importance over time. Trajectories of decline are not always steady processes and short temporary recurrences are not rare, yet their overall decline is clearly visible.

A view on the ten concepts with slope values < 0.1 and > -0.1 unveils a third kind of trajectory, namely concepts that feature no substantial increase or decrease over time (Figure 3, bottom). Such concepts have mostly been present in all conference years and can be identified as the concepts defining 'space syntax canon'. While these observations provide insights into the general trajectories of concepts in the field of space syntax, little has been said about moments of concept emergence yet.

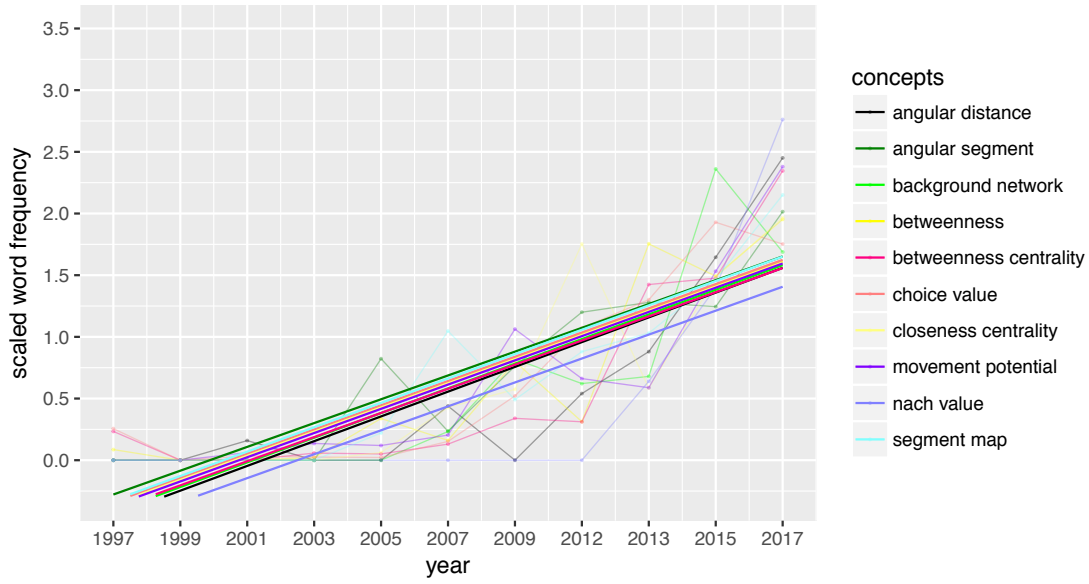

Figure 2: Concept emergence: The 10 most increasing concepts and terms. Scaled word frequencies per conference year (1997 to 2017) with superimposed trend lines. slope value?

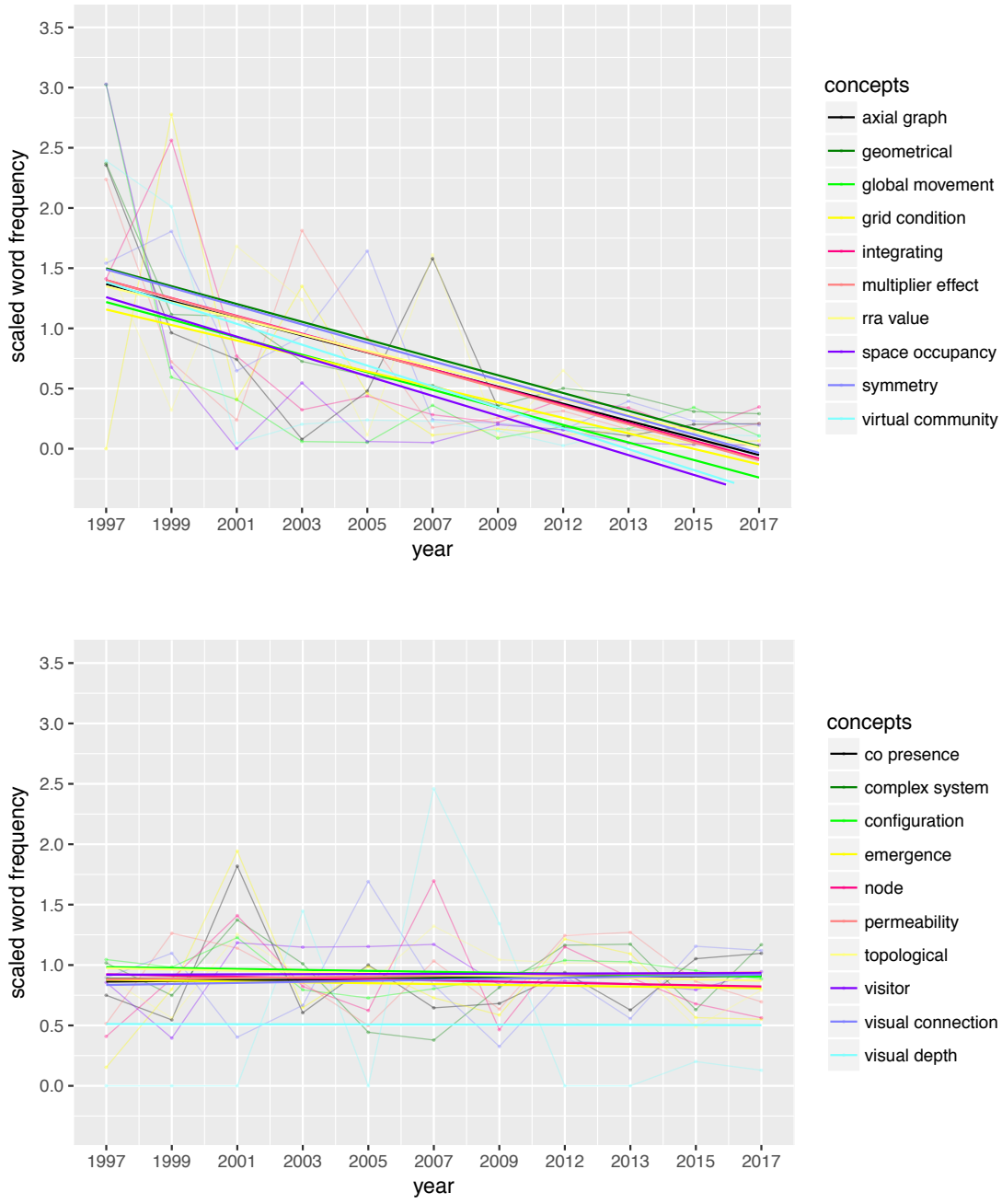

Figure 3: (Top) Concept decline: The 10 most decreasing concepts. Scaled word frequencies per conference year (1997 to 2017) with superimposed trend lines. (Bottom) Concept consistency: The 10 most consistent concepts. Scaled word frequencies per conference year (1997 to 2017) with superimposed trend lines.

