MASTER THESIS

Generative planning decisions

for informal settlements based on space syntax

ausgeführt zum Zwecke der Erlangung des
akademischen Grades eines Diplom-Ingenieurs

unter der Leitung

O.Univ.Prof. Dipl.-Ing. Dr.phil. Georg Franck-Oberaspach
Dipl.Ing. Dr. Gabriel Wurzer

E259.1
Institut für Architekturwissenschaften
Abteilung für Digitale Architektur und Raumplanung

von

Michael Vasku, BSc
0525848

Wien, am 2.11.2012

Abstract

Space syntax is supposed to be an objective method for evaluating spatial configurations. As it is just an evaluation, its contribution to a design process is dependent on the designer's estimation. If its aim is to lead to specific results defined by the space syntax theory, designers have to patiently figure out what changes they have to make in order to achieve these requirements. This thesis describes a generative approach to finding particularly good interventions based on space syntax analyses of axial maps representing any given urban street network.
The space syntax theory provides the theoretical background for this research. More precisely, a case study was undertaken through applying such a strategy to improve and connect a segregated street network of an informal settlement to its neighborhood. Controlling and redirecting movement in slums may cause positive effects. Combined with other remedial actions, conditions in slums can be sustainably improved. This idea approach is based on and inspired by a consulting project by the company Space Syntax Limited, a spinoff company created by the University College London (UCL). On behalf of the Municipality of Jeddah, Saudi Arabia, the consulting company designed a regeneration program for declining informal settlements. (Karimi ans Parham, 2012)
In the case study, the proposed generative method is applied to an informal settlement in Jeddah - that exact area was then redeveloped during the consulting project.

Motivation

In numerous case studies, Space Syntax proofed to be an effective method to understand, reconstruct and predict movement in urban layouts. (Hillier 1987; Peponis, Hadjinikolaou, Livieratos and Fatouros 1989; Hillier, et al., 1993; Peponis, 1997) Several case studies that investigated issues -important when dealing with informal settlements - were published, as social formations (Peponis 1985, Hanson and Hillier 1987, Hillier 1989) or social settings of housing developments (Hillier, Burdett, Peponis and Penn 1987, Hillier, Hanson and Graham 1987). Further topics were handled as attempts to explain the distribution of crime and pollution in urban areas (Hillier 1988).

Due to this background, space syntax is not only used for scientific reasons but also to predict, qualify and quantify qualities on design proposals and the impact on their neighborhoods. Therefore several design projects already incorporate space syntax during the design process stage (Dursun 2007) by designing and adopting different design alternative and continually testing them in order to gain desired results in the space syntax analysis. Designers jump between designing and evaluating and oftentimes layouts demand several iterations. Furthermore, it is not an easy task to figure out the right changes in weight.

A space syntax analysis is an automatically processed computation, which resembles usual analyses in other fields as for instance in physics. In recent years, it has gotten increasingly more common to optimize architectural designs on behalf of physical characteristics, be it because of wind, solar exposure or sound propagation. The author is not aware of any example nor of any attempt of using space syntax to drive a generative process. The intention of proposing a method doing so is not to make a designers work redundant. It is a technocratic approach that allows the finding of a good result in terms of a mathematical evaluation – an evaluation that shows such immaculate results that would be unlikely to find through design drawing methods preformed by hand.

There are several cases in which the knowledge of an improved scenario might be useful. A case study, which improves the urban structure of an informal settlement in Jeddah, Saudi Arabia, was chosen to show a particular task formulation. The theoretical background of improving situations in slums with the help of space syntax was mainly formulated by Karimi and Parham (2012) and Karimi et al (2007).

Informal settlements

In 2010, half of the world's population was living in cities. Between 2010 and 2020, 95% of the global population growth (766 million) will be residing in urban areas (690 million).
Recent estimates suggest that 32.7% of the world's population is living in slums, whereas in 2005, there were 998 million slum dwellers in the world; if current trends continue, the slum population will reach 1.4 billion by 2020. (UN-HABITAT, 2007, vi)

A precise distinction between the terms "informal settlements", "squatter housing", "unplanned settlements" and "slums" is not of importance for this thesis. A 'squatter' lacks land tenure; a 'slum' lacks space, durability, water or sanitation, while 'informal' implies a lack of control over planning, design and construction. Their characteristics, function and appearance as well as their negative and positive aspects are often similar.

The United Nations Human Settlements Programm (UN-Habitat) defines "slums" on page 21 in its "State Of The World's Cities Report 2006/7" as following:

> Slums are settlements in an urban area in which more than half of the inhabitants live in inadequate housing and lack basic services. Developing an operational definition – one with measurable indicators – required further refinement, recognizing that slums can be geographically contiguous or isolated units. UN-HABITAT therefore focuses on the household as the basic unit for an analysis.

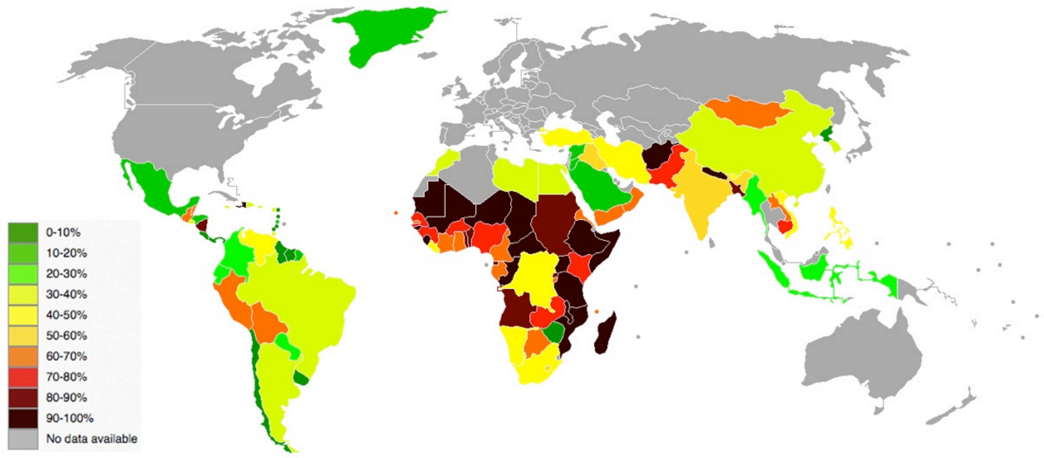


Figure 1: Proportion of each country's urban population living in slums. Data from UN-HABITAT, Global Urban Observatory, 2001 estimates; source: http://commons.wikimedia.org/wiki/File:Ficheiro-Urban_population_living_in_slums.png?uselang=de

Due to the UN-HABITAT Report, a slum household is defined by a group of individuals living under the same roof in an urban area that lacks one or more of the following five conditions:

Durable housing:	A house is considered "durable" if it is built on a non-hazardous location and has a structure permanent and adequate enough to protect its inhabitants from the extremes of climatic conditions, such as rain, heat, cold and humidity
Sufficient living area:	A house is considered to provide a sufficient living area for the household members if not more than three people share the same room.
Access to improved water:	A household is considered to have access to improved water supply if it has a sufficient amount of water for family use, at an affordable price, available to household members without being subject to extreme effort, especially on the part of women and children.
Access to sanitation:	A household is considered to have adequate access to sanitation if an excreta disposal system, either in the form of a private toilet or a public toilet shared with a reasonable number of people, is available to household members.
Secure tenure:	Secure tenure is the right of all individuals and groups to effective protection against forced evictions. People have secure tenure when there is evidence of documentation that can be used as proof of secure tenure status or when there is either de facto or perceived protection against forced evictions.

This definition helps to identify slum areas, but also runs the risk to limit the efforts of regeneration and sustainable urban development to this set of criteria. Furthermore, it should not be concluded that areas that fulfill some of the household conditions but lack the remaining ones, do not need any treatment.

Responsible interventions should care about reasons that lead to the listed conditions, to prevent the progression of urban decay in areas that have not qualified as slums just yet. Reasons that lead to enormous deficits in governance, infrastructure, and economic and social equity are:

- High density
- Lack of spatial order (quantity and quality of infrastructure)
- Lack of access (evacuation and emergency vehicle access)
- Lack of public facilities
- Hazardous locations
- Advantageous locations (employment, low travel costs)

Emigrants to the overstressed cities are forced to live in dangerous areas. Many construct their houses by themselves and form informal settlements in places like floodplains, swamp areas and unstable hillsides - areas, which do not qualify enough for real estate or industrial development. Due to the lack of industrial interest, infrastructure is inadequate to non-existent and lack of basic services to support human life, safety and development is prevalent. Thus, the only land accessible to slum dwellers is often fragile, dangerous or polluted. Slums are often recipients of the city's nuisances, including industrial effluent and toxic waste. Instead of helping them to improve, local governments oftentimes put blame on slum dwellers accusing them to be responsible for their poor living conditions.

The global report on human settlements titled “The Challenge of Slums” (2003) addresses the negative aspects. Exploring the previously mentioned characteristics of slums, the report covers consequences caused by high concentrations of poverty and social and economic deprivation, which may include broken families, unemployment or economic, physical and social exclusion. Due to stigmatization, slum dwellers suffer from discrimination and geographic isolation that lead to limited access to better jobs. Women and children suffer the most from these circumstances. Water-borne diseases such as typhoid and cholera as well as more opportunistic ones that accompany HIV/AIDS are extremely common. Slum areas are also commonly believed to have high crime rates, however, this is not universally true, as many slums show strong social control systems.

The report addresses positive aspects as well, which should not be ignored. Yet, they should not justify the existence of slums and be taken as an excuse for the slow progress in achieving the goal of adequate shelter for all. Slum areas provide low-cost and the only affordable housing to most, while enabling immigrants to enter urban society. Their vivid economic activity and proximity to city centers provide big advantages over the subsistence farming that many slum dwellers have fled. Many informal entrepreneurs operate out of slums and provide services to clients throughout the entire city. The enterprising spirit found in these places, which is among other things evident in the countless tiny businesses, can be seen by the constant upgrading and the expansion of houses. Most slum dwellers struggle to make an honest living, without considering their poverty and unemployment. In cities in developing countries, the majority of slum dwellers earn their living from informal sector activities located either inside or outside slum areas. Slums allow the mix of many different cultures, which leads to new forms of artistic expression. Longstanding slum communities tend to be much more tightknit than many prosperous parts of the developed world, where neighbors hardly know one another.

> *"Out of unhealthy, crowded and often dangerous environments can emerge cultural movements and levels of solidarity unknown in the suburbs of the rich."*
>
> (Anna Kajumulo Tibaijuka; UN-HABITAT, 2007 page vi)

Among architects, planners and theorists there is a growing realization that slums posses unique social strengths. They seek reasons in the spatial environment and find examples of successful urban development. Slums embody many of the principles frequently demanded by urban planners: They are accessible, of high-density, and of mixed-use. Buildings are often made of materials that would otherwise land on dumpsites, which is why some claim that slums are to exceptionally ecologically friendly to some extend. Some countries have begun trying to mitigate the problems with slums rather than to eliminate the slums themselves.

Some even demand that slums should prompt the rest of us to reconsider our own cities. A few designers even try to emulate these urban areas. Exempli gratia: architect, Teddy Cruz, has taken the shantytowns of Tijuana as an inspiration for his own designs. He is currently working on a development in Hudson, N.Y., that draws on their organically formed density. (Ouroussoff, 2008)

Improving conditions in slums

Informal settlements became relevant for the municipalities of the cities they are in, when designers realized that ignoring them and leaving them to take care of themselves was no longer an option, just as little as expelling slum dwellers or constructing new developer superblocks combined with a little city beautification. Improving slums by addressing the household conditions listed by UN-HABITAT requires an enormous budget. Actually no city in any developing country meets this expenditure, which is the reason many countries have almost abandoned concerning themselves with their slum areas. But addressing (solely) the household conditions would not lead to a sustainable improvement anyway, as one would only address the effects but not what causes them. It would only alleviate the current conditions, but would not necessarily stop the process returning to slum conditions after a period of time.

There is another much less costly and interruptive approach that is favored by various institutions like Non-Governmental Organization and international aid agencies, which is independent from authorities. By helping people to help themselves, living conditions will improve and slums will fix themselves at their most basic level. Yet still, slum upgrading involves improving the physical environment of slums. This includes improving or installing basic infrastructure as for example water, sanitation, solid waste collection, access roads and footpaths, storm drainage, electricity, public lighting, public telephones, etc. Upgrading also demands the regularizing security of land tenure and promoting home improvement, as well as improving access to social programs (e.g. health, education, child care), transportation and municipal services.

The World Bank published a study in 2003 as part of the World Bank's Directions in Development series, called "Slum Upgrading and Participation: Lessons from Latin America" (Imparato and Ruster, 2003). It presents the results of an investigation on participatory strategies in slum upgrading, provision of services for the urban poor people and low-income housing initiatives in areas of urban poverty in Latin America. The book aims to provide practical, hands-on guidance to local officials and policymakers (urban planners, municipal managers, and social sector workers) - people who are confronted with the task of designing and managing slum upgrading, shelter programs and projects at local scales.

> *On the other hand, in recent years new forms of partnership with civil society have become increasingly common. Such organizations as development and environmental NGOs and professional associations (of engineers, architects, or lawyers) are showing increasing capacity and a more professional attitude. Groups based on ethnicity, like black or indigenous movements, are also on the rise. Although with different motivations, many of these groups purport to speak for the sectors of the population that stand to benefit from urban upgrading and low-income housing programs.*
>
> Imparato and Ruster, 2003, page 255

At first glace, this approach seems promising, but in reality this concept does not work efficiently and by far too slowly, due to the vast deteriorated areas. Even the authors of the World Bank's report on slum upgrading mentions this position. (Berner, 1997, page 31 as cited in Karimi and Parham, 2012, 8151:3)

The Space Syntax approach

Space Syntax Limited, a spinoff company by University College London (UCL), suggests their own new approach that aims to create a condition to allow informal settlements could self-correct themselves. The method was developed during a commissioned consulting project for the Municipality of Jeddah, which led to a regeneration framework for deteriorating unplanned settlements based on the space syntax theory. The aim is to turn the "vicious circle of urban decline" observed in informal settlements to a "virtuous circle of regeneration". The difference to the previously mentioned slum upgrading strategy is explained as follows:

> *"The very inherent problem in the concept of self help is that it does not try to identify the fundamental reasons that turn an area to a slum; it rather focuses on remedying the conditions by enabling people, assuming that by doing so problems will be resolved by themselves. In reality, both ends of the spectrum, the total elimination or pure self help approaches, lack rigour, evidence and a supporting urban theory, which is needed for creating a fundamental approach."*
>
> Karimi and Parham, 2012

With the help of an urban theory - space syntax – the consulting company tried to objectively evaluate the links between the physical manifestations of the city with it socio-economic attributes. This issue is actually what the theory was designed for in the very beginning (Hillier and Hanson, 1984; Hillier, 1996). The link between society and organically formed urban environment has been shown in previous research on urban issues (Vaughan, 2007; Hillier and Vaughan, 2000; Penn and Turner, 2004; Karimi, 1998).

Informal settlements are settlements that are shaped for reasons and the way they are shaped reflect what they are. Urban areas, as they grow, develop two types of structure: an internal – or local – structure, which facilitates the local functioning of the area; and an external – or global - structure, which enables them to interact productively and efficiently with the rest of the city (Hillier, 1996, pp. 343–4). The strength of each of these structures, and in fact the balance between these two, determines the overall performance of an area. In reality the problem of slums does not begin with a physical manifestation, such as informal or unplanned growth; it rather begins with socio-economic forces. Poverty, migration, economic devastation, rapid growth, failing economies, and other reasons of this kind create a particular group or class of people, who have to find somewhere in the city to live: quickly and very cheaply. The obvious result is that these people tend to move to the most undesirable areas of the city. The urban swamps, transport residual lands, steep slopes, flood plains, old parts of the city, villages trapped by the rapidly-growing city (Dovey and King, 2011; Anyamba, 2011), as well the old or historic centres of the cities, are the types of areas that are chosen by these people (Patwari, Tang, and Mitchell, 2010). In most cases these areas have certain characteristics in common: they are segregated within the global urban structure (while they maintain an active edge in some cases), they have a problematic local system, and badly lack infrastructure (Dovey and King, 2011)

Karimi and Parham, 2012

In Karimi (2012), the author argues that although informal settlements are organically formed, their internal structures show several problems and are segregated areas within a global structure. They do not show similar qualities as organic cities do, which were developed over a long period in the past. Informal settlements are shaped too quickly, lacking time and economic conditions to create the kind of attributes that may induce a self-correcting opportunity. On the one hand, the author points out insufficient social and urban facilities, the lack of public space and an inefficient network for movement causing poor accessibility. On the other hand, these exact areas are populated by social classes, which do not have the means, power or even knowledge to improve these conditions. If municipalities ignore these areas, they are not considered in citywide planning decisions. This makes the internal spatial structure consistently weaker and external segregation increasingly stronger. Karimi 2012 identifies this situation as a 'vicious circle of decline' penetrating slums anywhere in the world.

The reality is that poverty and economic deprivation have always been and are very likely to stay with us for a long time. Designers, planners, community workers and to some extent even local authorities, cannot control the main social forces behind poverty and deprivation; what could be controlled, or at least be challenged, is how they manifest themselves in the built environment. This paper has no intention of finding solutions for eradicating poverty. Instead, it hypothesizes that by a deep understanding of declining informal settlements, be it a slum or not, we can develop solutions that could lead to a process of regeneration based on adaptive corrections of the fundamental problems of slums. These fixes, which have mainly a spatial nature, will lead to initial improvement in socio-economic aspects of the life in these areas, and in return will generate better spatial conditions. The better spatial conditions will encourage/enable the residents to improve their socio-economic status further, or will attract social classes that could contribute more to this improvement. The continuation of this circle will create a positive process, or a 'virtuous circle of regeneration', which in the longer term could permanently improve the household conditions that define an area as a slum.

Karimi and Parham, 2012

The suggested approach described in Karimi 2012 basically uses space syntax to identify the structural segregation and therefore enables an efficient design of interventions and scenarios that opposes the "spatial discrimination".

After the following introduction to the space syntax theory, there will be a more detailed description of this approach applied to declining informal settlements in the city of Jeddah.

Introduction to

Space Syntax

Space syntax is a terms that describes a set of theories, which investigate the relationship between spatial layouts and the inhabitants producing and using them rather than the relationship between space and an individual subject (Hillier and Hanson, 1984). The theory deals with topologically derived configurations from layouts and offers techniques that allow the environment to be considered as independent variables in different kinds of research. Configurational measures are applied to units of space represented by geometric elements that are created by parts of buildings, whole buildings and entire cities. The approach has no limits in scale and can be applied to large urban scales as well as to buildings scales or even to a detailed ground plan respecting its exact geometric properties. Depending on what aspect of functionality - what aspect of human spatiality – is subject to investigation, lines, convex spaces, isovists, or points are the elements for the analysis calculation and visualization.

Background

Starting in the 1970's, Space Syntax was initially a research program, developed by a team led by Professor Bill Hillier in the unit of Architectural Studies at the University College London.
The theory was published in two books:
"The Social Logic of Space" (1984) by Bill Hillier and Julienne Hanson and
"Space is the Machine: a Configurational Theory of Architecture" (1997) by Hillier .

The original intention of the space syntax research was to remark architectural changes, which began to appear in cities, especially in London, in the 1960's. The research group investigated a paradox, or what they thought was one: the contradiction between London's striking architecture and the discomfiting and un-urban nature of its spaces.
Since then, Space Syntax has grown to become an independent research area with an active international community.

Right from the beginning, Hillier stated that any good theory of architecture should have descriptive and evaluative components and preferably be applied and used for various purposes. Several case studies that investigated issues that were important for dealing with informal settlements, were published, like social formations (Peponis 1985, Hillier 1989 and 1995) or social settings of housing developments (Hillier, Burdett, Peponis and Penn 1987, Hillier, Hanson and Graham 1987). Further topics were handled, as for instance attempts to explain the distribution of crime and pollution in urban areas (Hillier 1988) or even the (informal) communication causing higher productivity in various buildings. (Choi, 1999; Penn, Desyllas and Vaughan 1999). Perhaps most importantly, it proved to be a method for predicting natural movement in urban areas (Peponis, Hadjinikolaou, Livieratos and Fatouros 1989; Hillier et al. 1993;) Investigating the possibility that Space Syntax could be a predictor of environmental cognition, researchers have begun to demonstrate that Syntax variables correlate with human spatial preferences (Peponis et al. 1990; Haq 1999).

