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Analysis of Urban Spatial Growth in Xalapa, Mexico: Application of Complex Network Model

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Abstract: The Science of Complexity has recently attracted attention due to its ability to explain and predict the complex phenomena in the fields leading from natural to social sciences, which are unexplainable with the existing scientific theories and methodologies. Thus, applying it to architectural & urban research fields could lead to successful explanation and prediction of architectural phenomena. This study attempts to explain the process of urban spatial growth as a complex network system. For the positivistic approach to research, the time series spatial changes of xalapa city in Mexico are examined and natural growth characteristics are prominent. The results show that the urban spatial structure represented by the Axial-line network follows the power-law. Between 1776 and 1980, urban spatial development grew by preferential attachment, i.e., complex system network Growth logic. Between 2000 and 2010, urban spatial development expanded while maintaining a minimum depth in the city center, i.e., Minimum depth attachment. Between 1980 and 2000, urban spatial development grew following both logic characteristics simultaneously. With this result, it could be said urban spaces are complex adaptive systems and that uneven rules act on the formation or development of these spaces.

Key words: complex system, power-law, complex network model, space syntax, urban spatial growth

1. Introduction

1.1 Background and Objectives

Modern architecture and spatial environments reflects modern society and its various values. It is difficult to simply define the meaning of the spatial environment from a single building or the whole city. Complex system is a common aspect not only in the fields of architecture and urban planning but also in the natural systems and the social systems. The science of complexity which is based on the complex system theory, has recently attracted attention as it can successfully explain phenomena that conventional reductionism science cannot explain such as natural disasters and the proliferation of financial crises. Since 1980, science of complexity has developed to a point where it can identify and predicting the rules inherent in phenomena such as earthquakes, meteorological changes, and price changes in financial markets. In this regard, the science of complexity can consider the possibility of interpreting the complex phenomena of spatial environment by applying complex system theory to the field of architecture and urban spatial development.

1.2 Study Scope and Flow

Emergence is a core concept of a complex system. When emergent behavior occurs, urban space can be regarded as a complex system. Representative emergent behaviors include Power-laws, fractal geometry, and critical phenomena. The critical phenomena are mainly in the form of power-laws, and the fractal geometry is the geometrical manifestation of the power-law. Therefore, this study examines emergent behavior in real urban spaces through the Power-law and searches for the growth of the spatial network using an empirical and chronological method.

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The spatial scope of this study includes entire urban areas located in Xalapa City. First analysis was conducted by drawing up axial-lines using space syntax theory in Xalapa City from GIS data (from 1175 to 2010). Then, control values were calculated by analyzing the reproduced spatial network according to the analysis method of space syntax. The analysis tool used "Deptmap X" developed by CASA (Center for Advanced Spatial Analysis) at UCL (University College London) to analyze the power-law characteristics of the Rank-scale distribution of the calculated control value. In other words, the linearity in the log-log plot was examined. A second analysis examined the similarity between the growth process of an urban spatial network and the growth of a complex network. It was verified by periodically comparing whether the urban spatial network had grown according to the logic of "preferential attachment" and "minimum depth attachment" (Fig. 1).

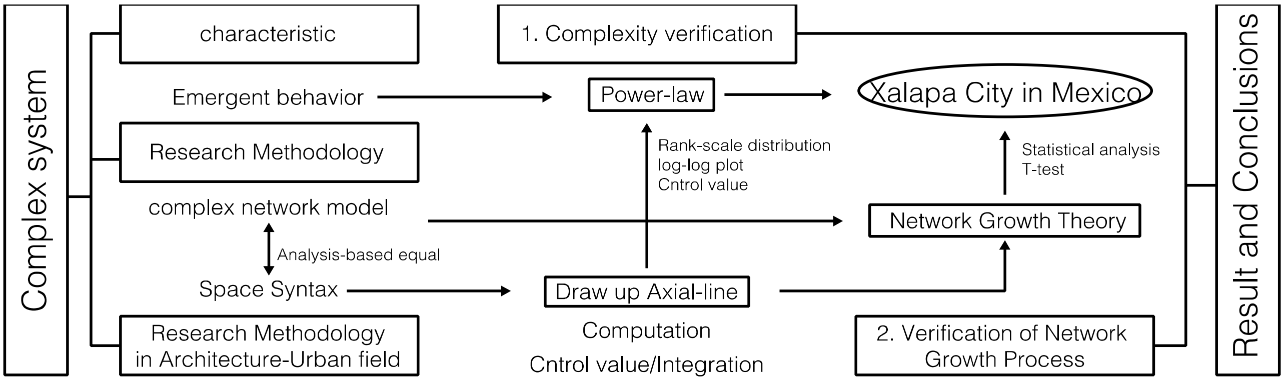


Fig. 1 Flow of research.