By focusing on years in which concepts occur for the very first time, we can identify those occurrences of high linguistic and conceptual novelty as well as those lacking such. We have counted the occurrence of new concepts per conference year (Table 3). By definition, the first symposium in 1997 was the one with the highest number of 'newly' introduced concepts. Due to the difficulty in determining whether all these concepts were truly 'new' at the time, we instead concentrated on the 2nd–11th symposia. Here, *a clear trend of decreasing conceptual novelty* is apparent. In 1999, 23 new concepts where introduced, yet five conferences later in 2009 only three new concepts where introduced. The conferences in the years 1999, 2001 and 2005 had the highest number of newly introduced concepts. Such a shift in conceptual production might be related to an increasing endeavour to investigate the application of concepts in research. At the same time, these results need to be considered with care, as concepts that have very recently emerged, such as 'avoidance' (Koch 2015) might not have been utilised often enough to feature in the initial list of 6,000 most frequent words. New concepts and terminologies introduced

especially in more recent years might not have found enough frequency to feature above the threshold considered in our filter.

Table 3: Number of newly emerged concepts per conference year.

Concepts	191	23	28	10	23	6	3	0	3	0	0
Year	1997	1999	2001	2003	2005	2007	2009	2012	2013	2015	2017

A closer look at the moment of emergence and development of newly introduced concepts can shed light on this situation. Figure 4 and Figure 5 show plots of scaled word frequencies (see 2.2 for definition) of all words that have been newly introduced in the conference years of 2003 and 2007, and exhibit conceptual emergence. In 2003, a series of 10 concepts was introduced with different relative frequencies. Here, not only the relative frequency at the moment of introduction differs substantially, but also its development in the following years. Whereas for example, the use of the concept 'choice measure' was relatively low in the year of its introduction, it became consistently higher over the following years, with little variation in its development. In contrast, the concept of 'visual depth', shows a 'M'-shaped development. First this concept was highly used in the year of its introduction, then not used at all in 2005, followed by high usage in 2007 and 2009; finally, it disappeared entirely after 2009. Such a spark of usage in one year, followed by decline also characterises concepts that emerged in 2007 (Figure 5). Here the concept of 'visibility cost' has been introduced for the first time; its usage decreased significantly in 2009 and was never used since. An example of concepts whose temporal development indicates a related usage in text are 'foreground network' and 'background network'; the development of their curve shows that they are co-dependent or that there is a interrelationship between the two concepts.

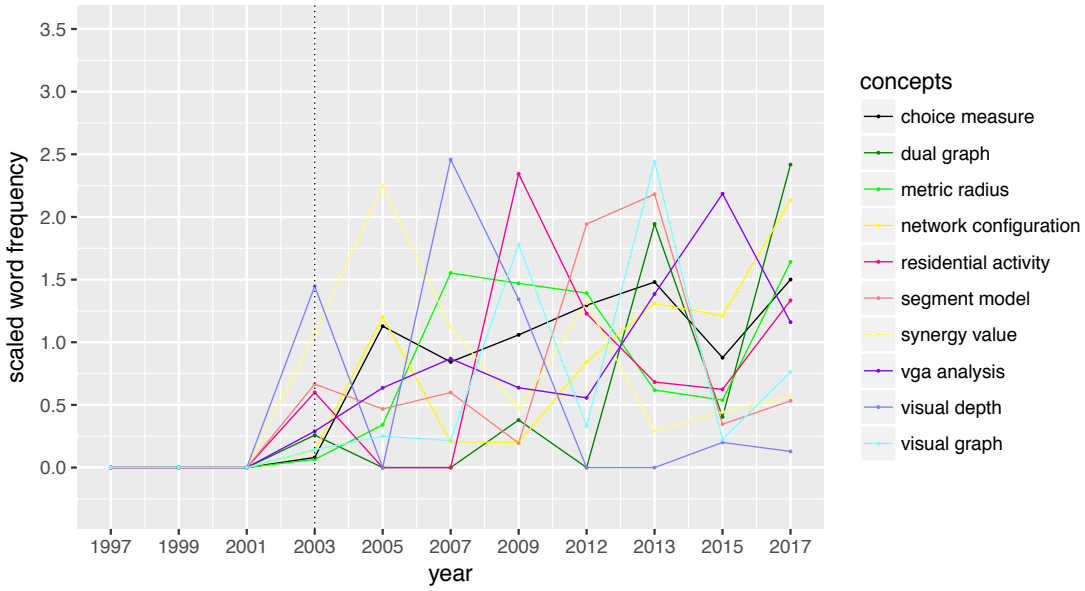

Figure 4: The 10 concepts that emerged in 2003. Scaled word frequencies per conference year (1997 to 2017).