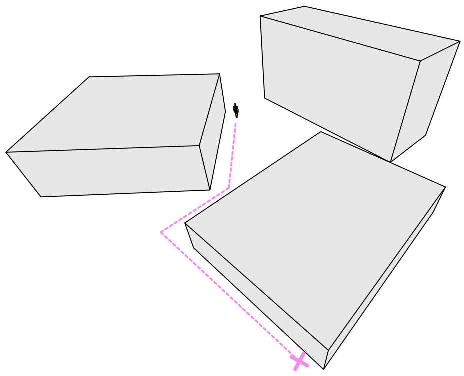
To the author, this approach has also always been an opportunity to physically describe a metaphysical impression of the experience of space. "Intelligible layout" a property discussed in Space Syntax literature, describes properties leading to an intuitive understanding of configurations (Hillier, 1996, pp.40). Although space syntax does not cover more complex processes of the human mind, it implies that this understanding is 'non-discursive'. It can be understood but not described. (Hillier, 1996, pp. 38)

Foundations

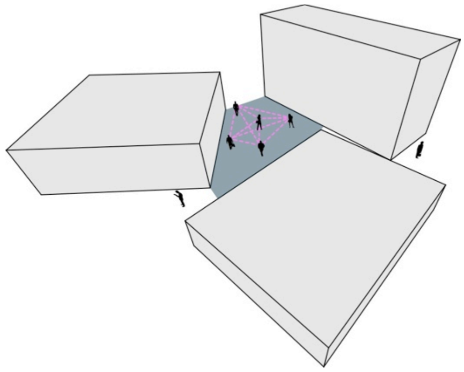
At the beginning of this research, there was the observation that streets and urban void are the common ground of both, the physical geometric property and social (inter-) activity.
One could compare this understanding to the one of Giambattista Nolli who drew a map of Rome in 1748. His map, known as the Nolli Map, provides an immediate and intuitive understanding of the city's urban layout using the simple graphic method of rendering solids as black and voids as white. In addition, Nolli extends the visualization of exterior urban space to the interior space of public buildings. Doing this he presents the city's topographic and geo-spatial structure, the patterns of private and public buildings, and their relationship to the entire urban ensemble.
Social activity in cities can be understood as recursive patterns. There is a two-way relationship between space and its users: a society does not only create the spatial systems that it uses, but it is also directly affected and influenced by the spaces it inhabit - be it the inhabitants of a settlement, an urban neighborhood or the users of a complex building. Some of the influences were even caused by various social and political circumstances.

There are three principles expressed with geometry, which describe different aspects of how people interact with their surrounding. These three basic assumptions are preliminaries, on which the space syntax theory is based and through which it tries to reveal the organization of space, buildings and cities.

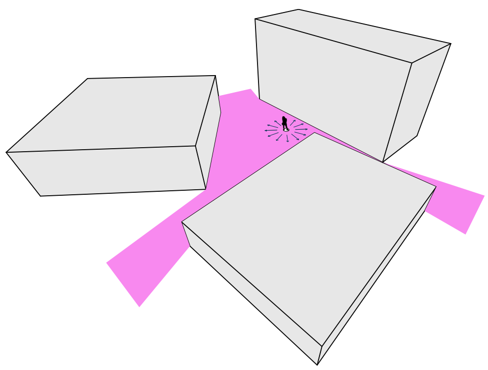
> *Space syntax is built on two formal ideas, which try to reflect both the objectivity of space and our intuitive engagement with it. The first is that we should think of space not as the background to human activity, as we think of it as the background to objects, but as an intrinsic aspect of everything human beings do in the sense that moving through space, interacting with other people in space, or even just seeing ambient space from a point in it, all have a natural and necessary spatial geometry: movement is essentially linear, interaction requires a convex space in which all points can see all others, and from any point in space we see a variably shaped, often spiky, visual field we call an isovist (Benedikt 1979).*
>
> Vaughan 2007, page 208



Lines:
The shortest connection between two points. People move and think in lines. Cities mainly follow the concept of linear logic: streets, boulevards, avenues and alleys



Convex spaces:
People interact in convex spaces. When streets meet to create public squares, they mostly create convex space. Public urban space is basically there for human interaction, as trading and entertainment. Squares use to be convex shapes, as people cannot interact when they do not see each other



Changing visual fields:
Organically grown urban layouts hardly show a regular grid structure. This leads to constant changing properties of the visual fields as observers move around an environment. Visual fields are also named 'isovists', which were first described and analyzed by Benedikt (1979).

Space Syntax describes spaces using these three geometric concepts and sets them into relation. The relation between each space to all other spaces within a system is called spatial configuration.

Spatial configuration

It is its own spatial description concept, which provides relative comparative measurements between one space and all other spaces. Space is not just about the properties of one individual spaces, but about the relations between the observed space and the many spaces that make up the spatial structure of a system, be it a building or a city. Space Syntax is a theory about understanding and describing architecture and urban space by its configuration – the simultaneously existing relations amongst the parts, which make up the whole. Configuration is mostly expressed by color.

Applying different algorithms enables statistical comparison between values assigned to every space. These values relate to cultural properties, investigating social phenomena, its causes and consequences.
In space syntax terminology, a spatial configuration is the representation of a spatial relation, wherein each relationship affects and is affected by either all others or a predefined size of its neighborhood. From this it follows that any modification of any single spatial relation will have an effect on the whole configuration or at least a major part of it. Depending on what aspect of human spatiality is investigated, a certain size of an influencing neighborhood is chosen.

> *"Configuration refers to the way in which spaces are related to one another, not only pair-wise but also with respect to the overall pattern that they constitute. In other words, configuration is about the overall pattern that emerges from pair-wise connections rather than elements or single connections taken by themselves"*
>
> Peponis, Zimring and Choi, 1990, p556

At this point it is crucial to point out two key-properties of configuration. The first is that depending on the observer's position, a (complex) system seems different. The second property is that small changes in the spatial system might affect the structural properties of the whole. Both statements will be explained in detail later.

Every time the word "spatial configuration" is described in Space Syntax literature, it is stated that language is not strong enough to describe it. Words we use to describe spatial relationships - at least in the English language – for example, 'adjacent' and 'between' (Dalton and Hölscher, 2006, page 3) are not sufficient to describe a more complex spatial relationship.

This also might lead to the idea that configuration is non-discursive, due to its intuitive nature: people cannot explain it, but they can understand it:

> *"However, the fact that our minds recognised configurations as being the same even when there is no name at hand to link them shows that our ability to recognise and understand configuration is prior to the assignment of names. Configuration seems in fact to be what the human mind is good at intuitively, but bad at analytically. We easily recognise configuration without conscious thought, and just as easily use configurations in everyday life without thinking of them, but we do not know what it is we recognise and we are not conscious of what it is we use and how we use it."*
>
> Hillier, 1996, page 27-28

Since configuration is non-discursive but intuitively grasped, there is a need for a diachronic experience in order to understand spatial configuration in real life. Series of sequential experiences can be gained through movement. Movement is a measurable unit in which a pattern of spaces affects its users.

Movement

Space Syntax offers the possibility to explain, simulate and predefine human movement in layouts. The fundamental proposition of the theory is, that the configuration of the urban street network is in itself a major determinant of movement flows. This implies that topological and geometric properties are crucial for people's movement in urban layouts. There are several published studies and papers investigating this statement as well as listing exceptions. (Hillier et al (1987), Hillier et al (1993), Chang and Penn (1999) and Penn et al (1998)).
Movement flow is the basis to spot the concentration of people. Human co-presence enables higher social phenomena – or in more simple words: quality of urban space is the co-presence of a critical amount of peacefully interacting people.

A parallel was drawn between aggregate human behavior and emergent statistical effects from the structure of line networks. One might think that metric distances are the basis for navigational calculation, as conventional urban modeling assumes. Contrary space syntax research results have shown, that a metric distance assumption is unrealistic in cognitive science. People's notion of distance is undercut by the visual, geometrical and topological properties of spatial networks.

> *For example, estimates of distance have been shown to be affected by the division of routes into discrete visual chunks (Golledge 1992, Montello1997, Kim 2001), by a tendency to correct bends to straight lines and turns to right angles (Allen 1981),and even by the direction in which the estimate is made (Sadalla, 1980, Montello 1992, Golledge 1995). As a consequence, much current cognitive work on spatial complexity explores how far route choices reflect the frequency (Duckham 2003) or degree (Conroy-Dalton R 2001, 2003, Hochmair 2002) of directional change, rather than metric distance, reflecting current choices in space syntax.*
>
> Bill Hillier and Shinichi Iida, 2005

Graphs in Space Syntax

The foundations of graph theory were laid in 1736, when the mathematician Leonhard Euler considered the problem, whether there existed a closed walk that crossed exactly once each of the seven bridges of the river Pregel. (*Figure* 2) Due to this incident this historically notable problem in mathematics is commonly known as the "Königsberg bridge problem". In mathematics and computer science, graph theory is the study of graphs, which are mathematical structures used to model pairwise relations between objects from a certain collection. In particular, it involves the ways in which sets of points, called vertices, can be connected through lines or arcs, called edges.

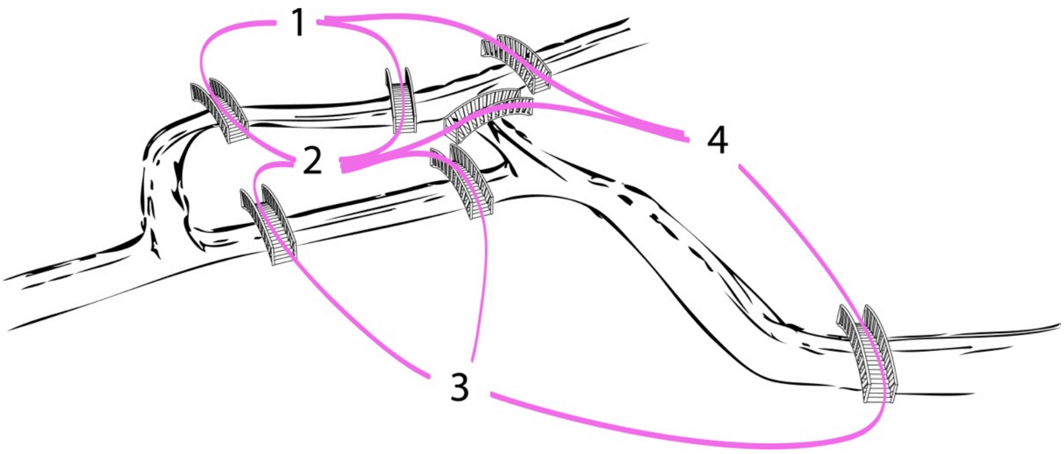


Figure 2: scematic graphic of the seven bridges of Königsberg

The key method in space syntax theory for evaluating a spatial configuration is a technique based on mathematical graphs. Although the application of graph representations to urban or social problems is widely known, the way they are used in space syntax is quite unique. Network graph analysis enables to identify more and less strategic positions within a system. More accessible spaces tend to attract a higher rate of pedestrian movement than more segregated ones. Relative rates of flow can be predicted based on graph analysis. Based on research cases that proved this, there is a relationship between these strategic positions and people's movement. In space syntax literature this relationship is called spatial structure.

There is a long tradition of research articulating urban form using graph-theoretic principles. Nystuen and Dacey (1961) developed such representations as measures of hierarchy in regional central place systems, while Kansky (1963) applied basic graph theory to the measurement of transportation networks. Graphs are implicit in the definition of gravitational potential based on the weighted sum of forces around a point first applied to population systems by Stewart (1947), and subsequent work on identifying accessibility as a key determinant of spatial interaction is based on an implicit graph-theoretic view of spatial systems (Hansen, 1959; Wilson, 1970). The widespread use of network analysis in geographic science reviewed by Haggett and Chorley (1969) establishes such analysis as central to spatial analysis. In a similar manner, graphs have been widely used to represent the connectivity between rooms in buildings (March and Steadman, 1971) and to classify different building types (Steadman, 1983). They have long been regarded as the basic structures for representing forms where topological relations are firmly embedded within Euclidean space.

Batty, 2004

Justified graphs

The easiest way to explain the concept of justified graphs is by using a visual example. *Figure* 3 shows a simple ground plan of a house. Below the ground plan, there is a graph, which represents the accessibility of the individual rooms. This graph is called an access graph, in which each circle (vertex) represents a room and each linking line (edge) represents a door. Neglecting the geometrical layout, the graph is then rearranged, without changing its structure. To create a justified graph from the perspective of node number 2 (that means from outside the house), every vertex number accessible from vertex No. 2 is aligned in the row above it, that is the room represented by node Nr. 3. The same is done for that position and needs to be repeated until there is no vertex left.
The result is a justified (access) graph. It represents the accessibility of all other rooms starting in room Nr.2. It relates to the situation of someone standing outside the house thinking about the options where to go and how to get there.

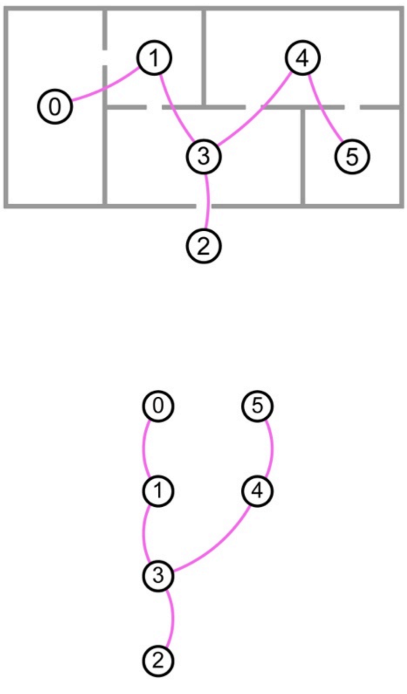


Figure 3 justified graph:: graph vertices represent rooms in buildings

An observer's position

As stated before, two properties of configuration are taken to be crucial. The first is that depending on one's position, a complex system seems different. In other words: a spatial configuration is different when seen from different points in the layout.

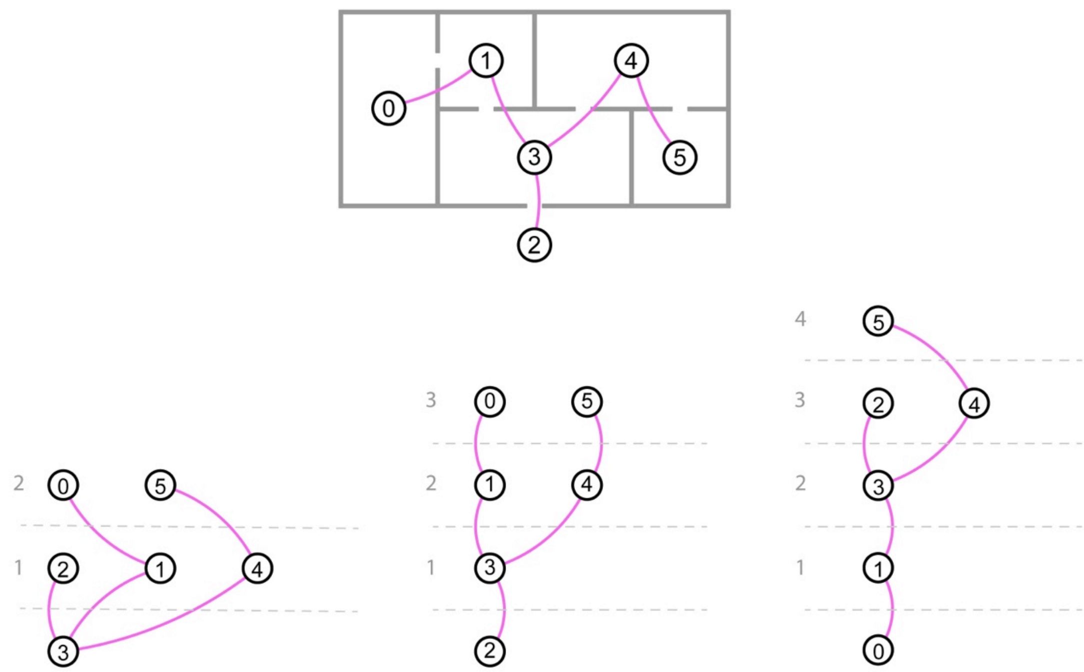


Figure 4 justified graph: spatial units assigned to graphs: graph vertices as room in buildings

Getting back to the example explaining the justified graph concept, a justified graph is created from the point of view from room Nr. 3 and one from room Nr. 0. Comparing the justified graphs shows that the graphs look all quite different. One is shallow and one is deep, while having the same structure. One can do this for each room. Each graph gives a different picture of what the layout looks like from each space. This is used to express the real property of a layout.

The alignment of a justified graph helps us to measure a position's integration. This visualization of each graph shows clearly the amount of steps we need to take to get from a particular space to another. This will be high or low according to whether we have a shallow graph (graph from vertex No. 3) or a deep graph (graph from vertex No. 0). The property that the graph from a space is shallow is called integrated, and the property that it is deep, segregated. Each space in the layout is measured in terms of its integration, which is expressed by a value. The relationship between all these values is then highlighted by color. This allows searching for patterns visually - therefore made more intuitively. Colors are assigned to numerical values, derived from a quantification algorithm. A color gradient, similar to a heat map is used, that colors the elements compared depending on their value starting from red to yellow, from green to blue. In *Figure* 5 total depth measurement values are used for coloring.

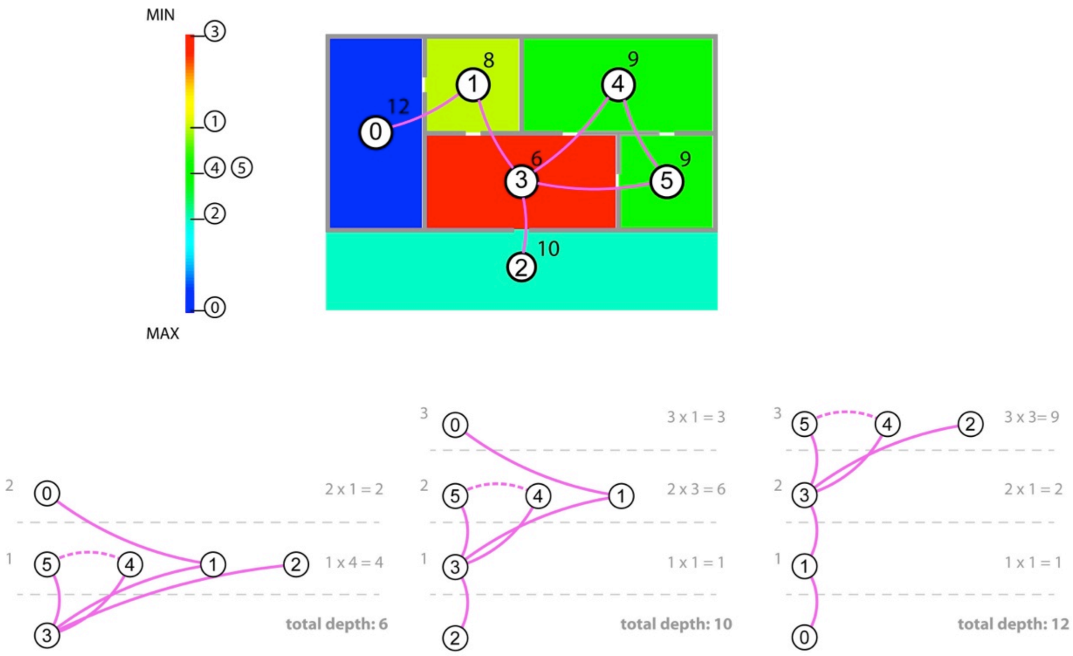


Figure 5: spatial configuration expressed with color based on total depth values

Visualizing a graph's property by color helps to understand and compare different graphs. The paper "The hidden geometry of deformed grids" by Hillier (1999) shows the necessity of the colorizing strategy, as graphs cannot be intuitively understood. (*Figure* 6)

"One place where we are unlikely to find the answer is in the nature of graphs themselves. They are the least geometric of entities. Consider the set of small graphs shown in figure 5. Even though the ten graphs are very simple it is very far from obvious that the graphs are all the same. We are deceived by the geometric differences into thinking that the graphs are different. Even after it has been said that the graphs are all the same it is painfully difficult to try to trace through the relations in each graph to check whether or not this is the case. And these are very simple graphs."

Hillier, 1999, page 178

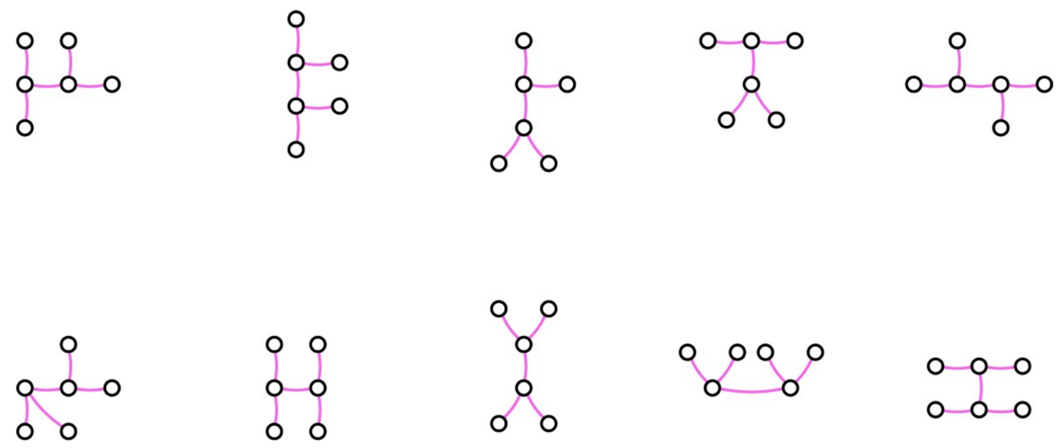


Figure 6 no intuitive understanding of graphs

Hillier B., 1999, "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; p 179

Changes in a system

The second property of configuration is that even minor changes in any part of the spatial system will affect the structural properties of the whole.

Looking again at the ground plan shown before to explain justified graphs, a door between room 3 and 5 is added (*Figure* 7). When constructing the new justified graph and comparing it to the one from the previous example, we see major changes in their structure. The whole system appears very differently from the same position due to this small change.

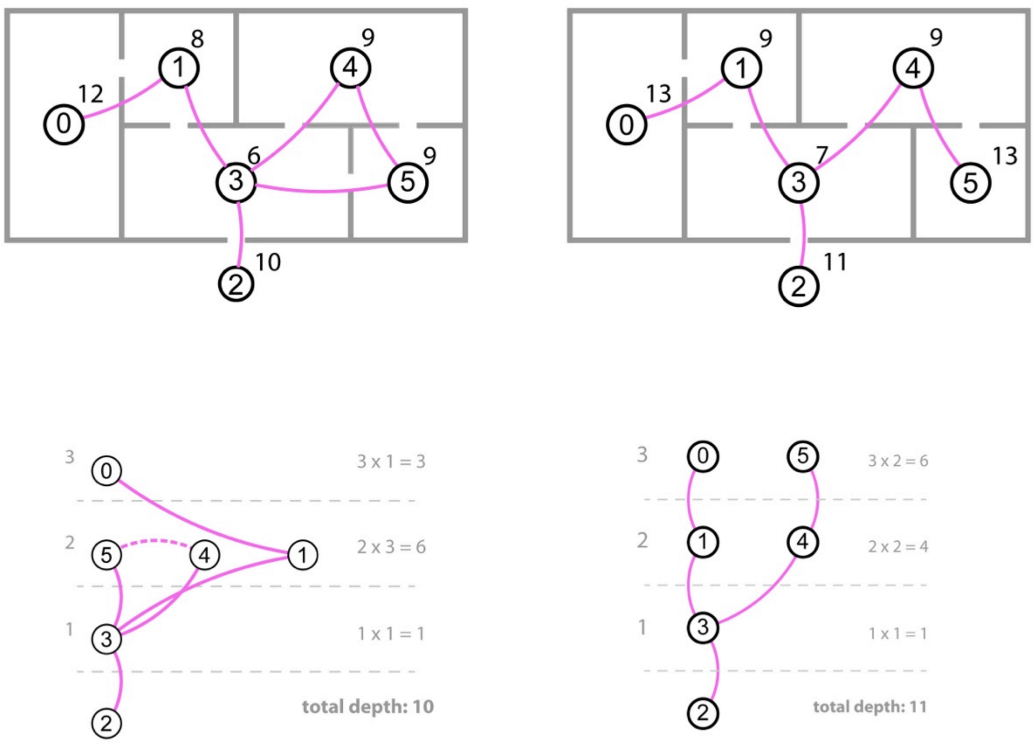


Figure 7: local changes in a system cause global effects

Topological units of space

The configuration of a spatial layout is described in terms of the pattern based on connections between defined 'units' of spaces. The difficulty but crucial criterion for such spatial units is that they have to represent measureable, comprehensible and comparable topological values, as they are later put into relation to others within a configurational system. Choosing the right spatial units for an analysis is crucial for success, as the whole theory is based on it. Therefore, this often serves to be the subject of discussion and the source of criticism of this theory.

Basic Syntax theory proposes three conventional ways of breaking up a layout into its constituent spaces: node analysis, convex spaces and axial lines. Segment lines resulted from pursuing research on axial lines and led to a road-center lines representation. There is also a more advanced method of choosing spatial units that measure visual stability based two-dimensional representation of space. This method is called 'visual graph analyses' (VGA).

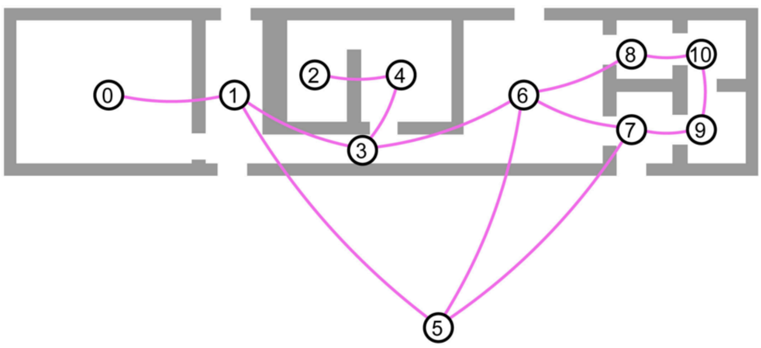
Most real spaces can be analyzed by any of these approaches. However, as the different kinds of modeling capture different aspects of space, it is the matter of the subject of interest, which one is appropriate to be used in a particular case.

The different concepts of spatial units are discussed in this chapter.

Node analyses

Node analysis is the most straightforward approach and particularly suitable for studying dwellings. The vertices of the graph, where the calculations are applied to, represent an entire room within a layout, while the edges represent usually door-like connections between them. Figure 8 shows a possibility of shaping a spatial configuration pattern of a society's culture, by assigning configurational meaning to functions in a layout. One can identify cultural commonalities or differences, as integration values for different functions within a layout can be compared.

> *For example, at the simplest level, we can show how cultural differences are expressed through the layout of rooms in domestic space. If we take the French farm house in Figure 1.3, we find the salle commune (the space of everyday living and reception of informal visitors) is the most integrated internal space and the grande salle for formal reception the one of the most segregated, along with the bureau of the male owner… We also find that the salle commune lies on all rings of circulation, so that if you remove it, the layout becomes virtually a single sequence of spaces.*
>
> Hillier and Vaughan
> The City as One Thing



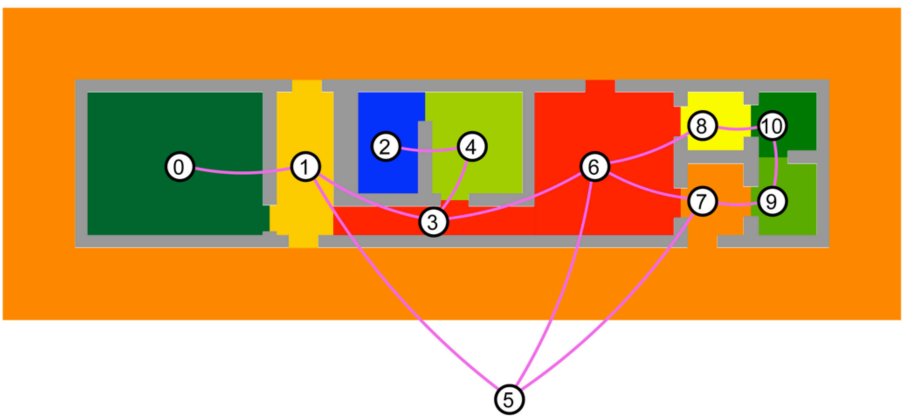


Figure 8: french farm house - taken and edited from "The City as One Thing", Hillier and Vaughan, 2005)

Convex spaces

Referring to the assumption stated earlier, that human interaction happens in convex spaces, the units of space have to be changed, when the geometry of rooms is not simple and rectangular as in the previous example. Convex spaces possess the property that all points are directly visible from all other points within the space. The very concept of the node analysis stays the same but rooms are broken up into the “fewest and fattest” convex spaces that cover the entire layout. They are the largest units that can be fully perceived at once within the layout and are therefore taken as local constituents.

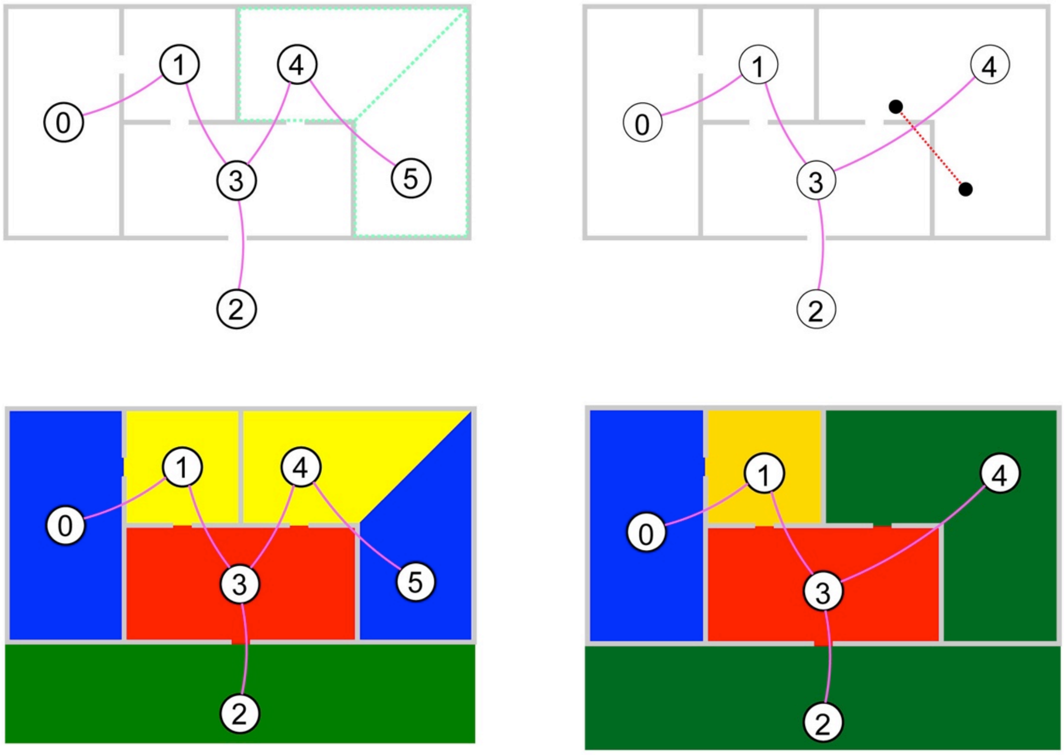


Figure 9: left: analysis based on convex spaces; right: analysis based on node analysis, where every node represents one room

Axial lines

In axial-line analyses, unites of space are represented by straight axial lines of sight as two-dimensional lines on a plan. All possible connections between convex spaces have to be reduced to the least number of straight lines, while making sure to complete all circulation rings in the system. This idea is often described with the quote 'fewest and longest straight lines covering all convex spaces'. (Hillier and Hansson, 1984, page 91-92) The result of this process is an axial map, which captures the sense of connections that a person gets while moving in space. It refers also to how people recall the global constituents of a layout. Each line is considered as a vertex in a graph representation, whereas intersections between lines define connections between vertices.

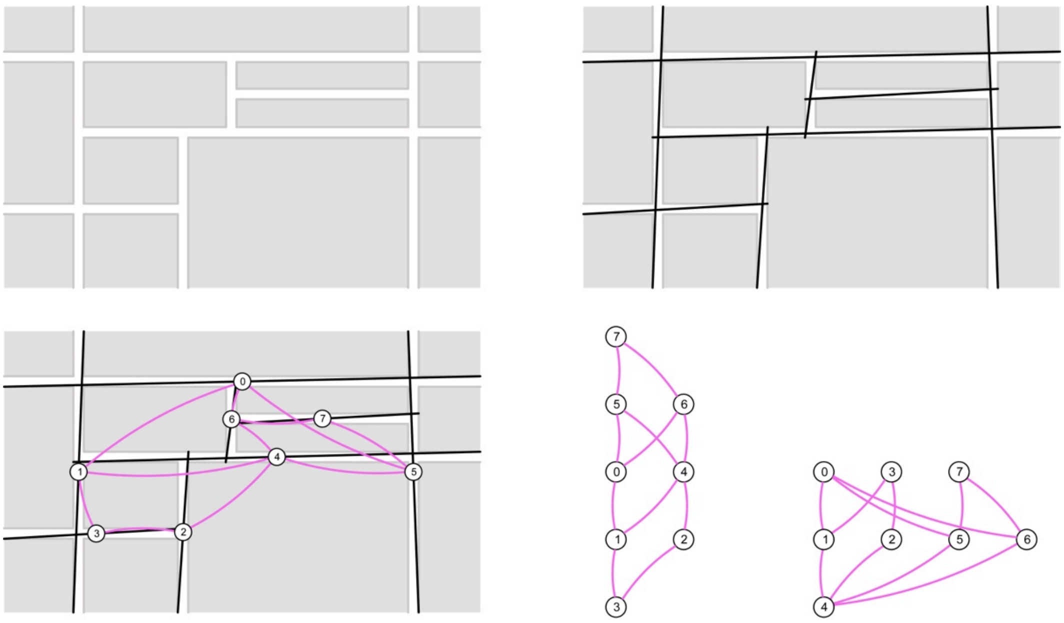


Figure 10: Creating an axial line map and constructing a graph representation

Basically axial maps can be applied to both - architectural and urban scales. Thus they are more suitable for urban analysis, as they capture basic features of line like voids such as streets. Streets form a net of long and intersecting lines like spaces. It is therefor far more often used in urban analysis, which turned out to be the most important field of research and consultancy activities.

Axial lines in Urban Street Networks

The interior of buildings is usually divided into rooms. Urban space does generally not have a similar obvious division into units. The space syntax approach refers to the predominantly linear nature of urban space. Axial Line Analysis is particularly suitable when analyzing large systems like entire cities, which consist of hundreds or even thousands of individual streets. Streets are the crucial factor of a city; the focus is on them and not on the crossroads. Wherever two axial lines intersect, a link is made between the corresponding two nodes in the graph representing the network.

Constructing the connectivity graph in a space-syntax manner makes the analysis of the topological relations between streets more abstract. By removing the relational graph from the physical space in which it is defined in the first instance, distances between locations are measured in a graph-theoretic rather than the Euclidean sense. This implies that a graph based on two-dimensional axial-lines is non-directed and might even turn non-planar, as shown in *Figure* 11.

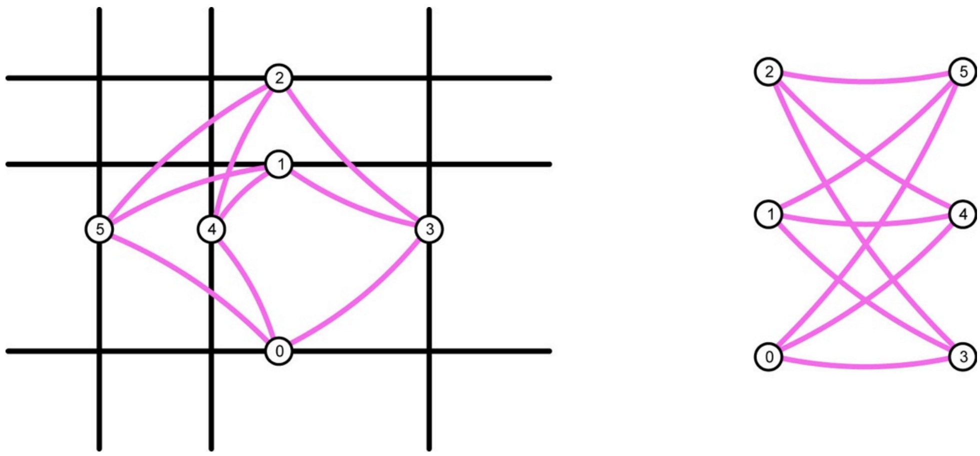


Figure 11: a simple rectengular grid is represented by a complete bipartite graph (K3,3 graph)

When a street network is directly translated into a graph representation, as done in conventional traffic engineer modeling as well as in space syntax segment line analysis, its nodes represent the road junctions and edges the road dissects. This method seldom leads to non-planar graphs, unless the subject of investigation is a confusing system of tunnels. The theory argues that streets are not locations in such interpretation. Thus the relations between any two streets can never be uniquely embedded in Euclidean space. This has the effect of internalizing the line structure of streets into the graph and capturing key features of the geometry of the street network.

The distinction between the two approaches for translating urban street networks into a connectivity graph and calculating its integration does not only help to predict an inhabitant's movement but leads to an understanding of how the social city relates to the physical environment.

> *"what is the role of geometry in constructing the patterns of space that characterize cities and how does it relate to the structures identified through line graph analysis? The answer proposed is that line graph analysis does not ignore the geometric properties of space but internalizes them into the graph, and it is precisely because it does so that it is able to pick up the nonlocal, or extrinsic, properties of spaces that are critical to the movement dynamics through which a city evolves its essential structures. Nonlocal properties are those, which are defined by the relation of elements to all others in the system, rather than those which are intrinsic to the element itself. The method also leads to a powerful analysis of urban structures because cities are essentially nonlocal systems."*
>
> Hillier 1999, page 169

Theory of natural movement

The configuration of the urban street network is the largest spatial pattern in the city. Its structure is the fundament of movement flows and therefore a co-presence in space, which has major consequences for a city's geometry and its social quality. It is intuitively clear, mathematically necessary and empirically demonstrable. To planners and architects, it gives the opportunity to understand what consequences urban geometry has and why collections of building come to life - or fail to thrive - as living cities. This is not a matter of psychology, but the way the grid system is put together. This is called the theory of natural movement (Hillier et al. 1993).

> *If we define an urban street network as a system of lines linking some set of origins and destinations, and to the extent that movement can occur from all origins to all destinations, then movement along the lines making up the network will be substantially determined by extrinsic measures of those lines.*
>
> Hillier ,1998 cited in Desyllas, and Duxbury, 2001

Through movement

Considering the urban situation showed in *Figure* 12, there is a main street, some cross-, side streets, the theory assumes that the streets are lined with houses, where people live in. These people move between those houses, which mark a starting point of a journey as well as its destination. Another assumption supposes that every journey is a direct route using the shortest path. Intuitively it is clear that more people will pass through the main street than the side streets and even less through the back streets. Also, more people will pass through the central area of the network, especially the central sections of the main street than use peripheral ones (through movement). The understanding that there are certain road segments where journeys between all pairs of spaces pass through more often than others helps to identify basic concepts of land-use. It will also make more sense to locate shops in one of the spaces that displays more traffic, whereas light traffic streets attract people to living purposes. However, it may not always be intuitively obvious what spaces qualify as which. Counting for every road segment, the amount of simplest or shortest paths between all pairs of spaces in the system provides the measure of through-movement. (*Figure* 12). In syntax, this is called the choice measure, whereas in graph mathematics it is know by the term “betweenness“.

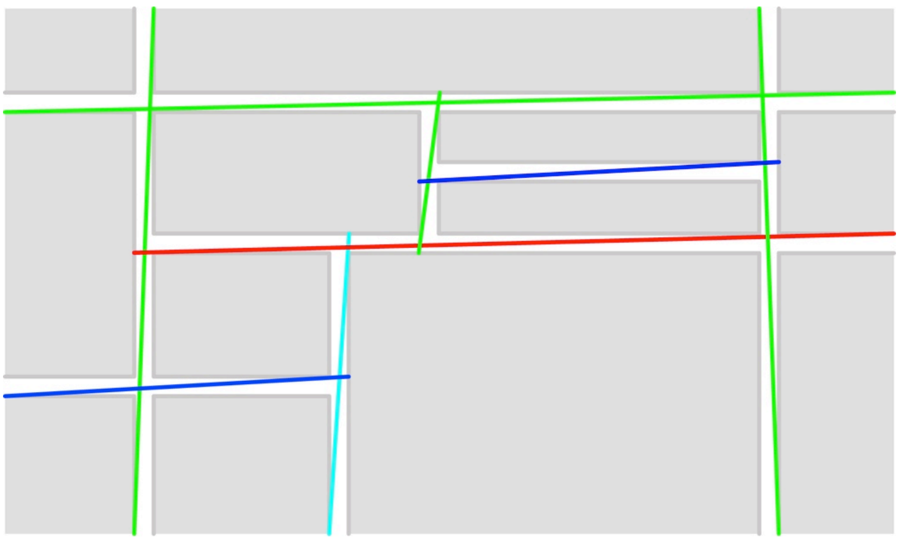


Figure 12: choice analysis applied to an axial map

To movement

The main street is more accessible than other streets. *Figure* 13 shows these locations, which have greater potential to be destinations than others, simply because of easier accessibility. This defines neighborhoods, as people are likely to go to near destinations more often than to farther ones. There are some locations that are in some sense 'closer' to all locations within a certain radius than others. The measure of accessibility for to-movement of a space in a system is the integration measure, which relates to the graph's depth described earlier. A detailed explanation of integration in itself will be provided later.

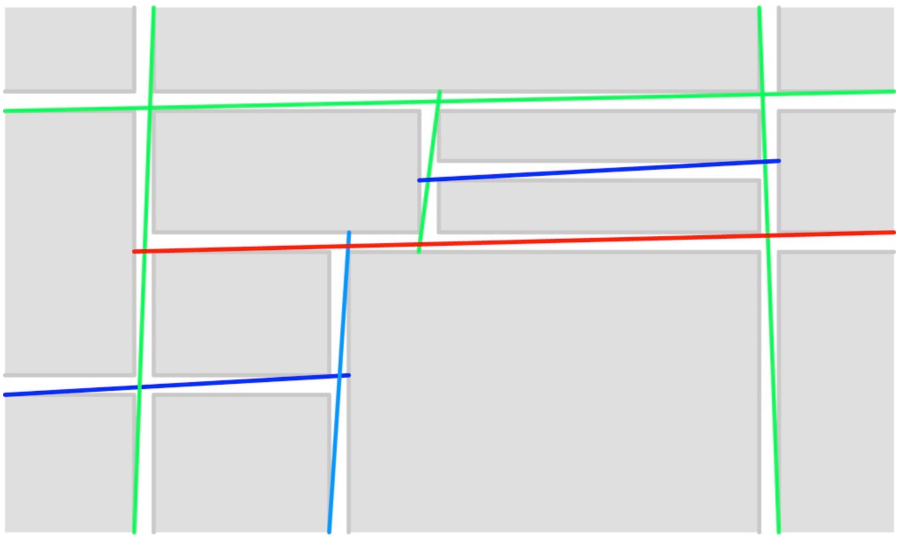


Figure 13: integration analysis applied to an axial map

There is a possibility to apply both measures at different radii by only considering elements within a predefined distance. Distances in this context are an amount of 'steps' in depth. Different radii for instance correlate to different kinds of activities and neighborhoods in the city.