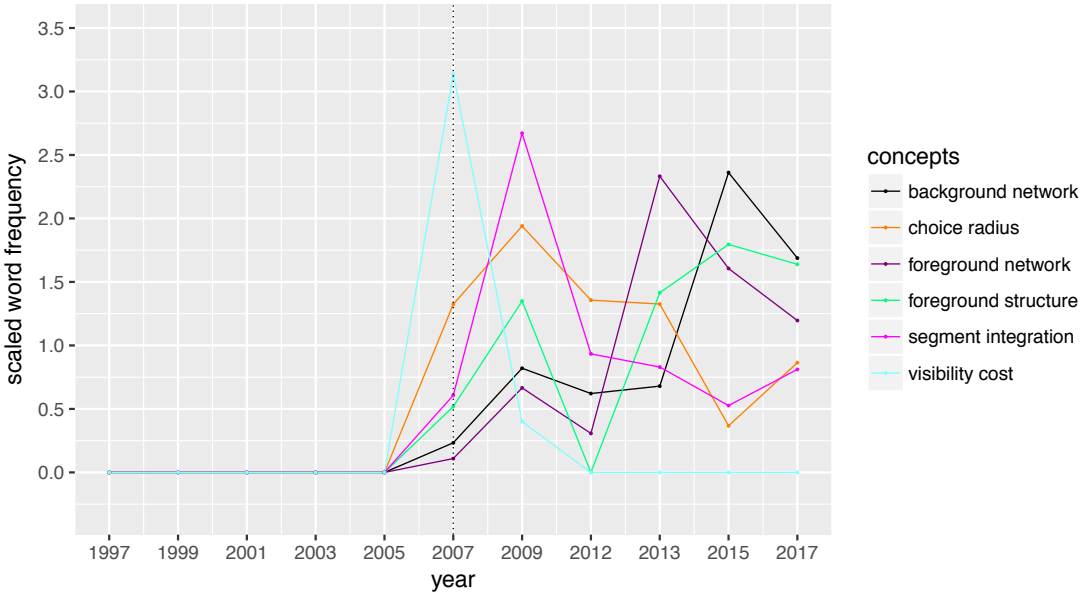

Figure 5: The 10 concepts that emerged in 2007. Scaled word frequencies per conference year (1997 to 2017).

Investigating trajectories of concept usage over time has provided insights into the wide-spread significance of some concepts of concepts; the moment of conceptual emergence; those concepts that show identical or similar trajectories. However, this investigation does not capture the actual relationships between two or more concepts. We can further explore these relations through network analysis.

3.3 CONCEPTUAL SYSTEMS

To understand how concepts and terms are related to each other, we construct a network system of related concepts. This network is based on significant correlations between the co-occurrences of concepts, and allows the visualisation of the conceptual system (a system of relations among words defining properties or phenomena) of the space syntax field. This is done by counting the occurrence of each of the 287 concepts for the entire corpus (1089 papers). The result is a co-occurrence matrix (287 x 1089) where each concept is represented by a vector of 1089 values counting the occurrence within each paper. These vectors are correlated with each other in all possible combinations (i.e. each concept against every other concept) and the resulting correlation matrix forms the basis of the network creation. Only concepts that feature a significant *p*-value ($p < 0.05$) and a correlation coefficient above a threshold of $R^2 > 0.1$ are then connected to each other. Figure 6 shows the result of this process: a network system of all identified space syntax terms and concepts. The network edges are weighted according to their correlation coefficient: the thicker the edge connection, the stronger the network relationship between two concepts. To provide some examples of these relationships from Figure 6, strongly correlating conceptual pairs are: 'movement economy'—'multiplier effect', 'description retrieval'—'spatial law', and 'social solidarity'—'transpatial'. The network node size is also weighted according to the network degree, or connectivity of a node; this gives an indication of how many other concepts a particular concept is related to (i.e. feature a correlation of $R^2 > 0.1$); this is comparable to a concept's connectivity, to make use of space syntax terminology. Moreover, each node is coloured according to the computed slope value of its trajectory trend line. Blue colours indicate declining usage over time, while red ones highlight those concepts that are increasingly used. With the help of this system, one can not only understand the relationship between two words but also potentially trace relationships through the networks' shortest path (where distance cost is the inverse correlation coefficient) between non-adjacent concepts, pointing to potential establishment of theoretical connections. Examples of such a path are from 'spatial practice' to 'affordance';

'spatial practice'—'social solidarity'—'affordance',

or from the concept 'angular betweenness' to 'convex partitioning';

'angular_betweenness'—'visibility cost'—'visual information'—'convex partitioning',

or from the concept 'non discursive' to 'spatial order';

'non discursive'—'cognition'— 'description retrieval'—'morphic language'—'spatial order'.

The conceptual system also offers relevant insights into clusters of concepts. Clusters of concepts feature substantially higher number of connections, as well as stronger correlation between concepts within the cluster than to concepts outside of the cluster. We highlight four fundamental clusters in the network. These four clusters are not only distinctive in their network relationships, but also in their temporal development. Cluster 1, a dense network of predominantly emerging concepts; cluster 2 a dense network of predominantly declining concepts; cluster 3 a sparser network with heterogeneous usages of concepts, and cluster 4 a less densely connected network of declining theoretical concepts. More significantly, the first two clusters are densely related to each other indicating the replacement of one category of methodological concepts by another while also maintaining their relationship with each other. In contrast, clusters 3 and 4 are more isolated. Therefore, there is intensification of a system of emerging methodological concepts and one system of declining concepts of similar nature, as opposed to a number of theoretical concepts that have sparser relationships with one another. This indicates a lack of investment in tight interconnections among theoretical and methodological concepts or a severance between analysis and theory, hence a decline of theoretical innovation.