Understanding urban environments

By simply applying the integration and choice measures to a least axial line map, correlations of calculated values with observed movement rates were found. In various studies, 60% to 80% of the differences in movement flows could be accounted along lines solely by the configuration calculation of the grid. (Hillier 1989, Hillier and Penn 1996) Further investigation and several case studies using the space syntax theory led to more observations that helped understand environments. If independent of any urban scale an urban grid is drawn, one receives very few long axis lines and a very large number of comparatively small lines. Carvalho and Penn (2004) relate this to the fractal nature of urban street networks. Hillier points out a relationship between line length and the angle of intersection of axial lines:

> *We find that angles of intersection have an equally improbable relation to another geometric variable: line length. For the most part, we find that highly obtuse angles of incidence are associated with longer lines and the near right angles with shorter lines. In general, the longer the line, the more likely it is to have a highly obtuse angle of incidence at (or dose to) one or both of its ends. Conversely, the shorter the line, the more likely it is to have a near right angle of incidence at its end. With less consistency, though with enough to be suggestive, the 45° lines tend to be shorter than the obtuse angle lines but longer than the near right-angle lines.*
>
> Hillier, 1999, page 172

Axial Lines criticism:

The popularity of this axial line analysis might also be the reason, why it is also the most discussed approach compared to other analysis methods. Researchers within and outside the space syntax community criticize it. This criticism focuses not as much on the algorithms, mostly taken from mathematical graph theory, but moreover on its method of representing space. Ratti (2004) highlights representational problems associated with axial lines. An emotional scientific discussion with Hillier followed this paper: Ratti 2004, Rejoinder to Carlo Ratti (2004), Rejoinder to Hillier and Penn (2004).

All-line axial lines

A rarely used alternative to axial maps is the 'all line' axial map. This measure has been applied to a limited number of cases (Penn, Desyllas et al. 1999). As the name indicates, the difference to the least axial line map is that this approach is based on all axial lines, defined by the longest lines of sight between any two visible corners of buildings. The reason for the development of this method is, that an all-lines axial map can be generated automatically by software, whereas no reliable automation for least axial line maps is presented. The software for all line axial map generation is called "Spacebox" and was developed by Nick Dalton in 1990 (Hillier and Penn 1992).

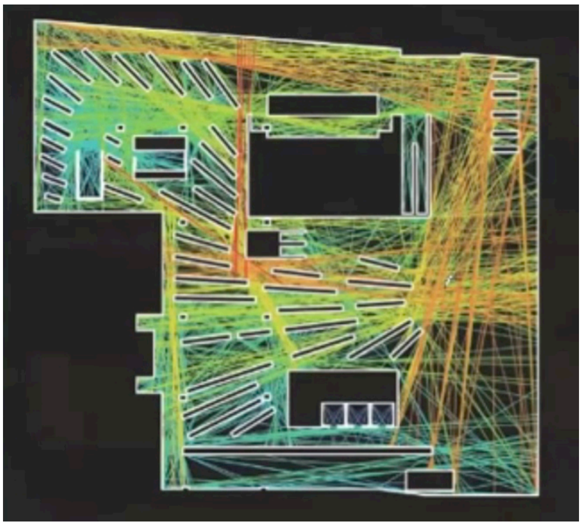


Figure 14: all line axial analysis of the Seattle Public Library, floor 3

"A Space Syntax Analysis of Seattle Public Library conducted as part of an invited talk at the 2011 International Space Syntax Symposium. Author Professor Ruth Conroy Dalton using Depthmap Software" source: http://www.youtube.com/watch?v=5M1EdgI7d30

All-line axial lines criticism:

This method has two major disadvantages:
Large areas defined by simple polygons (as rectangular squares) will have very few lines. Few lines then will effect the calculation, especially in combination with the second counter-argument: the generation of lines of sight is entirely dependent on the complexity of the polygons describing the situation. This means that all line maps produce graphs that are 'weighted' towards areas that need more polygons for their graphical representation. A similar problem arises when working with curved elements represented by straight segment lines.

Segment lines

This approach was introduced to overcome the problem of neglecting metric information. The axial lines analysis calculation calculates distance by counting the number by jumping to another straight line, which means counting the amount of turns to reach a destination. Critics frequently addressed this defect, as this does not seem to be the way humans make spatial judgments when choosing routes.

Most people simply care about minimizing distances. The attempt to develop a method based on this assumption yields that the assumption was wrong, as axial line analyses weighted for metric distance journeys decreased correlations with observed movement (Steadman 2004). There is evidence that movement in cities is compromised by the geometrical and topological structure of the network configuration far more than metric distance. To reflect and solve that, Hillier and Iida (2005) introduced an update on the axial line analysis method.

Starting from the same "least line axial map," each line is divided between any intersections into segments. These intersections represent the nodes of the graph while the segments indicate which nodes are linked.

Integration and choice measures are calculated based on three different weighting definitions of distance (see *Figure* 16 for an example of each weighting method):

- Shortest path (metric)
- Least angle change (geometric)
- Fewest turns (topological)

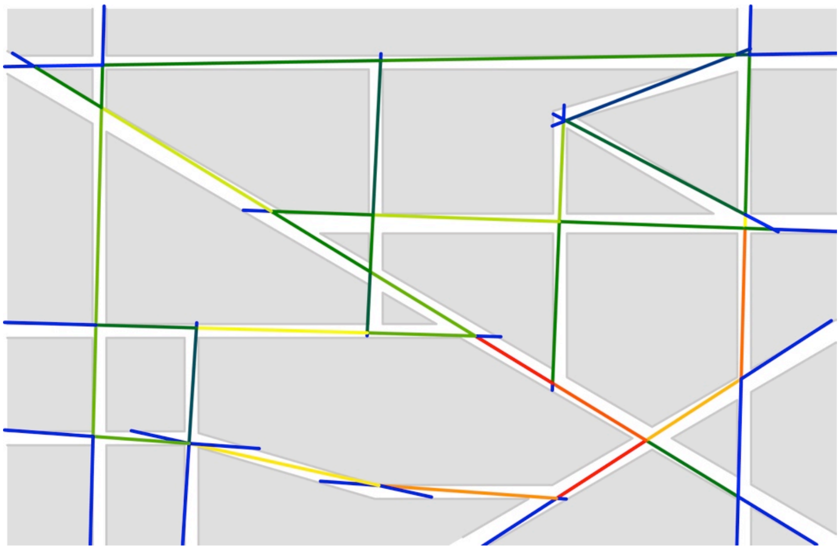


Figure 15: metric choice analysis applied to a segmented axial line map

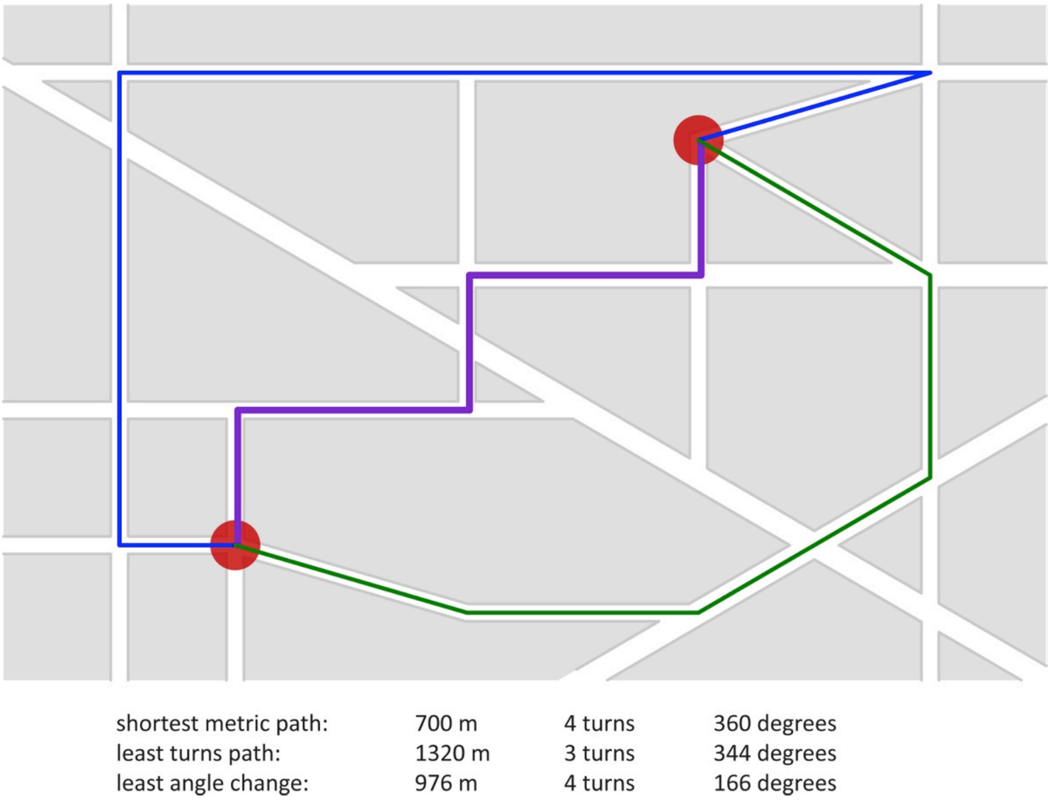


Figure 16: violet: shortest metric path; blue: least turns path; green: least angle change

In Hillier and Iida (2005), these three methods where applied to the same urban grid in four different urban areas in London. Afterwards, they were compared with the observed pattern of movement, showing that the least angle change analysis had the highest correlation. Good results were also achieved with the fewest-turns algorithm; the worst results were produced by the metric shortest-path analysis.

Radius

Compared to the limitation of steps in axial line analysis using a step radius value, the segment lines analysis calculation computes different radius units for the three computation methods:

- Maximal metric distance from each segment,
- Maximal angle for shortest, least angle change,
- Maximal amount of turns for fewest turns analysis.

Road centered lines

Due to the improved results derived from the segment analysis method, the question arose, whether there was the real need to base the algorithms on such interpretative representations such as axial lines. Considering that angular segment analysis algorithm produces better correlation especially with observed vehicular flow than standard axial analysis, road-center lines were suggested. (Turner 2005; 2007) Road-center lines are not just less interpretative, but they are especially easily available within geographical information systems. This data basis even allowed space syntax inspired measures to be combined with transportation network analysis representations in order to create a new, cognitively coherent, model of movement in the city. There have been several papers published offering new variants of space syntax, which attempt to bring together similar analyses with geographical information science (GISci) (e.g. Jiang and Claramunt, 2002; Batty, 2004; Cutini et al., 2004).

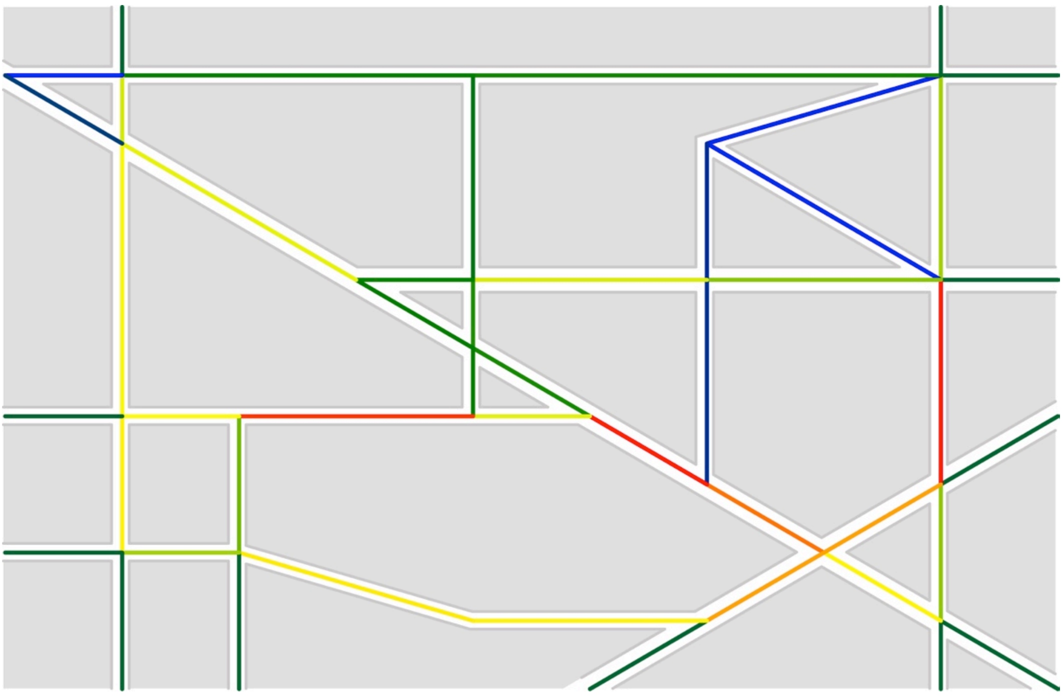


Figure 17: angular choice analysis applied to road centre lines

Grid based analyses: Visual field- and visual graph analysis

As axial line modeling tries do predict movement in networks, visual-field analysis aims at predicting people's movements in free-float spaces, especially assuming that persons do not know the space in advance. To a certain extend, one could relate them to the all-line analysis method, which by far does not feature as coherent and intuitive of a visual representation as otherwise. These analyses are often applied to study spaces that are not 'street-alike', but rather complex and overlapping. Most studies deal with public squares or semi-public indoor space of buildings like museums or shopping malls.

In visual-field analyses, the spatial units on which the calculation is based, are central points of equal squared tiles distributed in a grid in a two dimensional ground plan.
Visual-fields, also called 'isovists' (Benedikt 1979), are drawn from the center of each cell. Based on the isovists' properties introduced by Benedikt (area, real-surface perimeter, occlusivity, variance, skewness, circularity), different measurements can be calculated and graphically compared using heat maps.

In visual graph analysis (VGA), overlaps between the individual isovists are counted and represented in a graph. Using the graph representation, an algorithm calculates how many steps (visual fields) one needs to get to see the whole space from any point within the space. This approach relates to space syntax idea of qualifying strategic positions in environments. Also other space syntax analysis can be used to investigate the effect of spatial layout on functioning.

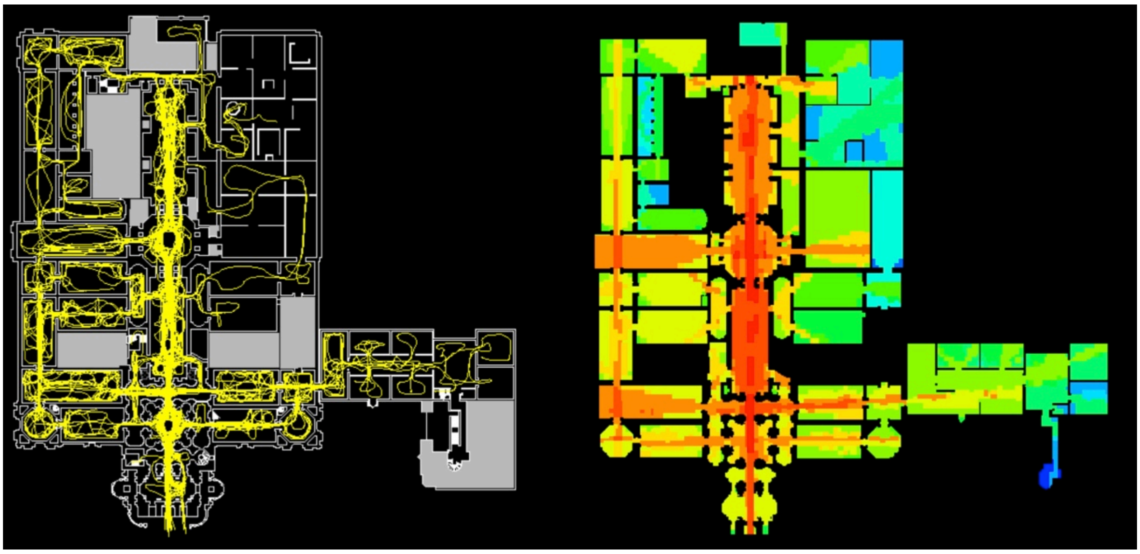


Figure 18: source: Batty, M., R. Conroy, et al. (1998). The Virtual Tate. London, CASA.

The most famous study where this analysis was used is an investigation of the Tate Britain gallery by UCL. (Batty, Conroy et al. 1998; Turner and Penn 1999) *Figure* 18 on the left shows traces of 100 people entering the Tate Britain Gallery in London and moving around for ten minutes. On the right side, in *Figure* 18, you can see a heat map of a visual integration analysis of all the visual fields from every point in the room layout. It is easy to see that the movement and space patterns resemble each other as patterns quite closely.

By investigating statistical correlations of the calculated visual integration values with observed movement, it turns out that about 68% of the differences in movement rates in rooms can be accounted for by the visual field structure. This kind of data demonstrates that people seem to be guided by their special perception of the Gallery and less by guides or the attractiveness of exhibited artworks. (Hillier et al. 1996).

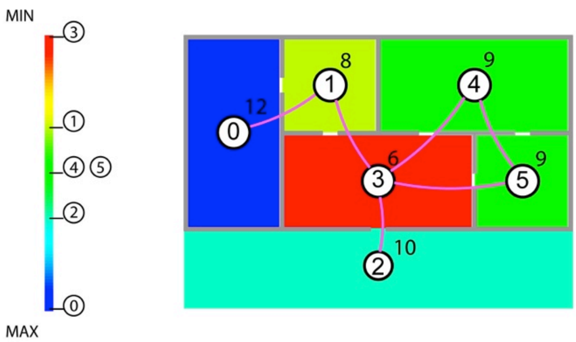
Quantification

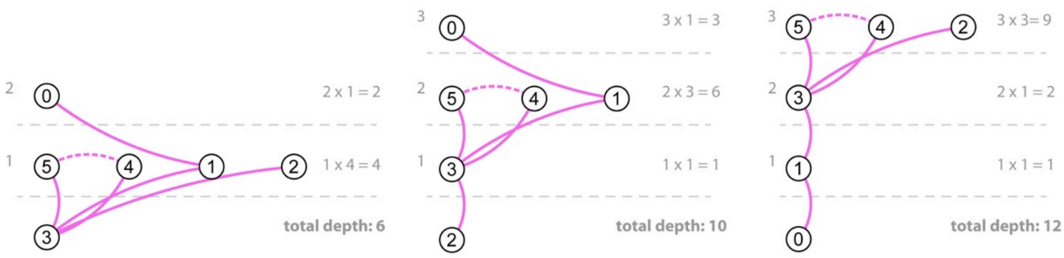
Space Syntax theory quantifies the way in which a spatial unit is connected to all the other units within a given system. Basic mathematical graph theory is used for doing these calculations. A connection between two locations is said to be shallow or deep when few or many intervening units have to be traversed when going from one to the other. By identifying the location that needs least steps to all other positions, one can classify the most integrated position in a configuration of spaces.

It should be pointed out that in the concept of integration, the idea of topological depth and not metric distance is used. Depth is the most important concept in Space Syntax.

Total depth

It was already stated that layouts may look similar in a plan, but their configurational relationships make each of them unique. This is a factor of how they are connected, both to adjacent units as well as to all the others. A graph, or even better a justified graph visualizes their topological relations. It facilitates the count of the amount of spaces one needs to pass through – to go from one spatial unit to another. This value is called 'depth' – the amount of steps one needs to arrive at his destination. Within every configuration, each space unit can have different values showing that a spatial system appears to be different depending on where the observer is located. This can be also expressed in a mathematical way by taking a Justified graph and assigning a depth index to each space, depending on it's depth from the observers spaces. In the end all one needs to do is to sum the values. (Hillier and Hanson, 1984, pp. 108).



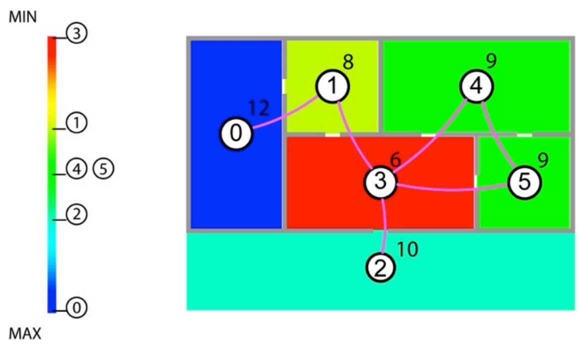


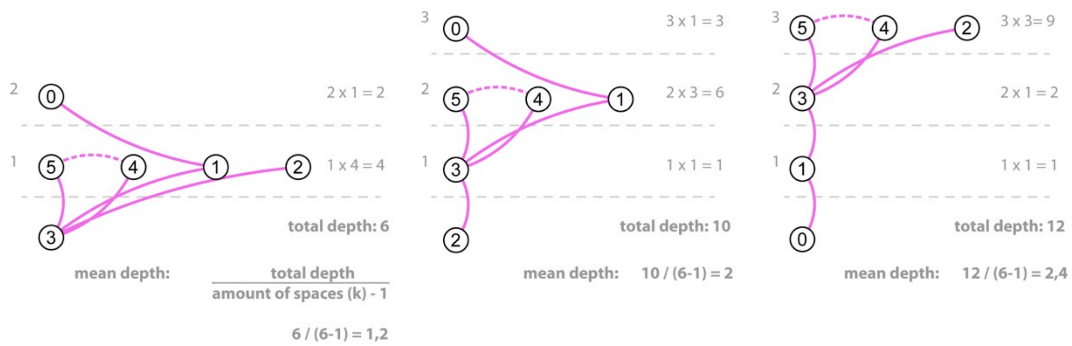
Mean depth

Extending the total depth analysis, a mean depth value can be calculated for every location. One obtains the mean depth by dividing the total depth by the number of spaces in the system minus one (the original space). The space unit that will have the smallest (mean) depth value is considered the most integrated. Integrated spaces are, on average, closer to all other spaces in a system. The one having the highest mean depth is considered to be the most segregated one. The observer located in any segregated area is more distant from all other spaces within the configuration.

$$MD = TD/(k-1)$$

MD… Mean Depth
TD… Total Depth
k… Number of special units/vertices





Integration and Relative Asymmetry

The measure of integration, or its opposite, segregation, is expressed by the reciprocal of the Relative Asymmetry (RA) value. (Hillier and Hanson, 1984; page 108).

$$Integration = 1/RA$$

Relative Asymmetry again is obtained by the analysis of a graph representing the number of changes in direction between unit of space and all other. It is based on the number and depth of spaces that must be traversed from one space to all other spaces in the configuration. This is given by the following equation:

$$RA = 2(MD-1) / (k-2)$$

RA… Relative Asymmetry
MD... mean depth
k... number of spaces in the system

Real Relative Asymmetry

The Size of a system might have an effect on the RA values, as the relativization with respect to the number of spaces is considered in the formula. This implies that it is not a reliable measurement to directly compare systems of different sizes. Therefore, a modified value, named Real Relative Asymmetry (RRA), was introduced. (Hillier and Hanson, 1984, page 109-113) It is the comparison of RA values with those for a theoretical 'root' or a diamond shaped pattern. It is given by following equation:

$$RRA = RA / D_k$$

D_k is the scaling factor reliant on the system size. It represents the D-value of the system with the same number of elements as the real system and is found by a provided table (Hillier and Hanson, 1984, page 112) or by calculation. Therefore consideration of RRA values seems to give the possibility to compare between different environments.

However, there are several counterparts against this attempt of relativization, as it is not comprehensible why it is solved by D-values. To explain RRA, literature usually refers to Krüger (1989), whose proposals are not absolutely clear.
Krüger proposed the scaling factor based on a 'reference configuration' having the same number of elements as the environment being analyzed. There are two alternatives described for a reference configuration, where a reference RA value is obtained: one shows a 'diamond shaped pattern' the other one a 'corner of a grid'. One has to choose between the alternatives, depending whether the whole analysis is based on 'node-grid-graphs' or 'axial-line-graphs'. This distinction is not straightforward but depends on the 'significant level of the difference of their mean RA'. (Krüger, 1989, page 33)

Due to the counterparts to this attempt of relativisation, there is a more popular method. It is a 'normalization' of the independent parameters of integration and described in Teklenburg (1993)

Choice

The measurement of accessibility for to-movement of spaces in a system is expressed by integration values. There is other potential that can be measured and is crucial to understand and predict people's movement. The through-movement, called the choice measure, counts the frequency of a space to be part of the simplest or shortest paths between all possible pairs of spaces in a network.

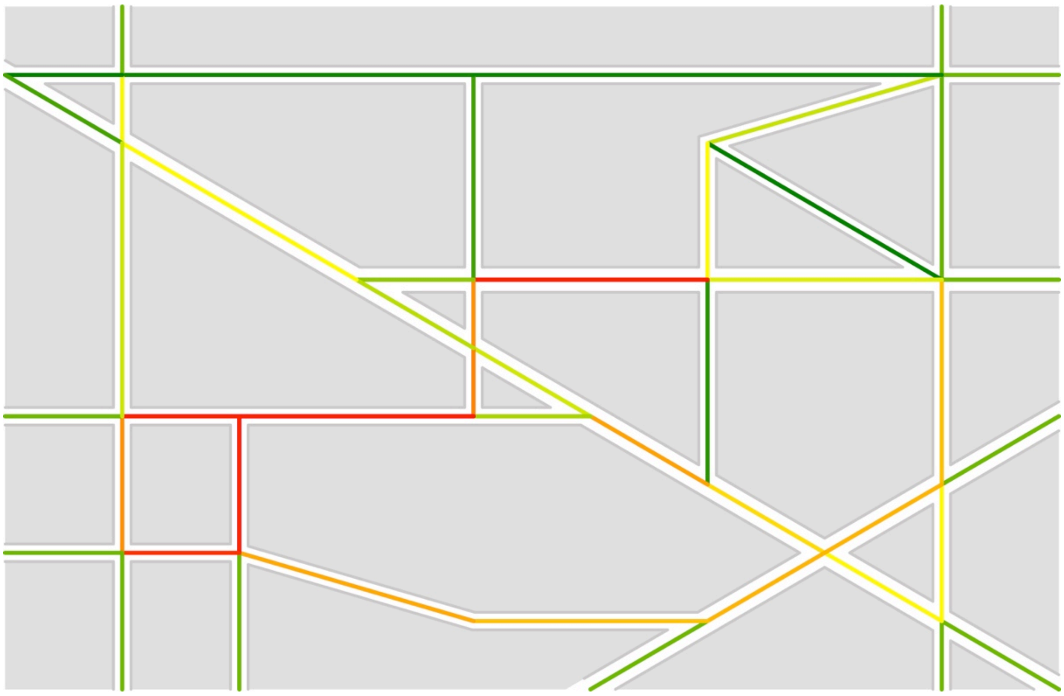


Figure 19: road centre line map showing choice analysis based on shortest metric paths

Connectivity

Connectivity is a local measurement that is obtained directly from a single unit. The calculation is simple and is mainly used in axial line analysis. It counts the number of other axial lines that are directly connected to one line. For other spatial units like nodes representing rooms, this value counts all neighboring rooms.

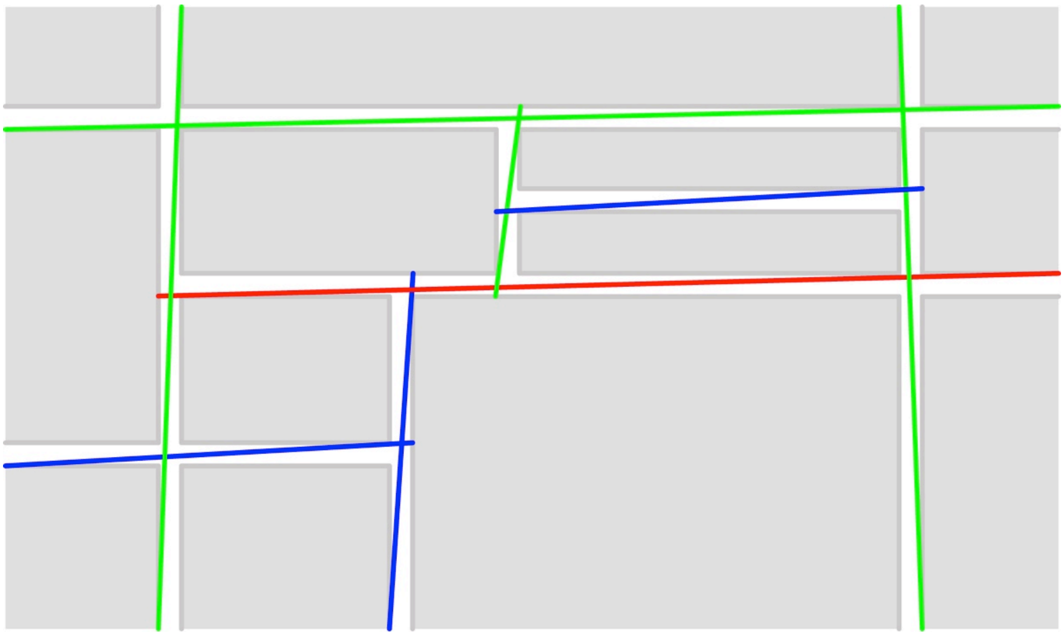


Figure 20: axial line map with connectivity analysis

Intelligibility

Intelligibility refers to the entire system's configuration and is a higher order of measure. It expresses the correlation between global integration and local connectivity - between global and local variables. Pearson's Product Moment Coefficient determines their correlation. The stronger a correlation, the more a global configuration may be understood from its directly observable local connections. Intelligibility values can be used to quickly compare between different environments.

Radius

There is also the possibility to apply both movement measures (integration and choice) not only based on the whole system to obtain a global analysis, but to concentrate on more local areas. This makes sense especially for investigations at urban scale, looking for movements within neighborhoods. Using a radius can control the size of the analysis' impact. Radii can be both, topologic and metric.

Topological radii calculate integration or choice values up to a certain depth (step size).

Metric radii define a geometric radius, assigning a center-point of a circle to every spatial unit. The calculation then considers all spatial units within the circles radius for the calculation.

The application of radii enables comparison between local and global properties of a street network. This concept of radius, as used in space syntax graphs, represents a mathematical innovation unique to this field.

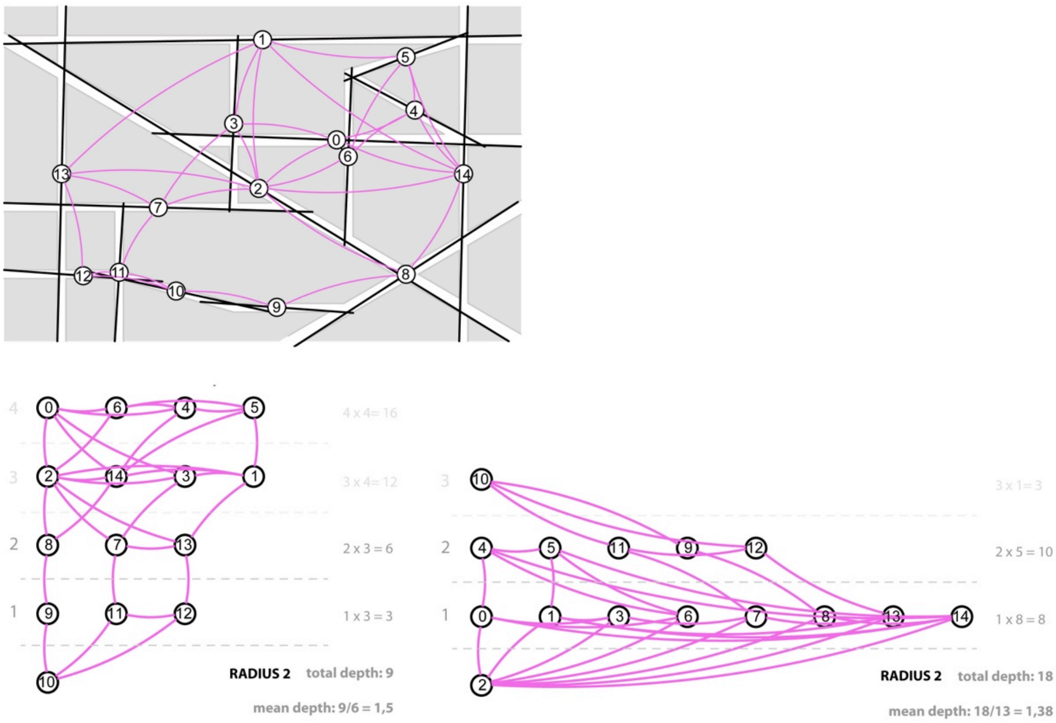


Figure 21: total depth measurement with the Radius 2 for axial line No. 2 and No. 10

Regeneration framework

for unplanned settlements in Jeddah based on space syntax

Using the ability and experience of space syntax to understand urban phenomena, Space Syntax Limited, a spinoff company created by the University College London (UCL) was commissioned by the Municipality of Jeddah to design a long-term regeneration program for the city's deteriorating unplanned settlements. A new approach was developed, which not only aims to serve as a plan for authorities, but is also intended to become a guide for all concerned parties: residents, NGOs and charities.

Analysis of Jeddah

Jeddah is the most important port city in Saudi Arabia in the Red Sea. As an important commercial hub, it has the largest seaport in the Red Sea and is the second largest city (3,4 million inhabitants) in the country after the capital city, Riyadh. It gained its importance through its location. The city is the gateway to the two most important cities in the Islamic religion. Mecca, the religious center of Islam, which is located about 72 km east, and Medina, the second holiest place in Islam, located about 300 km north. Every year the city hosts a huge influx of pilgrims, from Africa mainly across the Red Sea, and by plane from all-over the world. The local population consists predominantly of Africans, Persians, Turks, Yemenis, and Indians. Most of them work in the petroleum industry.

The city has grown exponentially since the 1950's and the prediction for the city's population for the next 20 years is the increase in population to 5 or 6 millions (Municipality of Jeddah, 2009, page 20 as cited in Karimi and Parham, 2012). Due to this growth the city merged many small and organically grown villages outside the historic city walls and turned them into organic quarters within a rapidly planned, grid shaped urban layout. While the modern city was being shaped with planned streets and regular plots of land for new urban blocks, the old villages turned into informal settlements. These areas were formerly well functioning, some even prosperous, before they rapidly turned into heavily deteriorated areas. The street networks found in these areas are highly localized due to their organic development. It creates a sharp contrast to the rectangular grid of its neighborhoods. This rectangular gird, however, provides better mobility and availability in global terms. Altogether there are around 50 unplanned settlements, each hosting 3 000 to 120 000 inhabitants, with an estimated population of one million people in total. (Municipality of Jeddah, 2009, as cited in Karimi and Parham, 2012) Not all of them are former villages. Immigrants created many informal settlements in the fringes of the city, in need for cheap places stay.

Figure 22: map of Saudi Arabia, showing the Country's most important cities and neighboring countries

These observations can be also displayed by space syntax analysis, as Karimi and Parham, 2012 describe:

> *The syntax measures of angular segment analysis (Hillier and Iida 2005) for local and global radii reveal an interesting phenomenon: unplanned areas come out as areas with high measures of local choice while the citywide super-grid, underlined by higher values of global integration, run outside these areas, even the ones that are located in the most central parts of the city (Karimi, Amir, Sahfiei, and Raford, 2007). In sharp contrast, these areas develop a very distinct local structure, which is captured by syntactic analysis at a lower metric radius (for instance 1200m or lower), as shown in Figure 5, but this structure does not fit into the spatial structure beyond the boundaries of the unplanned settlement.*
>
> *The spatial discontinuity between the local and the global scale of urban grid impedes socio-economic improvement in long term, especially through decreasing the share of unplanned settlements from the global 'movement economy' (Karimi, Amir, Sahfiei, and Raford, 2007). This spatial condition correlates strongly with the socio-economic conditions of fabric of these areas which have adversely changed in the past 30 years. The wealthier Saudi residents have been replaced by poorer Saudis and particularly by poor immigrants. As a result, poorer residents have moved to areas with poorer spatial accessibility.*

Karimi and Parham, 2012, page 8151:9

A spatial layout analysis at the citywide scale (Figure 24) highlights the fast highway network. Movement on this grid of streets divides the city, cutting connections between communities and isolating slums. In addition to this, the historic city center has become increasingly isolated through growth. Motorways cut through historic fabric ignoring the initial relationship between streets and public places.

The crucial point is that these areas got completely isolated from one another as well as from the wider city. Isolation starts the process of degeneration, as lack of movement leads to a worse economical situation for businesses. When less money is generated in a settlement, less is invested in maintenance leading to a worse physical quality. As physical condition worsens, original wealthy residents move away while still holding on to their property.

Emigrants arriving to the city mostly lack education and are unemployed. They have little choice and move to segregated areas, as they provide cheaper living. This quickly leads to overcrowding, squatting and further downgrading.
What is currently happening in the Favelas of Rio de Janeiro, just before the 2014 football World Cup and the 2016 Summer Olympics, is an example of how isolated spaces provide excellent conditions for criminal activities, which have to be solved through police and military force. (Romero, 2011) The rigid separation of citywide scale and local scale movement networks is found in other cities with large slum populations. This property is found less in cities that have not been divided by highways and where certain streets remain to be important at both the city-wide and local scales, thus exposing shopkeepers settled at those streets to passing trade at both scales.

The Spatial layout analysis at the local scale (Figure *23*) reveals a different set of streets as being favorable for shorter-distance journeys up to 800 meters or 10-minute walks. This indicates "walkability" of environments to be a valuable urban property. Almost all of these occur within the historic villages, in which slums can be found today. This hints at some other qualities of the areas besides low-cost accommodation: possibilities for established social networks, established local economies and less reliance on cars.

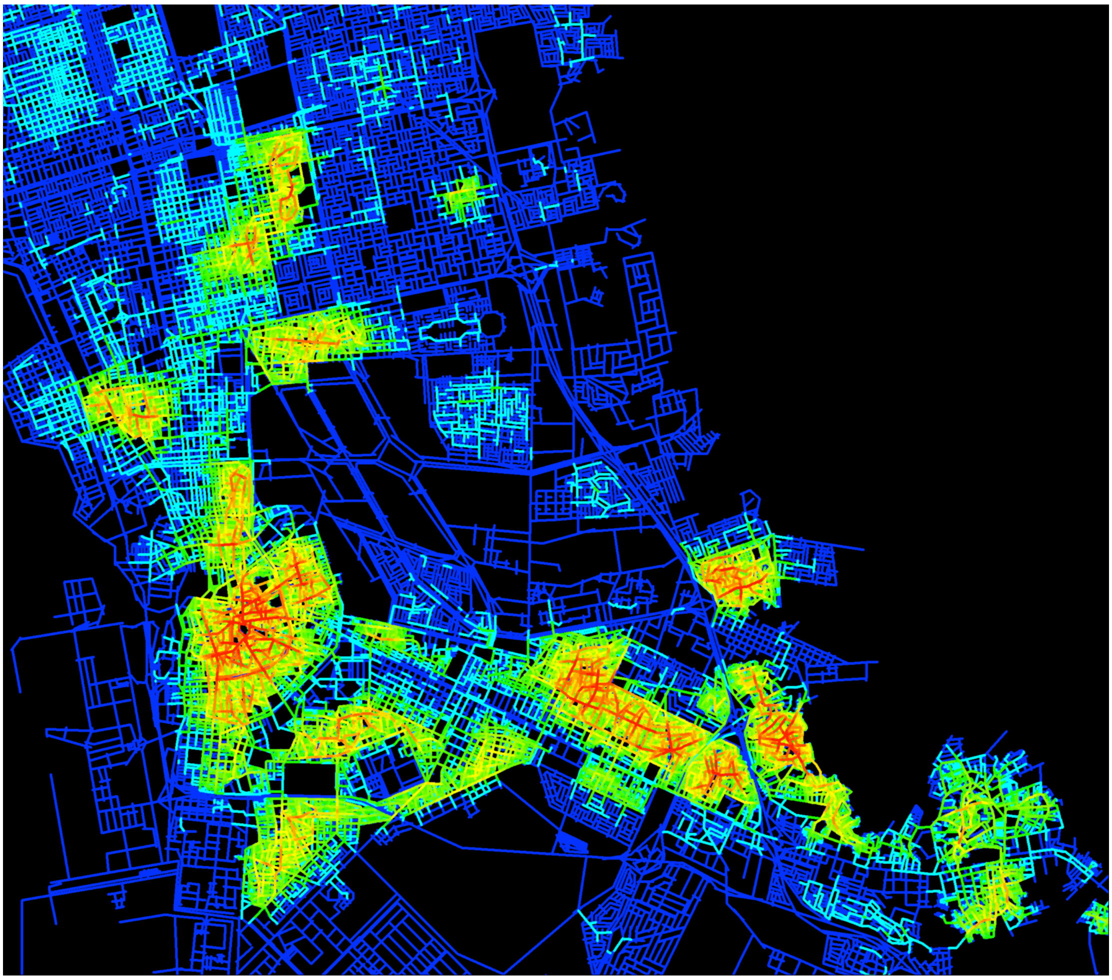


Figure 23: syntax measures of angular segment analysis for local radius – 800m

Source: digital screen presentation (slide 36) of "An evidence informed approach to developing an adaptable regeneration programme for declining informal settlements" by Dr. Kayvan Karimi and Ed Parham at the The 8th Space Syntax Symposium in Santiago de Chile (January 2012)

Almost all of these historic sites include very narrow spaces causing two major problems. On the one hand, it prevents access to maintenance vehicles leading to poor hygiene conditions. On the other hand, it handicaps access to emergency crews. This is often connected to fatal consequences. For example: in June 2011, a fire in Fire in the district Nimtoli, in Dhaka (India) killed more than 100 people because fire trucks could not get to the source of fire. (Dummett, 2010)

Figure 24: syntax measures of angular segment analysis for global radius

Source: digital screen presentation (slide 36) of "An evidence informed approach to developing an adaptable regeneration programme for declining informal settlements" by Dr. Kayvan Karimi and Ed Parham at the The 8th Space Syntax Symposium in Santiago de Chile (January 2012)

Certainly problems are not just limited to "unplanned" organic urban areas. There are also many defects within planned areas. The word 'planned area' in this context actually refers only to the fact that a grid was drawn in advance. Nevertheless, many of these areas have no access to water of sewers.

Regeneration program

The results of the extensive analysis enabled the understanding of problems of each settlement. By identifying target situations from local standards as well as best practice, the Space Syntax Limited research group identified a strategy for each area based on the needs of each settlement. The strategies are based on the concepts of growth leading to an "incremental and sustainable process of regeneration for declining informal settlements".