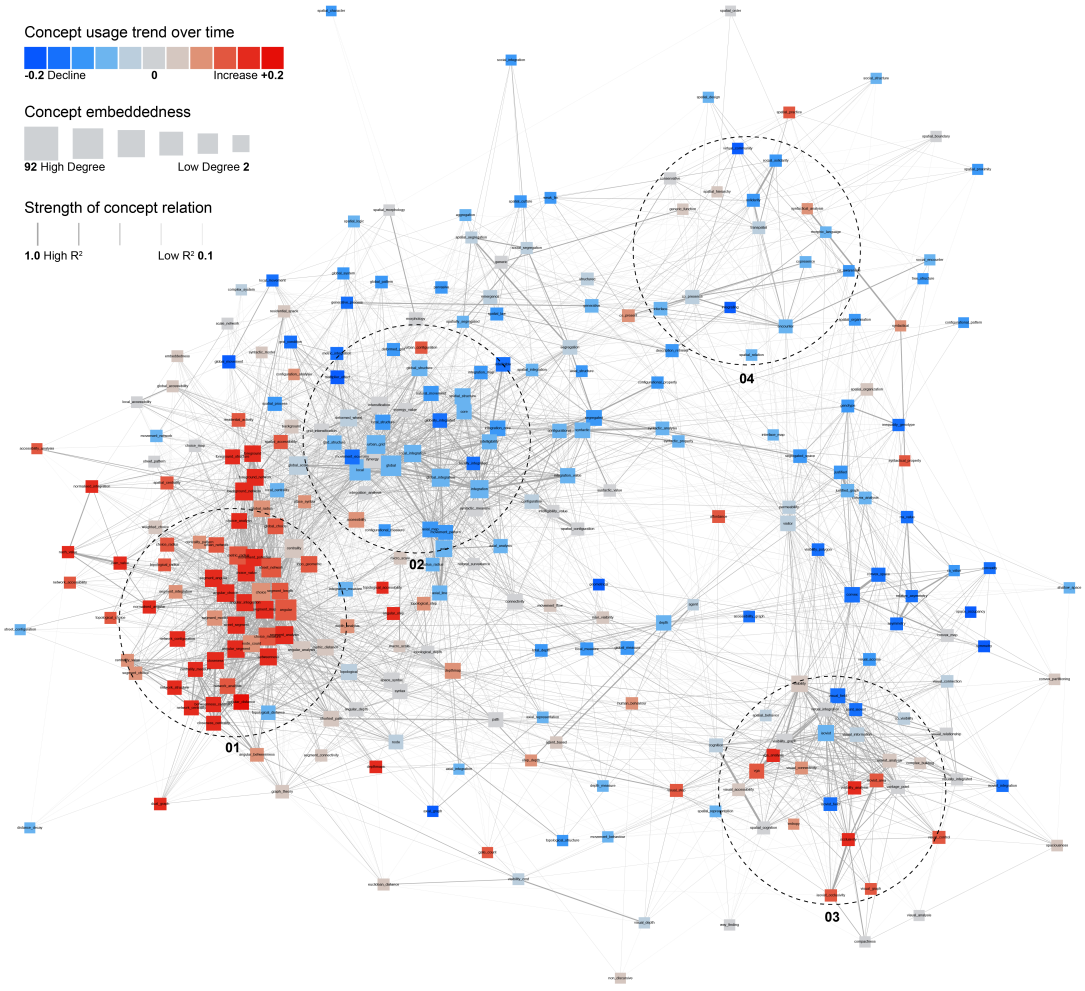

Figure 6: Network of concept relationships. Edge thickness indicates the strength of relationship based on the correlation coefficient, node size indicates the connectivity of concepts based on the network degree, while blue and red colours highlight decreasing and increasing usage over time. Dashed lines highlight distinctive conceptual sub-clusters.

A closer look at the clusters shows the nature of these conceptual subsystems, which are distinctive networks within the conceptual network. Figure 7, shows the network of cluster 1. The concept with the highest degree is 'angular', followed by 'betweenness centrality' and 'angular choice'. *All concepts are*

of rather methodological nature, with an emphasis on spatial network terminologies such as angularity, segments, centrality, shortest path, and choice/betweenness. Since all of the concepts exhibit an increasing trend, this cluster appears as *one of the most important research directions of the field of space syntax*. We can also identify further sub-clusters within this conceptual network; 'betweenness centrality', 'closeness centrality', 'network centrality' form a distinctive sub network, as well as technical terms like 'nach value', 'nain value', and 'normalized angular', which indicate specific sets of words that are simultaneously used by authors employing any of these concepts.

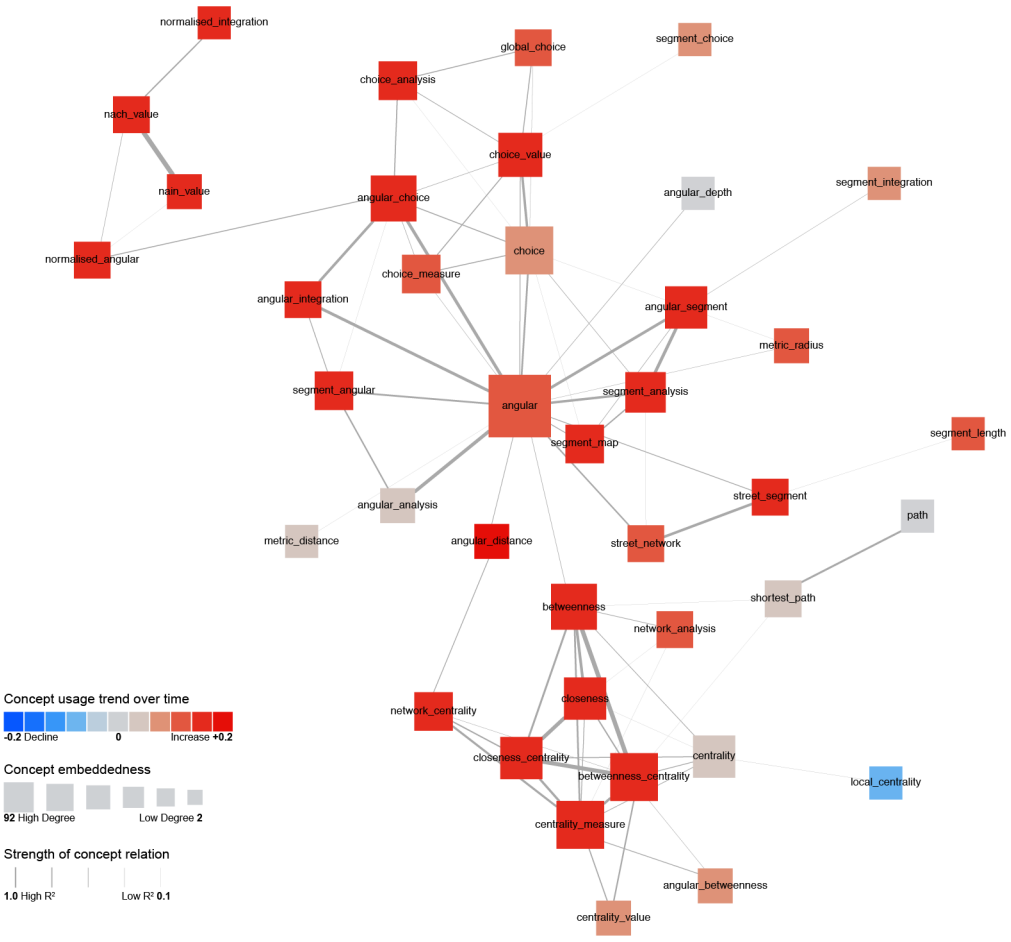

Figure 7: Network of concept relationships: cluster 1. Edge thickness indicates the strength of relationship based on the correlation coefficient, node size indicates the connectivity of concepts based on the network degree, while blue and red colours highlight decreasing and increasing usage over time.