> *The guiding idea behind this transformation is that by understanding how a settlement grows, evolves and functions, we can identify an urban structure which shapes the internal functionality and external interactions of the settlement. This structure, which is strongly associated with movement, use, density, social interaction and other urban attributes, often suffers from multiple failures, which pushes the area into a descending cycle of decline.*
>
> Karimi and Parham, 2012 page 8151:1

A ranking of the different areas was presented to the Municipality of Jeddah. It classified the potential to attract private sector investment, potential for self-improvement and areas, where the municipality has to interfere. To address problems of the areas in need of immediate partial intervention, changes at two scales were defined – one at the scale of the entire city, the second is the scale of the settlement itself. The intention of the area-specific strategies is to provide an individual, specific, needs based response that creates the minimum disruption but maximum benefit to each settlement.

At first, causes for the underperformance of each settlement were identified. Based on the analysis, the level of intervention required was defined to achieve target provision levels, set by the Jeddah Strategic Plan (Municipality of Jeddah, 2009, as cited in Karimi and Parham, 2012), international best practice standards and consultation with stakeholders. By benchmarking each settlement's results an intervention strategy was generated to react directly to the individual needs of the area.
Interventions were aimed to resolve the fundamental problems of these areas by improving the internal and external spatial structures by reconnecting the isolated and fragmented core of the unplanned areas to the citywide street grid while preserving the integrity of local physical and spatial structures as much as possible.
The spatial layout of the slum is improved by connecting the sets of local, intermediary and global routes to improve movement on all scales. Doing so, basic requirements for

successful urban trade are established. With these modifications land use can be distributed efficiently. Commercial usage, which requires exposure to pedestrian movement, can be located in these places, while residential land does not need as much movement and can be located at spots that fit this requirement better. Floor Area Ratio of plots is adjusted according to the levels of calculated density and movement on the nearby streets.

Many slums are already powerful socio-economic environments, even if they lack basic sanitation, quality shelter, and tenure. Nevertheless, social infrastructure must be improved in unplanned areas to meet current standards. Major investment in social infrastructure is required and will bring long term benefits to levels of education and health care, which in turn will benefit the economies of these areas. The amounts of social infrastructures were calculated using the local and international standards, but were revised according to the realities of the unplanned settlements.

The previously mentioned actions form an Area Action Plan, which could be used as the basis for different scenarios. In order to create flexibility and adaptability, due to financial reasons in particular, a number of interchangeable regeneration scenarios were created that offer a range of variable solutions. Primary four scenarios were developed, which have been tested on financial feasibility. Later a fifth scenario was added.

Scenario A: Complete redevelopment of a settlement by super-blocks carried out by developers.

Scenario B: Street upgrade and construction of linear bands of new development by developers, self organizing regeneration of the rest of the settlements by residents

Scenario C: Street upgrade and formation of development bands by JDURC/Municipality (Jeddah Development & Urban Regeneration Company), construction of development bands by developer, self organizing regeneration of the rest of the settlements by residents

Scenario D: Street upgrade by JDURC/Municipality, self-organizing regeneration by residents. It is an improvement plan to only introduce the most efficient way of distributing and prioritizing the regeneration efforts and external funding to enhance the living conditions and urban performance of the area

Scenario E: Minimum intervention regeneration plans. Local authority and the regeneration company wanted to minimize their intervention. This framework seeks to improve an area with the absolute minimum physical disruption to an existing settlement. In this scenario, major changes to the spatial condition are not considered; instead, the spatial structure of the area is used to optimize the improvement and distribution of aid in these areas. The founding principle of this scenario is to provide an upgrade in living conditions to the widest group of people. It does this by proposing a spatial structure, which defines improvements in the areas, which are most likely to be used by everyone in the settlement.

While the outcome of each regeneration scenario is different, they still share the same spatial structure, which means, that it is possible to combine different scenarios in each area. This allows that if for instance the developer's interest is sufficient at the beginning of the intervention process, Scenario A can be followed to start the regeneration process. For any combination of reasons, it may not be possible for Scenario A to be applied throughout the rest of the settlement. As a result of the ways project boundaries have been defined, it is possible to switch from Scenarios B to D in other areas. If none of the A-D Scenarios are possible, Scenario E could be adopted to work with whatever resources available and wait until more help is provided to switch to one of the other scenarios.

In this sense, the regeneration process could be started with minimum resource and progress further when more resources are available. As all proposed scenarios are completely compatible it means that the approach to development is flexible enough to respond to any change in circumstances. More importantly, involved institutions, such as local authorities, NGO's, international aid agencies and local residents will have a reliable framework to consolidate their efforts and avoid making big mistakes or wasting resources.

> *The great advantage of this scenario is that improvements could be set up as small, independent projects which can be delivered by the Municipality, local NGOs, charities, or even by local residents, as and when funds are available. Such projects, if implemented well, have the potential to improve the overall character, sense of community and image of the unplanned settlements. In return, a social force will be created which will push the area to adopt more positive transformation of the spatial structure (Scenarios A-D).*
>
> Karimi and Parham, 2012, page 8151:20

Generative Approach

The proposed generative approach does not try to solve the whole multi-layered problem of improving informal settlements, as the aforementioned approach by Space Syntax Limited does. In fact, it isolates one aspect, where the space syntax theory is fully applied. It is based on the following observation:

> *In most cases these areas have certain characteristics in common: they are segregated within the global urban structure (while they maintain an active edge in some cases), they have a problematic local system, and badly lack infrastructure*
>
> Karimi and Parham, 2012, page 8151:4
> Based on Dovey and King, 2011

This observation leads to the idea of adapting the existing spatial structure in a specific way to connect the isolated and fragmented core of an unplanned area to the citywide street grid. These adaptions should be chosen in a way that preserves the integrity of local physical and spatial structures as much as possible. In the design proposed by Space Syntax Limited, the changes in the spatial structure were drawn by hand, based on a space syntax analysis that led to a "deep understanding of the unplanned settlement." A new - more ore less direct - routing of roads was drawn to link public spaces in the local structure to main roads that were part of to the global network. The global structure was identified in an angular segment analysis based on a citywide model using a global radius of influence (Figure 24). Using the same model as base for an analysis with a local influence radius (Figure *23*) showed areas with valuable local organization and walkability
Further constraining the new road designs was the search for possibilities of minimal interventions on build stock, as every newly created public space resulted from loss of someone's private one. Although most of these private spaces are informal, meaning that they officially do not belong to the actual dwellers, it is important to keep the amount of inhabitants that need to be resettled as low as possible. This should be respected not only due to ethical reasons but also because of political issues, to gain acceptance for the urban interventions and not to challenge the public coherence, which may be very strong in such communities.

This constraint contradicts the initial intention of looking for modifications that maximize a system's integration in terms of space syntax. Even though Georges-Eugène Haussmann's impact on Paris turned out to be successful, just as Benito Mussolini's Via della Conciliazione, this approach remains questionable in many aspects. For this approach, it is crucial to find short but strategic routes to achieve positive impact. Doing so by using a computational strategy is the purpose and aim of this thesis. The process generates thousands of modifications to the urban network based on preliminary defined parameters. While every modification is analyzed separately, its impact on the system is measured. After the analysis is processed, the different values indicating every modification's impact are compared and ranked by their contribution. Their efficiency then can be set into relation to their length, which can be seen as an indicator for their costs and expenditure in terms of building stock, which has to be removed.

Grasshopper for Rhino

It was necessary to develop the discussed analysis techniques inside an environment that allows calculating analysis and a parametrically modifying geometry. From today's point of view, the most appropriate tool for such an implementation is Rhinoceros, also called Rhino, by the company McNeal, more precisely it's plugin named "Grasshopper". Grasshopper is an emerging tool for digital modeling - it expands Rhino in the segment of parametric modeling. The Plug-in is developed by David Rutton and is still in beta status, but it is already widely used by architects and engineers. Grasshopper's broad influence can be measured by the fact, that there are already several finished projects using this software. It has created a respectable and growing community of users worldwide.

Grasshopper is a visual programming language and therefore easy to use and fast to learn. Visual programming interfaces are in general used for various tools with increasing popularity, as it allows a comfortable workflow. Especially for users who are not as experienced in code-based programming, they are easy to understand. The visual programming interface is no new invention, however, Grasshopper convinces with a great usability and potential.

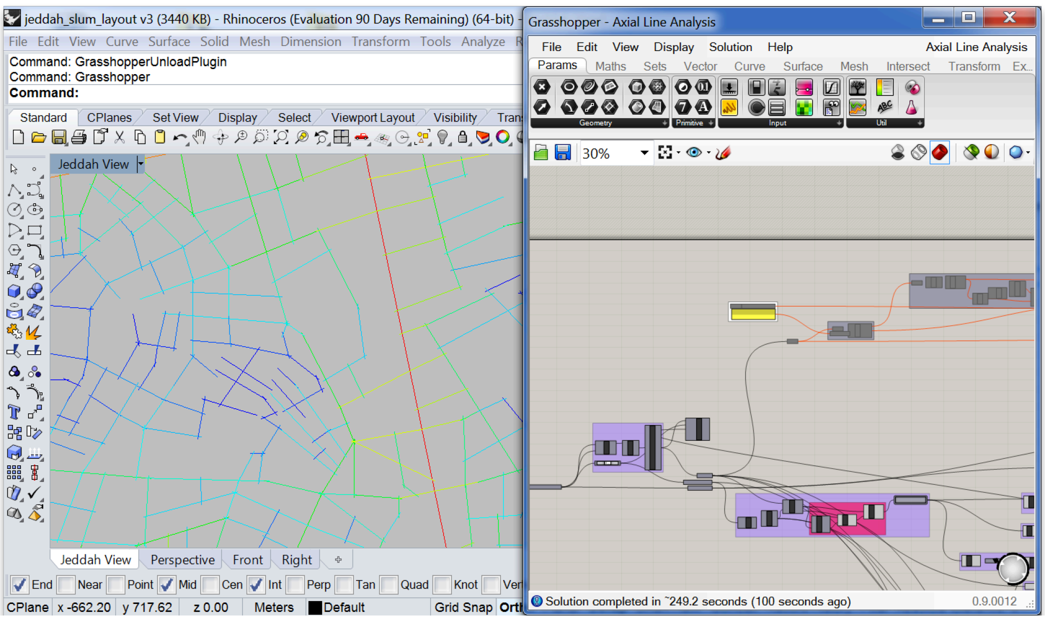


Figure 25: background: Rhino 5 (beta) showing an axial line analysis in the viewport. The Grasshopper Window is located on the right side in the foreground.

Implementation in Grasshopper

To run any analysis one needs two elements. On the one hand the "Spider Web Plugin" needs to be installed to Grasshopper. This Plug-in was developed by my colleague Richard Schaffranek at the Vienna University of Technology. It provides additional components to the grasshopper component library, which enable more advanced graph mathematical operations. To use it, one needs the definition calculating space syntax analysis. From this setup, any other use with space syntax analysis can be approached.

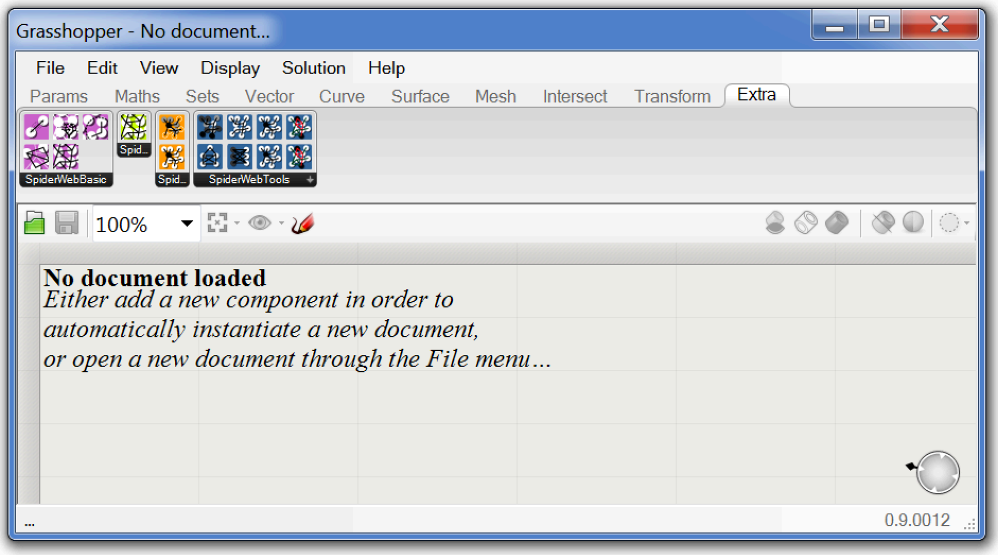


Figure 26: After installing the "Spider Web Plugin", one can find the new components in the "extras" Tab

Target area

The proposed method is applied to an area that was classified to be in need of immediate intervention by the municipality. It is located about 4 km north of the historical center of Jeddah. (*Figure* 27) That informal settlement is also an example for the case described before, where a historically developed village is surrounded by a quickly planned orthogonal grid of streets. (*Figure* 28)

Figure 27: geographical location of the target area; source: Google Inc. (online) maps.google.com

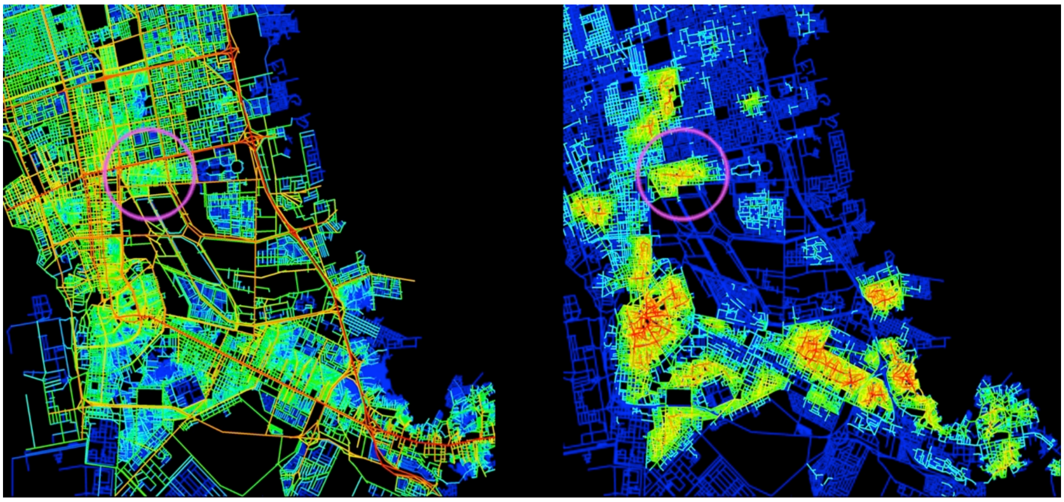


Figure 28: left: Integration analysis of the site with global radii and highlighted target area; right: integration analysis at local radii and highlighted target area. Based on slide 36 of the screen presentation "An evidence informed approach to developing an adaptable regeneration programme for declining informal settlements" by Dr. Kayvan Karimi and Ed Parham at the The 8th Space Syntax Symposium in Santiago de Chile (January 2012)

In the analysis applied by Space Syntax London on the network of the entire city at global radii, one can clearly see the citywide street network surrounding this area. (*Figure* 28) When applying local radii, the organized quality of its local structure can be clearly spotted.

Modus procedendi

The presented procedure applies the space syntax analysis based on axial lines. Nevertheless, the idea and methodology is not limited to axial line analysis and remains valid for any form of segment- or road-center-lines analysis (metric, topologic and geometric). Axial lines are chosen for this thesis because their processing time is significantly shorter than for a segment line analysis calculation.

The axial map of the settlement is extended by about one kilometer to its surroundings, to respect the actual neighborhood in the analysis. Applying an integration analysis using a radius value of five, already identifies the roads that are part of the citywide street network. It also shows the weak integration of certain spots within the settlement.

This thesis proposes three methods to intervene in the current street network applied in three different scenarios. The first two follow the intention by space syntax limited to apply changes within the area of the informal settlement:

- **Scenario I** generates new axial lines. It creates new connections between existing axial lines. This means that the total amount of streets within the system increases. In praxis, the consequence of a new street means the removal of existing buildings within this area.

- **Scenario II** proposes an extension of existing axial lines in the target area. This method keeps the amount of axial lines constant and affects buildings within the settlement.

- **Scenario III** intends not to create changes within the target area itself but at the immediately bordering neighborhood. In reality this would mean that an improvement of the slum-like settlements might be achieved by changing their surroundings. This scenario is of course a thought experiment, as it would be hardly possible to carry through major changes in a stable urban environment than in informal urban areas due to political, legal and financial reasons.

For every single axial line that is generated by each scenario, an individual space syntax analysis is calculated. Due to the complexity and extend of such a calculation, the calculation time is on average 356 seconds. After every calculation the following values are extracted and saved for later processing:

Generation ID	This integer identifies the axial line that was picked for the analysis calculation.
Line length	The actual length of the axial line
Intelligibility	The value obtained from the intelligibility evaluation of a whole system
Integration sum	The total sum of all integration values derived from every node in the network. This value indicates whether a generation improves the integration of the entire system or not.
Integration min	The lowest integration value of any node.
Integration min axis	The identification number of the axis referring to the node that contains the lowest integration value
Integration max	The highest integration value of any node
Integration max axis	The identification number of the axis referring to the node that contains the highest integration value
0,25 quantile	The 0,25 quantile of the distribution of all integration values in the system. This value indicates the impact on the systems integration within less integrated areas.
0,5 quantile	The 0,5 quantile of the distribution of all integration values in the system. This value indicates the impact on the systems integration within medium integrated areas.
0,75 quantile	The 0,75 quantile of the distribution of all integration values in the system. This value indicates the impact on the systems integration within more integrated areas.

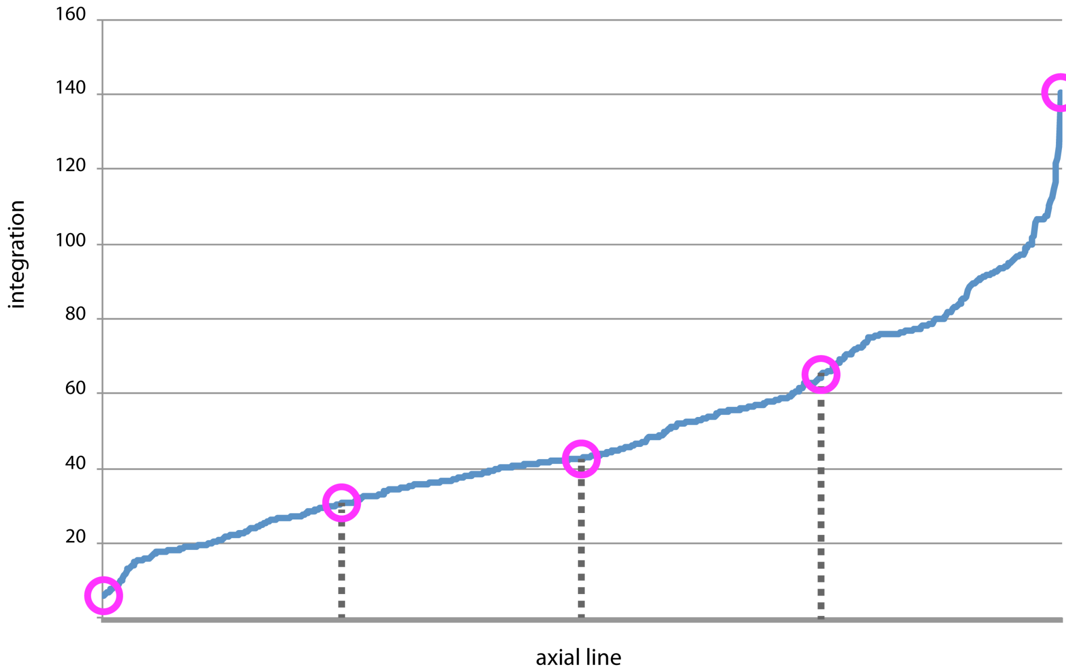


Figure 29: The graph represents all integration values of every axial line sorted in decending order.

All the values are put into a table to enable their comparison and evaluation. The table is sorted in descending order by size, once for each of these values: intelligibility, integration sum, integration min, integration max, 0,25 quantile, 0,5 quantile and 0,75 quantile. For each sorting, the adequate generation IDs for the highest one percent of all values are stored in a separate list. Based on the new list the accumulation of generation IDs is extracted. This brings out what axial lines have the biggest effect on the largest amount of measurements.