The second conceptual subsystem (cluster 2), features a different network morphology compared to cluster 1 (Figure 8). All concepts exhibit declining trajectories and point to *a strand of theoretical and methodological terminology that loses its importance in the field*. The concepts with the highest connectivity in cluster 2 are 'integration', 'axial' and 'global', to which two tree-like subgroups connect. The first subgroup, connected to 'integration', defines the work on segregation with concepts such as 'social segregation' and 'spatial segregation'; the second subgroup, connected to 'global', is formed of concepts such as 'intelligibility' and 'synergy'. Concepts that feature word pairs based on the 'local' to 'global' relationship show a clear declining tendency. This declining tendency might indicate an earlier argued need for new more complex differentiated conceptualisations of network relationships that go beyond the dichotomy of 'local' and 'global' (Krenz 2017). Overall, cluster 2 has more theoretical concepts related to properties of a configurational nature such as 'global' or cognition such as 'intelligibility' as opposed to cluster 1, which features more methodological concepts. Furthermore, cluster 2 seems to relate to the earlier methodological work in space syntax, when axial line maps formed the basis of analysis. Compared to cluster 1, this early methodological work has declined over

time, as the introduction of angular analysis (Turner 2000) and the subsequent method for angular segment analysis breaking axial line into segments resulted in more and more studies employing segment maps. This seems to coincide with a growing usage of concepts from network theory.

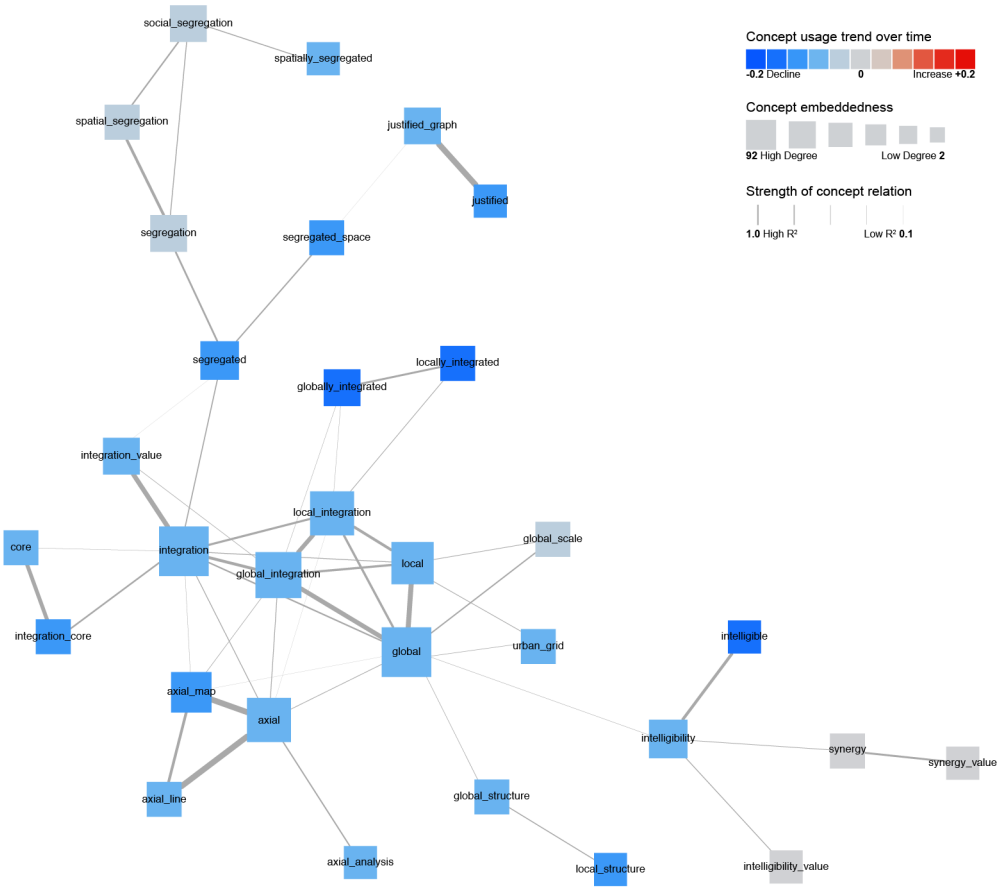

Figure 8: Network of concept relationships: cluster 2. Edge thickness indicates the strength of relationship based on the correlation coefficient, node size indicates the connectivity of concepts based on the network degree, while blue and red colours highlight decreasing and increasing usage over time.

The third conceptual subsystem (cluster 3) is not characterized by a clear trend in terms of the usage of its concepts (Figure 9). Instead, there are seven increasing and seven decreasing concepts among ten consistent ones. The concepts with the highest connectivity are 'isovist', 'visibility graph' and 'visual integration'. These concepts are *mostly used in the analysis of buildings and small-scale spaces and point to a particular strand of research*, which features a more heterogeneous development compared to 01 and 02,

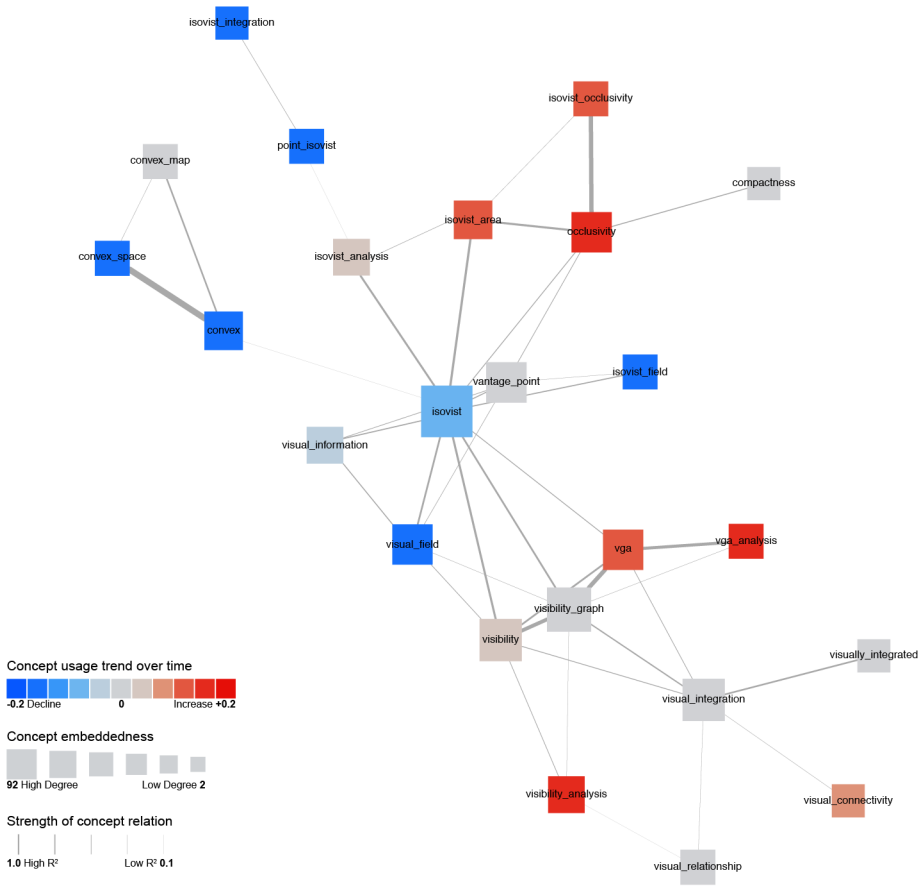

Figure 9: Network of concept relationships: cluster 3. Edge thickness indicates the strength of relationship based on the correlation coefficient, node size indicates the connectivity of concepts based on the network degree, while blue and red colours highlight decreasing and increasing usage over time.

Finally, a fourth cluster shows the relative decline in the use of early theoretical concepts (Figure 10). The network analysis of space syntax concepts shows that a constellation of methodological concepts and technical terms has not only come to be proportionally dominant over more discursive and theoretical terms, but *sociological concepts* and concepts related to the field of cognition studies like 'virtual community', 'solidarity', 'encounter' and 'description retrieval' *have declined in usage*.

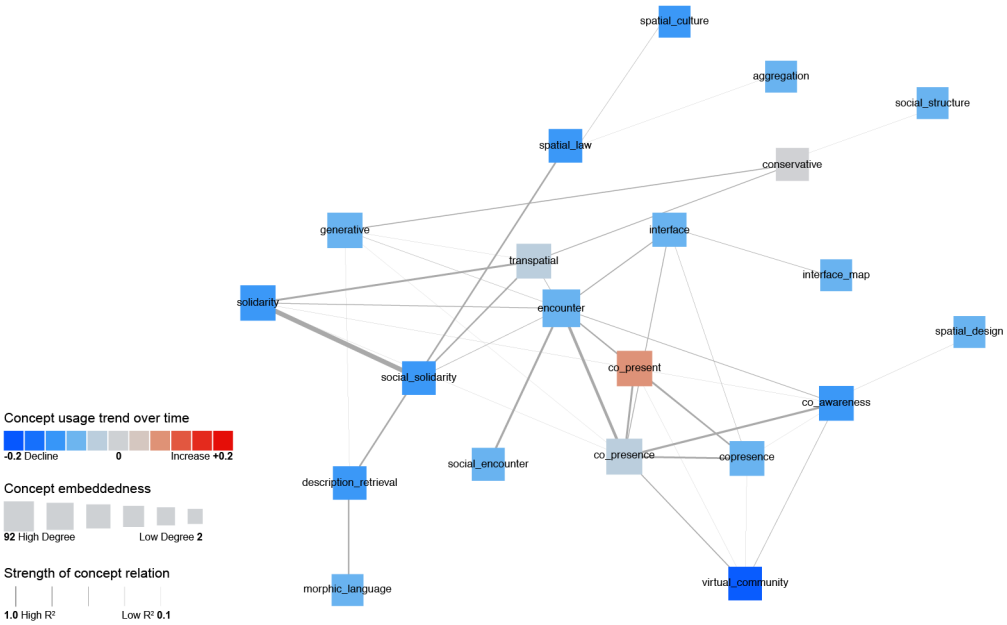

Figure 10: Network of concept relationships: cluster 4. Edge thickness indicates the strength of relationship based on the correlation coefficient, node size indicates the connectivity of concepts based on the network degree, while blue and red colours highlight decreasing and increasing usage over time.

4. CONCLUSIONS

Our analyses showed a number of trends within the space syntax field. As the field evolves, new concepts emerge (e.g. 'metric radius', 'topological radius', 'angular integration'), suggesting a search for analytical advancement and terminological novelty (Table 4). There is a clear *split between the uses of early theoretical and methodological spatial concepts* ('integration', 'axial line') and newer methodological terminology ('choice', 'segment') based on the decrease of the former and the increase of the latter.

Table 4: Scaled frequency of selected concepts per conference year.

Year	1997	1999	2001	2003	2005	2007	2009	2012	2013	2015	2017
metric_radius	0	0	0	0.067	0.348	1.583	1.486	1.399	0.612	0.527	1.598
angular_integration	0	0	0.176	0.448	0.440	0.375	0.591	0.853	1.327	2.033	1.569
integration	1.264	1.268	0.827	1.062	0.942	0.857	0.817	0.893	0.869	0.809	0.698
choice	0.301	0.267	0.810	0.342	0.612	0.948	1.037	1.154	1.342	1.397	1.277
segment	0.166	0.192	0.134	0.311	0.793	1.168	0.800	1.189	1.453	1.177	1.510

Previously defined primarily by axial analysis, increased computational power, *new computational techniques* and the *introduction of angular segment analysis* allowed the field to connect to network science and approaches using network analysis. This trend is indicated by the increasing use of network concepts, like 'betweenness centrality', along with the shift from axial analysis to segment analysis, with the growing exploration of GIS tools and road-centred maps (OpenStreetMap data), which can be downloaded at no charge and are technically comparable to segment maps. Network-related terms are replacing morphological terms. Accordingly, early terms from the Social Logic of Space (Hillier and Hanson 1984) such as 'relative asymmetry' and 'axial map' are consistently less used since the year 1997 (Table 5). Similarly, we identify a decline in topological analysis, i.e. an apparent shift from step-based distance to metric or angular analysis where distance is based on angles independent from

topological steps. This is evident in the less frequent use of the word 'topology' (with the exception of the terms 'topological accessibility', 'topological choice' and 'topological radius'). Angular analysis emerges as a central methodological basis, along with the concepts of 'closeness' and 'betweenness centrality'. Concepts like 'occlusivity' (Benedikt 1979) and 'visibility analysis' form a cluster of their own, as VGA and Isovist analysis becomes more commonly used due to increasing computational power (Benedikt and Mcelhinney 2019); this trend might also relate to the growing role of computational methods and analytics in Building Information Modelling. Here we have examples of the *influence of technology and technical means shaping language use and research focus*, thereby shaping the field itself. Based on these results we can suggest that there is a clear trend to use methodology, technique, technical development and analytical application as the main drive in the field, advancing knowledge through the analytical side of space syntax, but paying less attention to knowledge development through theoretical exploration.