Scenario I

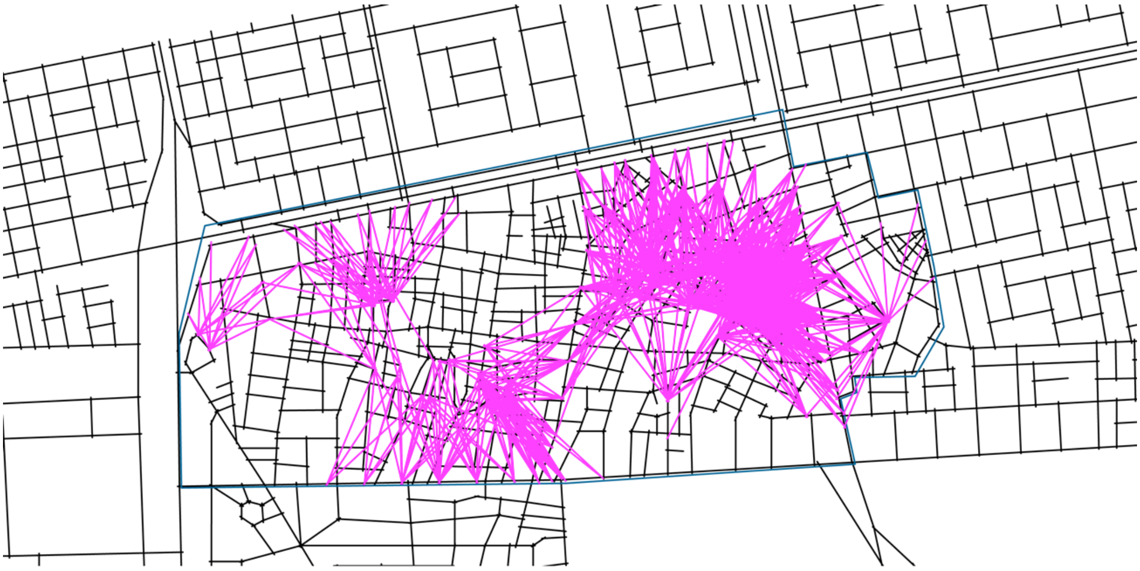


Figure 30: 1024 possible new axial lines defined in scenario I

Scenario I describes the method of generating new axial lines between existing ones. Theoretically there are infinite possibilities for new generations. So one has to limit the amount of generations to a manageable amount. In a first step, 10% of the most integrated as well as 10% of the least integrated axial lines are filtered. An external parameter named block size is introduced, which divides the previously selected axial lines into segments of a certain size. For the case study, the block size of 50 meter was chosen. This defines that every 50 meters along an axial line, a starting point (or an ending point) is located.

Next all possible connections between these locations are generated throughout a predefined working area. The working area in this case is defined by the extent of the informal settlement and it's neighboring streets.

Two new parameters define the maximal and minimal street length. All generated axial lines are filtered according to this specification. As the block size 50 m was chosen, the minimal street length is set to the same value. The maximal axial line length amounts 350 m. *Figure* 30 shows all generated axial lines, 1024 in total. That means that the whole calculation process for evaluating all 1024 generations took 101,25 hours.

Scenario II

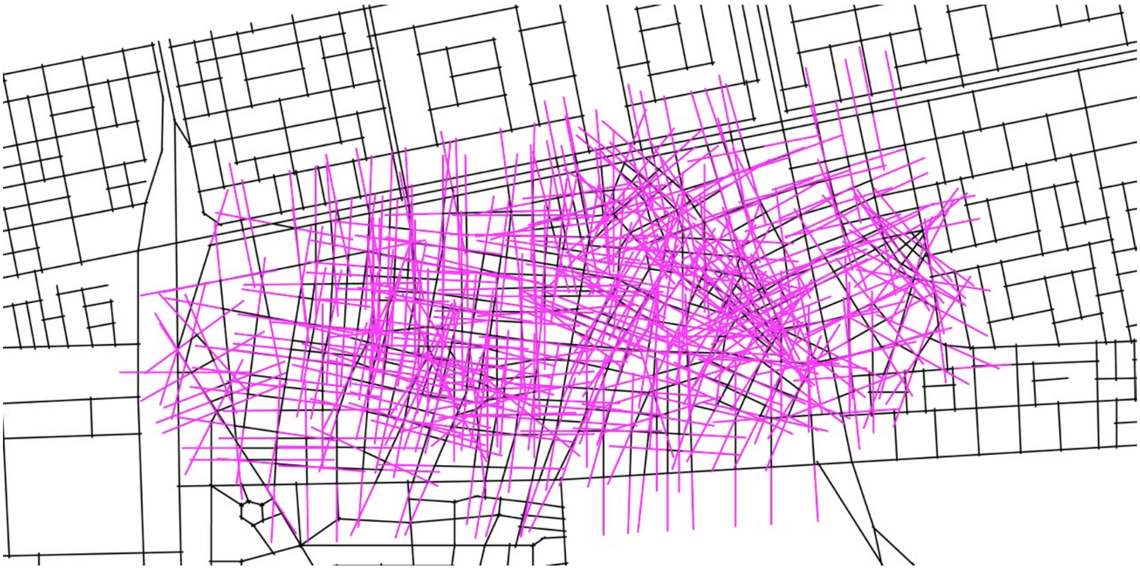


Figure 31: 898 possible new axial lines defined in scenario II

In this scenario every single axial line within the target area is extended by 150 meter. There are 449 axial lines in total. For each line, two possibilities are calculated: one for an extension in every direction. Scenario No. 2 enables 898 generations in total and the processing of all analysis took 88,8 hours.

Scenario III

Figure 32: 1294 possible new axial lines defined in scenario I

Scenario III applies changes to the direct neighborhood of the target area. A similar generation method, as used in Scenario I, had to be applied to lower the enormous number of possibilities:

At first, all line segments within an 80-meter distance to the target area border are selected. The external parameter "block size" divides the existing axial lines into segments of 50 meters. This defines that every 50 meters along an axial line, a starting point or an ending point of a new axial line is created. In this case study the limit of 300 meters defines the maximal length of newly generated axial lines. This leads to 1294 generated axial lines. The total calculation time for analyzing every individual possibility took 128 hours.

Results

Scenario I

table 1 presents the list of generation ID numbers that were identified to be the most efficient 1% of new courses of roads that improve the overall integration of the analyzed street network at several ranges of the measurement. – One has to keep in mind that these are the best improvements due to the rules of generation and its predefined parameters: maximal, minimal straight street length and block size.

intelligibility	integration sum	integration min	integration max	0,25 quantile	0,5 quantile	0,75 quantile
302	249	340	249	249	232	436
680	240	323	232	240	727	435
827	736		727	736	249	359
281	232		240	232	240	360
859	727		736	727	736	696
852	484		251	484	251	697
294	745		728	745	728	33
897	251		248	251	466	235
835	475		744	475	484	470
305	728		747	437	745	731

table 1: generation IDs indicating 1% of the most efficient new axial lines created in scenario I for all individual measurements of every line generation

Figure 33 highlights the most efficient new axial lines in the axial line map. On the one hand it shows possibilities one would not easily think of, on the other hand it clearly identifies spots, as for instance, the dense structure in the eastern central part of this informal settlement that need the most care. Some modifications also propose changes within the internal organization; others connect to streets of the global grid.

The computed result shows several similar axial lines. There is no benefit in tidying up such cases by computation, as this information should not be understood as the final stage of a design. It represents a catalogue for further design work, which needs to respect factors on site that were ignored prior to that stage.

Figure 33: axial line map highlighting 1% of the most efficient new axial lines in scenario I

Figure 34 compares values of the system before and after the intervention. The graph shows all integration values in ascending order for each axial line. It clearly shows the significant improvement of space syntax values, which is equally distributed throughout the entire spectrum.

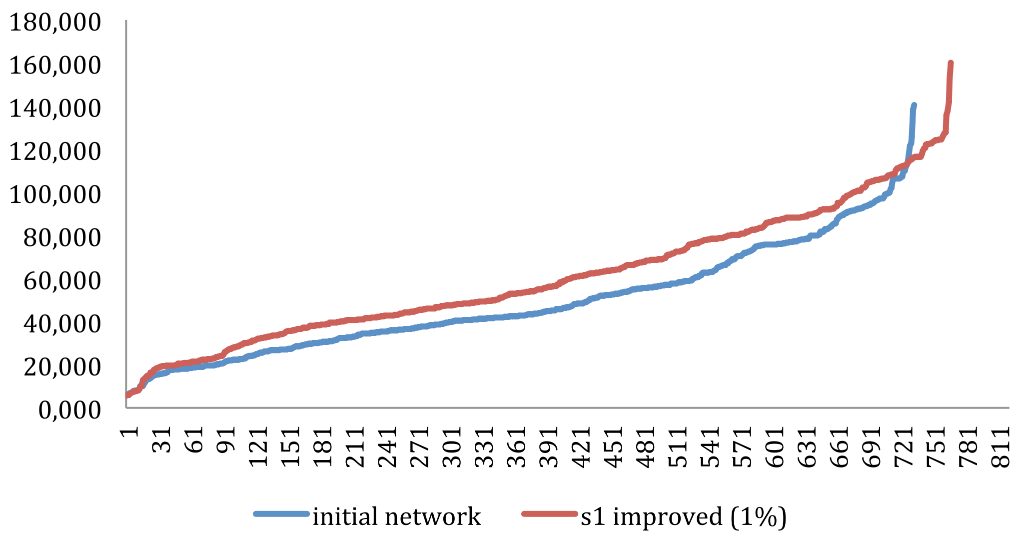


Figure 34: integration values (y-axis) ranked by decreasing (x-axis); blue: initial configuration; red: improved configuration

Scenario II

table 2 presents the list of generation ID numbers that were identified to be the most efficient 1% of new axial lines created in scenario II. The appendices "a" and "b" in the generation number define which endpoint of the axial lines needs to be extended. As in scenario I, one has to keep in mind that these are the best improvements due to the rules of generation and its predefined parameters.

intelligibility	integration sum	integration min	integration max	0,25 quantile	0,5 quantile	0,75 quantile
421a	63b	421a	421a	63b	446b	421a
446b	82b	208b	208b	357b	63b	446b
111a	201b	327a	444a	111a	444a	111a
63b	64a	275a	440a	77b	111a	63b
357b	286a	440a	428a	444a	77b	357b
77b	130b	111a	376b	446b	311a	77b
444a	200a	428a	237b	416b	421a	444a
62a	342b	212b	215a	421a	357b	62a
421a	63b	421a	421a	63b	446b	421a
446b	82b	208b	208b	357b	63b	446b

table 2: generation IDs indicating 1% of the most efficient new axial lines created in scenario II for all individual measurements of every line generation

Figure 35 highlights the axial lines shown in *table* 2 in the axial line map. Again it identifies the same spot as *Figure* 33 in scenario I - the dense arrangement of streets in the Eastern central part of the target area. Furthermore, *Figure* 35 unveils several good and useful possibilities of axial line extensions throughout the entire network.
This result also stresses the necessity of connecting the informal settlement to the northern neighborhood. Realizing such a connection in reality cannot be easily achieved, as the northern border of the target area is a highway of global importance.

As for the results in scenario I, there are several similar design options. Again, there is no benefit in filtering them by computation, as the intention is to create a computational generated guideline for further human design work.

Figure 35: axial line map highlighting 1% of the most efficient new axial lines in scenario II

Figure 36 compares values of the system before and after the intervention and clearly shows the significant improvement of space syntax values equally distributed throughout the entire spectrum.

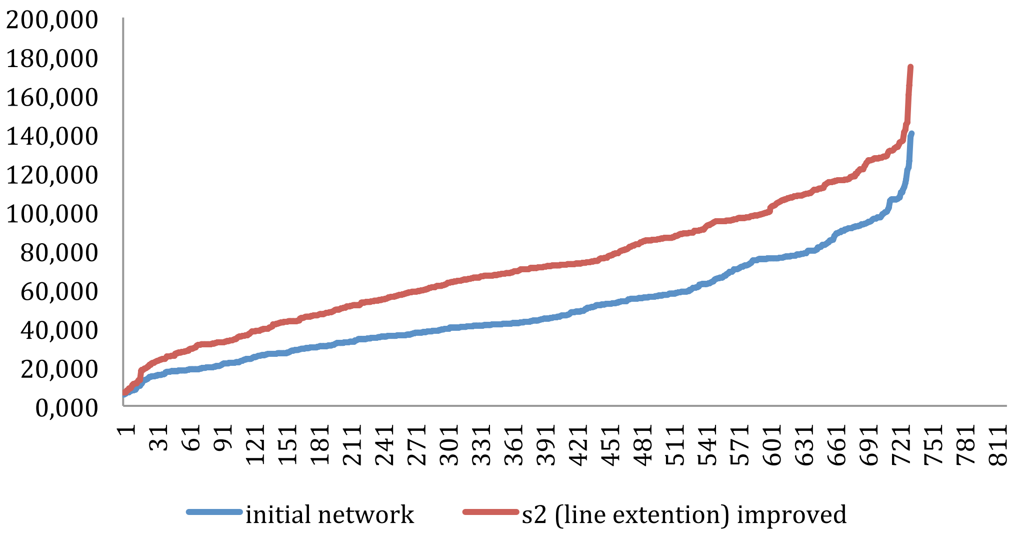


Figure 36: integration values (y-axis) ranked by decreasing (x-axis); blue: initial configuration; red: improved configuration

Scenario III

table 3 presents the list of generation ID numbers that were identified to be the most efficient 1% of new axial lines in the direct neighborhood of the target area.
Likewise in previous scenarios one has to once again keep in mind that these are the best improvements due to the rules of generation and its predefined parameters.

intelligibility	integration sum	integration min	integration max	0,25 quantile	0,5 quantile	0,75 quantile
1027	730	154	748	971	623	779
1054	409	175	746	11	625	789
846	60	65	752	398	780	731
1155	623	173	730	84	783	733
947	625	643	732	731	609	780
1147	731	904	729	733	1169	783
1237	733	908	754	539	1176	786
848	971	1026	401	779	84	788
940	11	254	722	789	1175	784
932	539	641	409	780	750	623

table 3: generation IDs indicating 1% of the most efficient new axial lines created in scenario III for all individual measurements of every line generation

Figure 37 highlights the specified axial lines shown in the axial line map. Again it shows that the biggest impact on the system can be achieved by bridging the highway bordering the informal settlement in the north. In addition, the results obtained in scenario III determine the connections in northeast border of the garget area to its neighborhood. That leads back to the road junction of two globally important roads, which inherit high integration values to every axial line intersecting them both.

Figure 37: axial line map highlighting 1% of the most efficient new axial lines in scenario III

Figure 38 compares values of the system before and after the intervention and clearly shows the significant improvement of space syntax values equally distributed throughout the entire spectrum.

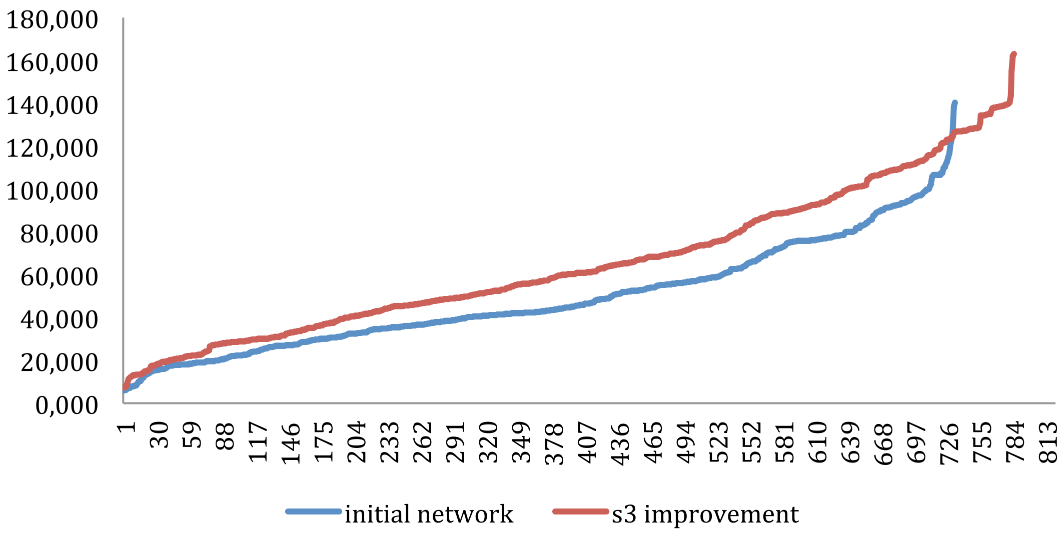


Figure 38: integration values (y-axis) ranked by decreasing (x-axis); blue: initial configuration; red: improved configuration

As with the results in scenario I, there are several similar design options. Again, there is no benefit in pursuing computation, as the intention is to create a computational generated catalogue as a guideline for further human design work.

Combining the three scenarios

Mergeing results

Figure 39: results from scenario I, scenario II and scenario III merged into one plan

There are two possibilities for combining all three scenarios into one plan.

One is to merge the results of every of the three scenarios. This ensures that every generation method contributes more or less the same amount of modifications to the system. *Figure* 39 shows all 118 newly generated axial lines and *Figure* 41 visualises the space syntax integration analysis using color.

Figure 40 compares values of the system before and after the improvement with merged results. It clearly shows the improvement of space syntax values equally distributed throughout the entire spectrum.

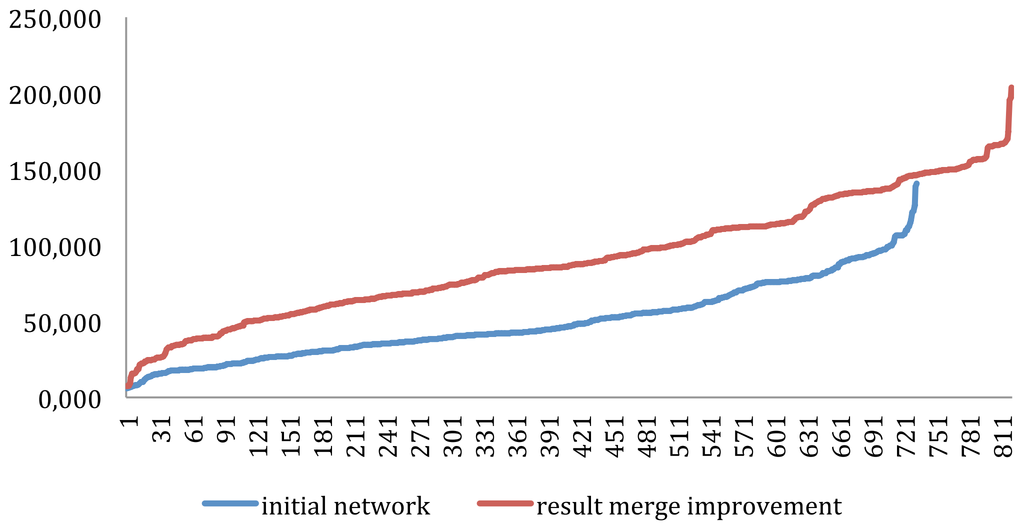


Figure 40: integration values (y-axis) ranked by decreasing (x-axis); blue: initial configuration; red: improved configuration

Figure 41: integration analysis based on merged results from all trhee scenarios

Mergeing data

Figure 42: 92 most weighty axial lines generated by all three generation methods.

The second possibility is to merge the obtained data from all scenarios' analyses into one table and filter the most weighted lines of all three scenarios. The top 20 lines identification numbers for each measurement are shown in *table* 4.

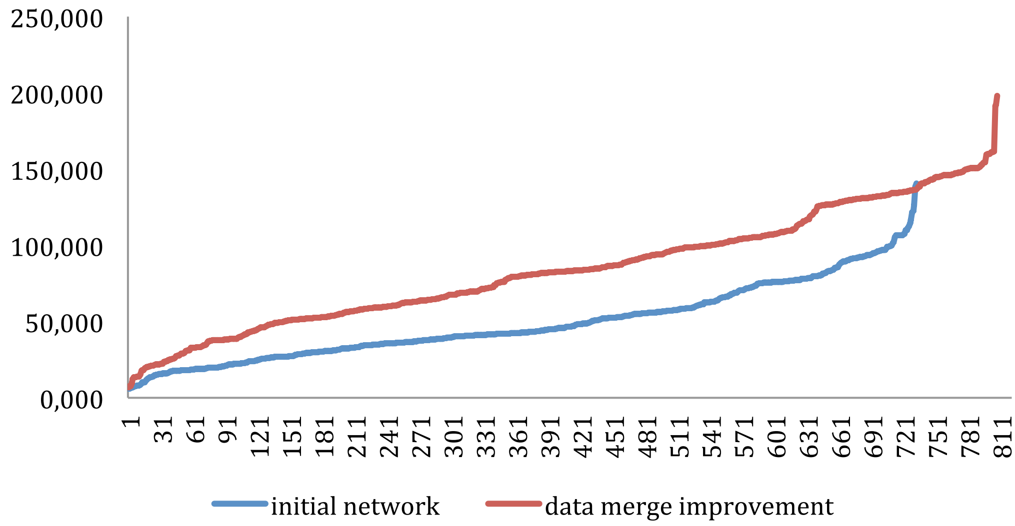


Figure 43: integration values (y-axis) ranked by decreasing (x-axis); blue: initial configuration; red: improved configuration

Figure 44: integration analysis of the merged data model

This approach enables the comparison of the effectiveness of each scenario. There are 62 out of 140 axial lines created in scenario I within the ranking of best 2% lines of each measurement. 52 axial lines within the pool are results from scenario III measurements and only 26 are from scenario II. As several new axial lines have a large impact on more than one measurement, 92 axial modifications are added to the system. All of them are highlighted in *Figure* 42. *Figure* 44 visualises the space syntax integration analysis using color.

intelligibility	integration sum	integration min	integration max	0,25 quantile	0,5 quantile	0,75 quantile
s3g1155	s2g421a	s2g63b	s1g249	s1g249	s2g63b	s3g779
s3g846	s1g249	s3g154	s1g240	s1g240	s2g357b	s3g789
s3g1237	s1g240	s3g175	s1g736	s1g736	s2g111a	s3g731
s3g1147	s1g736	s3g65	s1g232	s1g232	s2g77b	s3g733
s3g1027	s1g232	s3g173	s1g727	s1g727	s2g444a	s3g780
s2g134b	s1g727	s2g82b	s1g251	s1g484	s2g446b	s3g783
s2g342a	s1g484	s3g643	s2g421a	s1g745	s2g416b	s3g786
s3g1075	s1g745	s3g904	s1g728	s1g251	s2g421a	s3g788
s3g386	s1g251	s3g908	s1g248	s1g475	s2g62a	s3g784
s3g584	s2g446b	s3g1026	s1g744	s1g437	s2g311a	s2g446b
s3g872	s1g475	s3g641	s1g747	s1g34	s2g346a	s2g63b
s3g303	s1g728	s3g254	s1g252	s1g426	s2g68a	s3g623
s3g1141	s1g466	s3g640	s1g748	s1g361	s2g82b	s3g625
s3g1133	s1g248	s3g1023	s1g484	s1g432	s2g376b	s1g436
s3g1054	s1g744	s3g642	s1g745	s1g728	s1g232	s1g435
s3g1194	s1g747	s3g373	s1g656	s1g248	s1g727	s3g154
s2g70b	s1g49	s3g637	s1g49	s1g744	s3g623	s3g175
s3g940	s2g111a	s3g819	s1g28	s1g747	s3g625	s1g359
s3g942	s1g28	s3g824	s1g475	s1g252	s2g264a	s3g65
s3g949	s1g29	s3g197	s1g466	s1g748	s1g249	s3g173

table 4: 20 most weighty axial lines from all three scenarios ranked by individual measurements.The first three characters identify which scenario the generation is taken from

Discussion

Comparing scenario results

Scenario II did not deliver many strong individual lines compared to the other scenarios. This can be seen in *table* 4 (only 26 out of 140 lines). Howerver, *Figure* 45 shows that the modificatiion caused in scenario II still improves the overall network in a well balanced manner and even more effectively than those scenarios, which add new connections between existing streets. Furthermore, the utility of the line extentions in scenario II seems to be usefull for pursuing design work.