Table 5: Scaled frequency of selected concepts per conference year.

Year	1997	1999	2001	2003	2005	2007	2009	2012	2013	2015	2017
betweenness centrality	0.247	0	0	0.062	0.053	0.136	0.350	0.320	1.439	1.476	2.332
axial map	1.551	0.977	1.155	0.925	1.045	0.978	0.817	0.669	0.832	0.571	0.520
topology	0.729	1.559	0.733	0.632	1.119	1.298	0.904	0.739	0.630	0.867	0.806
topological accessibility	0	0	0	0	0.202	0.172	0	0.348	0.457	1.262	2.830
closeness	0.054	0.133	0.036	0.108	0.548	1.040	0.759	1.197	0.695	1.811	1.677
occlusivity	0	0.176	0.193	0	0.442	0.270	0.476	0.222	0.149	1.141	2.840
visibility analysis	0	0.185	0	0	0.320	0.874	1.588	0.883	1.497	1.238	1.424

As the field opens up to network approaches, there is a *growing recognition of theoretical parallels* of space syntax measures and earlier measures such as betweenness centrality and closeness centrality (Freeman 1977; Sabidussi 1966). These standard network concepts are now explicitly acknowledged by space syntax researchers, suggesting a growing openness towards network analysis in the field. This also seems to be the case with the recent borrowing of concepts in space syntax conference papers, such as 'affordance', 'agent-based', 'entropy' and 'spatial practice' (Table 6). The notion of 'affordance', first introduced in 2001 and continuously rising since 2007, is a concept able to bridge space, cognition and behaviour. After an initial peak in 2003, the concept 'Agent-based' is consistently increasing since 2012 and might be related to Agent-Based-Models (ABM), and trends in other fields that use simulation of behaviour in an environment (Wallentin 2017). The higher frequency of the term might also be associated with the use of the software tool *DepthmapX*. Finally, the concept of 'entropy' is a term that today cuts across many disciplines, from information theory and physics to biology, social theory and urban studies (Gleick, 2011; Hidalgo, 2015; Davies, 2019; Bailey, 1990; Batty, 2014). Its use within the space syntax field might be related to those other fields, ranging from assessing diversity in the environment to describing its levels of order.

Table 6: Scaled frequency of selected concepts per conference year.

Year	1997	1999	2001	2003	2005	2007	2009	2012	2013	2015	2017
affordance	0	0	0.066	1.172	1.296	0.295	0.869	0.647	1.021	1.432	1.608
agent based	0	0.381	0	2.458	0.331	0.846	0.382	0.342	0.847	0.827	1.150
entropy	0.100	0	0.402	0.992	1.668	0.713	0.552	1.141	0.502	1.482	1.226
spatial practice	0	0	0	0	1.498	0.365	0.442	2.118	0.887	1.276	0.724

Previous critiques of space syntax raised concerns about the apparent isolation of the field and risks of a self-referential terminology (Westin 2014, Netto 2016). Assessing these observations requires detailed qualitative analysis of the conference papers utilizing these terms, which is a next step in our research. Nevertheless, the increasing frequency of these concepts suggests the possibility of increasing influence

by other fields. On theoretical grounds, there are relatively few new concepts in the field. Concepts related to the notion of *morphogenesis* like 'generative process', 'spatial law', as well as 'morphic language' and 'description retrieval' are declining after peaks in 2001 and 2003 respectively. In contrast, concepts related to *cognition* ('spatial cognition', 'way-finding', 'visual information', 'visibility', 'visual connection' and 'visual integration') are stable, while concepts related to 'convexity' are declining in use possibly indicating decline of building studies in the area. One exception is the increased use of the concept 'visual control'. Importantly, we can observe a telling decline in use of *classic concepts rooted in social theory and anthropology*, like 'virtual community', 'solidarity', 'encounter', 'social structure', and 'segregated space'. Concepts related to broad definitions about movement ('movement economy', 'natural movement', 'movement pattern') are also losing importance. The increasing use of concepts such as 'human behaviour' and especially 'spatial practice', which seems to be reminiscent of Lefebvre's and De Certeau's works, suggests signs of sociological and behavioural explorations in alternative traditions to the Durkheimian framework proposed in Hillier and Hanson (1984).

Table 7: Scaled frequency of selected concepts per conference year.

Year	1997	1999	2001	2003	2005	2007	2009	2012	2013	2015	2017
spatial law	0	0	3.002	0.284	0.489	0	0.674	0.421	0.123	0.139	0.039
description retrieval	0.219	0	1.205	2.733	0.188	0	0.933	0	0.284	0.107	0.182
visibility	0.518	0.211	0.800	0.888	0.962	1.181	1.327	0.956	1.171	1.063	0.873
visual connection	0.915	1.133	0.420	0.685	1.705	0.838	0.325	0.903	0.543	1.117	1.077
virtual community	2.384	2.024	0.047	0.204	0.234	0.225	0.145	0.025	0.154	0.116	0.099
segregated space	1.864	0.256	1.353	1.602	0.623	0.493	0.184	0.804	0.402	0.531	0.559
movement economy	0.938	2.404	0.322	1.437	0.374	0.441	0.475	0.272	0.455	0.523	0.236
natural movement	1.960	1.486	0.660	1.018	0.499	0.630	0.554	0.548	0.531	0.488	0.839
human behaviour	0.149	0.369	0.410	0.968	1.282	0.601	0.953	0.331	1.256	1.420	1.456
spatial practice	0	0	0	0	1.498	0.365	0.442	2.118	0.887	1.276	0.724

In a way, it is expected that a well-defined set of theoretical concepts guide a research field (Kuhn, 1962), including new methodological developments, but the decrease in usage of such concepts coupled with the increase in the use of methodological and technical terms suggests that a scientific field is developing along more methodological and technical directions. Of course, the extent that this is the case must be subject to further scrutiny. On one hand, the apparent *decline in innovation* of theoretical concepts since 2005 (see Table 3 on the number of newly emerged concepts per conference year) may be seen as a function of the growing stability of a theory as a paradigm, in Kuhn's sense of a theory established around a set of concepts and methodological rules that ensure the coherence of its applications and further theoretical and methodological developments. On the other hand, it might be related to a growing conservatism apparent in the recursive use of its own conceptual terminology and its reproduction as 'normal science', to use Kuhn's words. Alternatively, growing competition from other fields such as network science might have played a role, inspiring space syntax researchers towards technologically driven explorations. Network science offers significant developments in the area of environmental research.