This is not true for results delivered by scenario III, as most of them concentrate on the northeast part of the informal settlement bridging two highways, which cause high integration values to every axial line connected to both. This is a known issue and is pointed out by space syntax researchers in several papers and lectures: a street with a high integration and choice value needs to provide enough space and attractive design for both, pedestrian- and car movement, to enable desired urban qualities. In this context, an elevated highway in Beijing is compared to the Avenue des Champs-Élysées in Paris – both roads with high space syntax values, but serving different forms of highly concentrated movement.

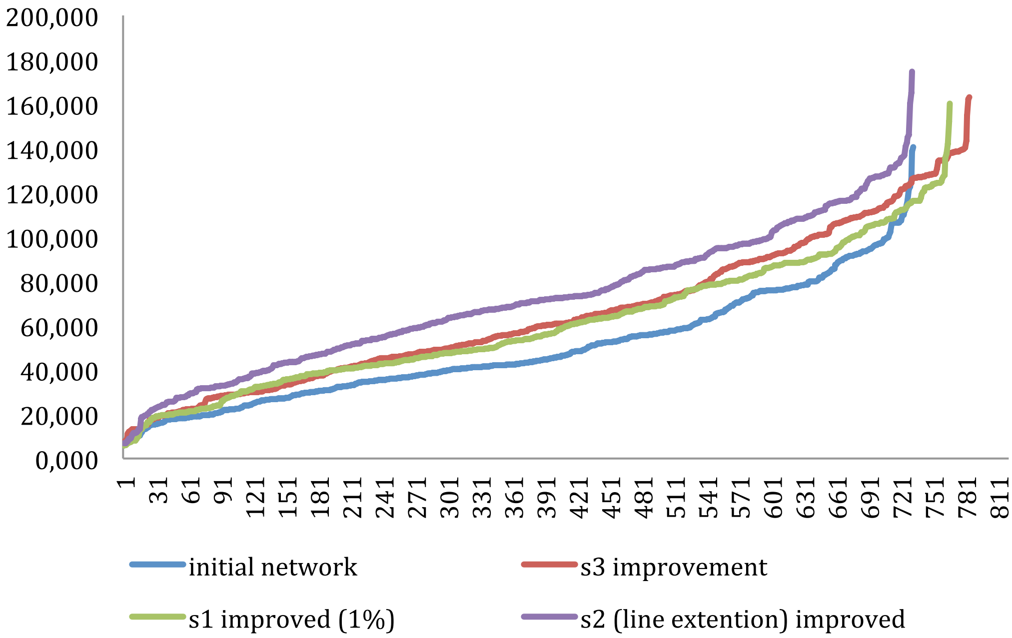


Figure 45: The graph shows all integration values (y axis) in ascending order (x axis)of each axial line in every scenario as well as in the original network

About Scenario III

Scenario III proposes a fundamentally different method based on another train of thought: the target area, representing the problematical informal settlement, actually shows space syntax values assessing its internal structure to have better walkability and structural quality than its surroundings. The reason for this is found in the historical development: the current informal urban settlement is a historically developed village swallowed and ignored by rash city development. Its fault results from its neighborhood's ignorance. Therefore scenario III intends not to generate changes within the target area but rather generate changes at the direct bordering neighborhood. That modality might even preserve the historical stock of the former village, at the expense of recently constructed buildings.

Observations

Further analysis of the partial results led to the unlikely interesting observation of an interrelation between values of intelligibility and integration sum. The graph in *Figure* 46 shows values of integration in y-axis ranked by decreasing order of intelligibility values in x-axis. It appears that while intelligibility is decreasing the integration sum is increasing.

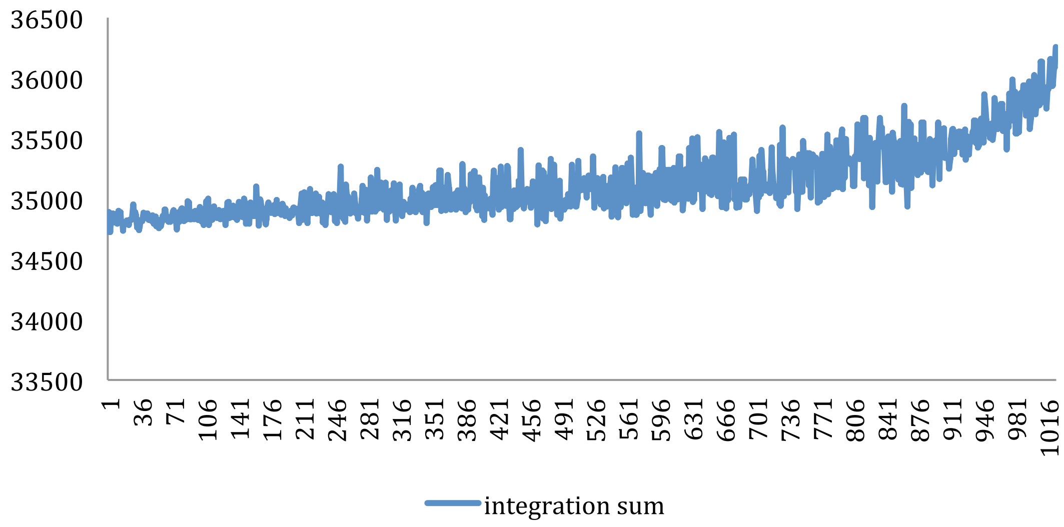


Figure 46: intterrelation between integration values (y-axis) ranked by decreasing order of intelligibility values (x-axis)

Calculation times

The fact of long calculation times is the reason for cutting down the amount of generated lines to a reasonable size by filtering only integrated and segregated starting points for new lines generations. Actually, it would be possible to extend either the percentage of chosen starting points or simply allow every location within the working area to generate lines. When doing so, the amount of generations in the case study rises up to 300,000 lines and more. This increases the calculation time to several years. The structure of the algorithm easily allows splitting up calculations between several computers. This means that one computer calculates the generation ID 0 to 29 999, the second computer calculates generation ID 30 000 to 59 999, and so on… Today's capacity of common virtual memory is not a major deal for the calculation, so even one computer can process multiple calculations simultaneously. Hardware, more precise CPU power, of course can swap the processing time. Multi-tread processing only allows multiple simultaneous calculations at the same time, as Grasshopper for Rhino 5 (64-Bit Version) cannot address multiple cores for one process.

Heuristic search

The initial intention was to look for the best combination of several generated axial lines and not to analyze generated axial lines one by one. Due to the large number of combination possibilities, only search heuristics could help in optimizing the results. While working on this thesis, it turned out that there was no point in doing so. Less time-consuming computational tests and detailed analysis of this issue proved that the best combination always consists of the axial lines ranked highest in individual calculations – the method that was described above.

There was also the idea of using a genetic algorithm to find optimized results for individual line generations. As the graph on integration sum values in *Figure* 47 shows, the distribution of maxima within the fitness graph is localized. For using a genetic algorithm, there would be the need of finding another method for generating new axial lines. However, it remains questionable whether a relaxation of the fitness landscape can be achieved.

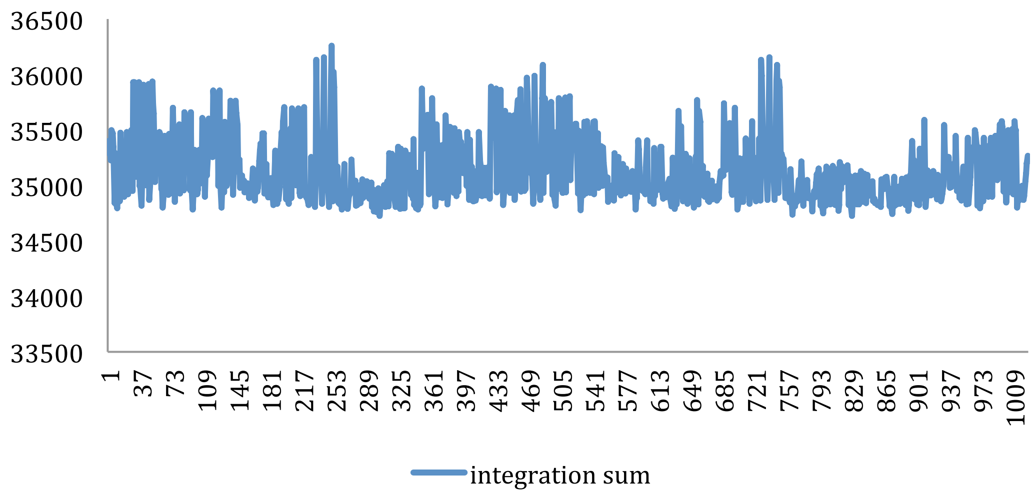


Figure 47: integration sum values (y axis) ranked by their generation ID (x axis)

Further research

It was already mentioned, that the implementation of heuristic search strategies is a field that requires further research. This will certainly lead to the development of other methods for the generation of axial lines.
Furthermore, information as for instance land use, building height or FAR (floor area ratio) could provide a basis for producing better options. Additionally, the assessment of generated variants could also consider information like building height, value of conservation or demolition effort. Introducing more data may enable a more detailed parametric design model, allowing to suit more requirements – for example a specified amount of FAR could also be defined as a benchmark.

The concept of the approach based on axial lines described in this thesis is easily applicable to other models, as for example, segment- or road center lines. First tests were successful but required significantly longer calculation times due to the bigger amount and complexity of the algorithms. Even more costly calculations would require adapting a generative approach based on VGA Analysis.

Conclusion

The approach described in this thesis does not deliver results that should be seen as the final stage of a design. It attempts to find possibilities to improve street networks based on the space syntax theory that uses graph mathematics to describe spatial quality. The results obtained through this method solely consider the mathematical properties of the axial line map and ignore various factors that cannot be put in relation or cannot be described mathematically.
It represents a guideline for further design work and provides a catalogue of options that cause highly effective impacts. These options could not be spotted easily by using conventional space syntax tools.

The method and the software developed for this thesis offer a broad range of other applications and were already presented in workshops and lectures at the Vienna University of Technology and the conference "Advances in Architectural Geometry 2012" in Paris.

References

Anyamba, T., 2011. Informal Urbanism in Nairobi. Built Environment, 37(1), p.21. Available at: http://www.ingentaconnect.com/content/alex/benv/2011/00000037/00000001/art00005.

Batty, M. et al., 1998. The virtual Tate. Chiron, Publisher:, p.1-14. Available at: http://discovery.ucl.ac.uk/181404/.

Batty, M., 2004. A new theory of space syntax. Syntax, 44(0), p.36. Available at: http://discovery.ucl.ac.uk/211/.

Benedikt, M.L., 1979. To take hold of space: isovists and isovist fields. Environment and Planning B Planning and Design, 6(1), p.47-65. Available at: http://www.envplan.com/abstract.cgi?id=b060047.

Berner, E. 1997. Defending a place in the city: localities and the struggle for urban land in Metro Manila. Ateneo de Manila University Press.

Chang, D. & Penn, A., 1998. Integrated multilevel circulation in dense urban areas: The effect of multiple interacting constraints on the use of complex urban areas. Environment and Planning B Planning and Design, 25(4), p.507-538. Available at: http://discovery.ucl.ac.uk/1005/.

Choi, Y.K., 1999. The morphology of exploration and encounter in museum layouts. Environment and Planning, 26(2), p.241-250. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.110.465&rep=rep1&type=pdf.

Cutini, V., Petri, M. and Santucci, A., 2004. From axial maps to mark point parameter analysis (Ma.P.P.A.) - a GIS implemented method to automate configura- tional analysis, in: Computational Science and Its Applications - ICCSA 2004, Lecture Notes in Computer Science 3044, Springer-Verlag, Heidelberg, p. 1107-1116.

Dalton, R.C., Hölscher, C., 2006. Understanding Space: the nascent synthesis of cognition and the syntax of spatial morphologies; Space Syntax and Spatial Cognition, Proceedings of the Workshop held in Bremen, 24th September 2006

Desyllas, J. & Duxbury, E., 2001. Axial maps and visibilty graph analysis: a comparison of their methodology and use in models of urban pedestrian movement. rdInternational Space Syntax Symposium Atlanta Georgia, 3, p.27.1-27.13.

Dovey, K. & King, R., 2011. Forms of Informality: Morphology and Visibility of Informal Settlements. Built Environment, 37(1), p.11–29. Available at: http://www.atypon-link.com/ALEX/doi/abs/10.2148/benv.37.1.11.

Dummett, M., 2010. Bangladeshi housing-block fire kills more than 100, BBC (online) 4 June, 2010. Available at: <http://www.bbc.co.uk/news/10232918> (Accessed 10 July 2012)

Dursun, P., 2007. Space syntax in architectural design 056. Syntax, 3(1990), p.056–01. Available at: http://scholar.google.com/scholar?hl=enandbtnG=Searchandq=intitle:Space+syntax+in+architectural+design#0.

Haq, S., 1999. Can space syntax predict environmental cognition. In Space Syntax Second International Symposium Proceedings. pp. 40.1-40.14.

Hillier, B. (1998). Describing Emergent Structure in Strongly Configurational Systems. Requirements

Hillier, B. & Hanson, J., 1984. The Social Logic of Space J. Costermans & M. Fayol, eds., Cambridge University Press. Available at: http://dx.doi.org/10.1017/CBO9780511597237.

Hillier, B. & Iida, S., 2005. Network and psychological effects in urban movement A. G. Cohn & D. M. Mark, eds. Proceedings of the 5th International Symposium on Space Syntax, 1(1987), p.475-490. Available at: http://eprints.ucl.ac.uk/1232/.

Hillier, B. & Penn, A., 2004. Rejoinder to Carlo Ratti. Environment and Planning B Planning and Design, 31(4), p.501-511. Available at: http://www.envplan.com/abstract.cgi?id=b3019a.

Hillier, B. 1988. Against Enclosure, N. Teymour, T. Markus, and T. Wooley, ed. 1988, Rehumanizing Housing, Butterworth, London, pp. 63-85.

Hillier, B. et al., 1986. Creating life: or, does architecture determine anything ? Architecture Behaviour, 3(3), p.233-250. Available at: http://discovery.ucl.ac.uk/166004/.

Hillier, B. et al., 1993. NATURAL MOVEMENT - OR, CONFIGURATION AND ATTRACTION IN URBAN PEDESTRIAN MOVEMENT. Environment and Planning B Planning and Design, 20(1), p.29-66. Available at: http://discovery.ucl.ac.uk/1398/.

Hillier, B., 1989. The architecture of the urban object. Ekistics 334 and 335, 5–21.

Hillier, B., 2007. Space is the machine: a configurational theory of architecture, Space Syntax. Available at: http://discovery.ucl.ac.uk/3881/.

Hillier, B., Hanson, J. & Graham, H., 1987. IDEAS ARE IN THINGS - AN APPLICATION OF THE SPACE SYNTAX METHOD TO DISCOVERING HOUSE GENOTYPES. Environment and Planning B Planning and Design, 14(4), p.363-385. Available at: http://discovery.ucl.ac.uk/1399/.

Hillier, B., Penn, A., 1992. Dense civilisations: or the shape of cities in the 21st century. AppliedEnergy 43(1 - 3) 41 - 66

Hillier, B.B. & Vaughan, L., 2007. The City as One Thing. Progress in Planning, 67(3), p.205-230. Available at: http://eprints.ucl.ac.uk/3272.

Hillier, W., Hanson, J. & Peponis, J., 1987. Syntactic Analysis of Settlements. Architecture et ComportementArchitecture and Behaviour, 3(3), p.217-231. Available at: http://discovery.ucl.ac.uk/86/.

Imparato, I., and Ruster, J. 2003. Slum upgrading and participation: lessons from Latin America. World Bank Publications.

Jiang, B., Claramunt, C. & Klarqvist, B., 2000. Integration of space syntax into GIS for modelling urban spaces. International Journal of Applied Earth Observation and Geoinformation, 2(3-4), p.161-171. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0303243400850102.

Karimi, K., Parham, E.,2012. An evidence informed approach to developing an adaptable regeneration programme for declining informal settlements . Proceedings: Eighth International Space Syntax Symposium. Available at: http://www.sss8.cl/media/upload/paginas/seccion/8151_1.pdf

Municipality of Jeddah, 2009. Jeddah Strategic Plan, building our future, preserving our heritage and values. Available at: http://www.jeddah.gov.sa/Strategy/English/JSP/JSPFiles/JSP-Eng-Mayors.pdf

Ouroussoff, N., 2008, Learning From Tijuana: Hudson, N.Y., Considers Different Housing Model. New York Times (online) 19 February, 2008. Available at: http://www.nytimes.com/2008/02/19/arts/design/19hous.html (Accessed 10 July 2012)

Patwari, S., Tang, B., and Mitchell, M. 2010. Learning from Delhi. Ashgate.

Penn, A. & Turner, A., 2004. Movement-generated land-use agglomeration: simulation experiments on the drivers of fine-scale land-use patterning. Urban Design International, 9(2), p.81-96. Available at: http://www.palgrave-journals.com/doifinder/10.1057/palgrave.udi.9000120.

Penn, A. et al., 1998. Configurational modelling of urban movement networks. Environment and Planning B Planning and Design, 25(1), p.59-84. Available at: http://discovery.ucl.ac.uk/183098/.

Penn, A., Desyllas, J. & Vaughan, L., 1999. The space of innovation: interaction and communication in the work environment. Environment and Planning B Planning and Design, 26(2), p.193-218. Available at: http://www.envplan.com/abstract.cgi?id=b260193.

Peponis, J. 1985. The spatial culture of factories. Human Relations, 38, 357-390

Peponis, J., 1997. The structure of urban space, movement and co-presence: The case of Atlanta. Geoforum, 28(3-4), p.341-358. Available at: http://linkinghub.elsevier.com/retrieve/pii/S001671859700016X.

Peponis, J., Hadjinikolaou, E., Livieratos, C., Fatouros, D. 1989. The spatial core of urban culture. – Ekistics 334, 43-55.

Peponis, J., Zimring, C. & Choi, Y.K., 1990. Finding the Building in Wayfinding. Environment And Behavior, 22(5), p.555-590. Available at: http://eab.sagepub.com/cgi/doi/10.1177/0013916590225001.

Ratti, C., 2004. Rejoinder to Hillier and Penn. Environment and Planning B Planning and Design, 31(4), p.513-516. Available at: http://www.envplan.com/abstract.cgi?id=b3019b.

Ratti, C., 2004. Space syntax: some inconsistencies. Environment and Planning B Planning and Design, 31(4), p.487-499. Available at: http://www.envplan.com/abstract.cgi?id=b3019.

Romero, S. 2011. Rio Slum Is ‘Pacified’ in Advance of Games. New York Times (online) 13 November, 2011. Available at: <http://www.nytimes.com/2011/11/14/world/americas/authorities-take-control-of-rios-largest-slum.html> (Accessed 2 October 2012)

Steadman, P., 2004. Guest Editorial: Developments in Space Syntax. Environment and Planning B Planning and Design, 31(4), p.483-486.

Turner, A. & Penn, A., 1999. Making isovists syntactic : isovist integration analysis. 2nd International Symposium on Space Syntax, 3(April), p.1-9. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.126.685&rep=rep1&type=pdf.

Turner, A., 2005. Could a road-centre line be an axial line in disguise? A. Van Nes, ed. Proceedings of the 5th International Symposium on Space Syntax pp 145159, 1, p.pp. 145-159. Available at: http://discovery.ucl.ac.uk/39854/.

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), p.539-555. Available at: http://www.envplan.com/abstract.cgi?id=b32067.

UN-Habitat, 2007. state of the world's cities report 2006/7: 30 Years of Shaping the Habitat Agenda

Vaughan, L., 2007. The spatial syntax of urban segregation. Progress in Planning, 67(3), p.205-294. Available at: http://discovery.ucl.ac.uk/3445/.

List of Figures