However, from the outset, space syntax provided a new way of describing the socio-spatial dimensions of buildings and cities not simply by representing and measuring spatial relationships through graph analysis, but also by providing a theory of space, one which 'should account for how and why different societies generate different spatial patterns' rather than interpreting a variable (different societies or social patterns) by a constant (one particular instance of behaviour or observable phenomenon). According to Hillier and Hanson, as opposed to analysing space, analysing behaviour and looking at their relationship, a theory of space considers that 'society already pervades those patterns that need to be analysed' while space carries social determination in its very form as object (1984 p. 8). A set of 'postulates' (ibid. p. 95-97) linking different categories and measures of space with social categories in the *Social Logic of Space* established what the authors described as an 'interpretive framework', a

layered and structured set of relationships between spatial morphology, spatial measures and socio-spatial interpretation (ibid.). Therefore, the strength of space syntax has historically lied not simply in its quantifiable and technological aspects, but also in the systemic interrelationship of conceptual and methodological ideas, spatial and social concepts. The rising emphasis on network ideas and methodology at the dispense of theoretical concepts indicates that the link between the theoretical and methodological side of space syntax has been severed defining a technological turn in the field. The larger implication is that when research aiming to explain how space is created for social purposes, whether by design or accumulatively, is solely driven by technological determinism, it makes questions such as *what a good space consists of* nearly impossible, for the simple reason that the answer has the empty force of truism. It is already built into the supposition and hence, is self-evident: technology.

Of course, we must take into account that even new concepts would have to find a high enough frequency to appear among the 6,000 most used words in space syntax, and be included in our analysis. Nevertheless, confirming earlier observations (Griffiths and Netto 2015; Netto 2016), it is reasonable to assert that there is *a clear 'technological turn'* in the field, one in which conceptual ideas increasingly have a 'ghosted' rather than active presence (Psarra, 2009). The next steps of research on the evolution of concepts in space syntax will look into subsets of words, namely the specific networks of theoretical concepts, methodological concepts, and technical terms, in order to see their relationships in more detail. We also expect to assess:

- The emergence of ideas in space syntax in relation to global academic discussions on comparable topics in other fields, such as approaches to street networks (Marshall et al 2018), spatial interaction (Batty et al 2014) and so on.
- The spatial distribution of usage and creation of terms and concepts in relation to geographic contingencies and potential regional intellectual clusters.
- The trajectories of specific terms: how they have emerged or declined, through qualitative analysis of sources.

GLOSSARY

ABM: Agent-Based Modelling
SLS: The Social Logic of Space
TTR: Types-Token Ratio
VGA: Visibility Graph Analysis

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APPENDIX

List of all 287 identified terms and concepts:

A: accessibility, accessibility analysis, accessibility graph, affordance, agent, agent based, aggregation, angular, angular analysis, angular betweenness, angular choice, angular depth, angular distance, angular integration, angular segment, angular step, asymmetry, axial, axial analysis, axial graph, axial integration, axial line, axial map, axial representation, axial structure.

B: background, background network, betweenness, betweenness.

C: centrality, centrality, centrality measure, centrality pattern, centrality value, choice, choice analysis, choice map, choice measure, choice radius, choice value, closeness, closeness centrality, co awareness, co presence, co present, co visibility, cognition, compactness, complex building, complex system, configuration, configuration analysis, configurational, configurational measure, configurational pattern, configurational property, connectivity, conservative, convex, convex analysis, convex map, convex partitioning, convex space, convexity, copresence, core.

D: deformed grid, deformed wheel, depth, depth analysis, depth measure, depthmap, depthmapx, description retrieval, distance decay, dual graph.

E: embeddedness, emergence, encounter, entropy, euclidean distance.

F: foreground, foreground network, foreground structure.

G: gate count, generative, generative process, generic, generic function, genotype, geometrical, global, global accessibility, global choice, global integration, global measure, global movement, global pattern, global radius, global scale, global structure, global system, globally integrated, graph theory, grid condition, grid intensification, grid structure.

H: human behaviour.

I: inequality genotype, integrating, integration, integration analysis, integration core, integration map, integration measure, integration value, intelligibility, intelligibility value, intelligible, intensification, inter visibility, interface, interface map, isovist, isovist analysis, isovist area, isovist field, isovist integration, isovist occlusivity.

J: justified, justified graph.

L: local, local accessibility, local centrality, local integration, local measure, local movement, local structure, locally integrated.

M: macro scale, metric distance, metric integration, metric radius, micro scale, morphic language, morphology, movement behaviour, movement economy, movement flow, movement network, movement pattern, movement potential, multiplier effect.

N: nach value, nain value, natural movement, natural surveillance, network accessibility, network analysis, network centrality, network configuration, network structure, node, node count, non discursive, normalised angular, normalised integration.

O: occlusivity.

P: path, permeability, pervasive, place syntax, point isovist.

R: ra value, radius radius, relative asymmetry, residential activity, residential space, rra value.

S: scale network, segment analysis, segment angular, segment choice, segment connectivity, segment integration, segment length, segment map, segment model, segregated, segregated space, segregation, shallow space, shortest path, social encounter, social integration, social segregation, social solidarity, social structure, solidarity, space occupancy, space syntax, spaciousness, spatial accessibility, spatial behavior, spatial boundary, spatial centrality, spatial character, spatial cognition, spatial configuration, spatial culture, spatial design, spatial hierarchy, spatial integration, spatial law, spatial logic, spatial morphology, spatial order, spatial organisation, spatial organization, spatial practice, spatial process, spatial proximity, spatial relation, spatial representation, spatial segregation, spatial structure, spatially segregated, step depth, street configuration, street network, street pattern, street segment, structured, symmetry, synergy, synergy value, syntactic, syntactic analysis, syntactic measure, syntactic model, syntactic property, syntactic value, syntactical, syntactical analysis, syntactical property, syntax.

T: topo geometric, topological, topological accessibility, topological choice, topological depth, topological distance, topological radius, topological step, topological structure, total depth, transpatial, tree structure.

U: urban configuration, urban grid, urban network.

V: vantage point, vga, vga analysis, virtual community, visibility, visibility analysis, visibility cost, visibility graph, visibility polygon, visitor, visual access, visual accessibility, visual analysis, visual connection, visual connectivity, visual control, visual depth, visual field, visual graph, visual information, visual integration, visual relationship, visual step, visually integrated.

W: way finding, weak tie, weighted choice.