2. Material and Methods

2.1 Understanding the Complex System

Complexity theory is a developing field covering a wide range of natural, social and economic phenomena (e.g., rainforests, markets, cities, languages, the internet). Complexity theory uses a variety of other theories to draw insights into the genesis of complex systems, and system characteristics and dynamics. While many approaches are eclectic, some theorists are working towards a unified theory of complexity [1].

Holland and others distinguish the "complex" from the "complicated". While the boundaries are fuzzy (as with "life" and "consciousness"), "emergence" distinguishes complex systems as a subset of complicated systems. Emergence means that "the (system) aggregate exhibits properties not attained by summation (of individual interactions within the system)". Examples of emergence include wetness as a property of an aggregate of water molecules, or "self-reproduction" as a property of sequences of "instructions" (for instance those instructions contained in strings of RNA and DNA).

There are a wide variety of approaches to understanding complex adaptive systems [2]. Holland draws threads from genetics, evolution, linguistics, computer science and information processing (among other disciplines) to work towards a more general theory. Common to all these are features and processes that generate complexity: the existence of boundaries between system elements, the transmission and selective re-transmission of signals across those boundaries (typically based on filters that recognise "tags" or small segments within those signals), recombination of signals into new configurations; and selection pressures that lead to adaptation and the appearance of new types of agents, sophisticated agents using autonomous internal sub-systems to anticipate the outcomes of a sequence of actions (i.e., an ability to plan), and more complex substructures forming from building blocks of extant substructures.

The most important element that describes complex systems is the concept of emergence. Actual systems vary in complexity depending on the scale they are observing. Depending on the characteristics of the system, they can be divided into coherent systems, complex systems, and random systems. Ecosystems, and human-social sciences have various scales and hierarchies. Decreasing scaling with individual elements increases the complexity of the components, and when the scales increase beyond a certain level, there is a constant order throughout the whole system. The complex system is characterized by a characteristic change (increasing or decreasing complexity) as the scale changes. In a complex system, this phenomenon is called “emergent” and the aimed to understanding the phenomenon is achieved by studying the mechanism of the emergent [3] (Fig. 2).

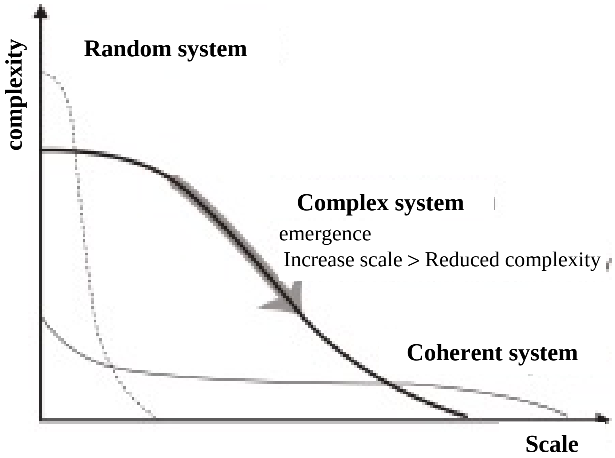


Fig. 2 Concept of emergence.

2.2 Research Methodology

The basis for the development toward energy saving under economic points A complex system can be defined simply as a system in which emergent behavior is observed. A power-law is a representative emergent behavior in a natural system and societal system. This is a theory that quantitatively explains natural social phenomena through mathematical logic. The critical research area of complex systems is modeling and simulation to confirm the recreation of emergent behavior, setting up hypotheses on the logic that leads to emergent behavior and using the simulation method to identify internal logic. The well-known methodologies of complex system modeling include a multi agent-based model, system dynamics model, complex network model, and nonlinear time series model. Among them, the complex network model has a quantitative spatial analysis technique and a methodological common base such as space syntax. Therefore, it is utilized in quantitative spatial analysis and modelling research in the architecture - urban research field (Table 1).

Table 1 Research methodology of complex systems and application of architecture-urban research field.

Analysis Tools	Spatial	Analysis software	Applicable Study Field
Multi agent-based model	O	SWARM, REPAST, NETLOGO	Behavior study, Morphology study, Design study
Complex network model	△	PAJEK, CFinder, NetMiner	Extended space syntax, Spatial structure evolution
system dynamics model	X	Stella & Ithink, PwerSim, VenSim	Policy study, Decision, Environmental change

2.3 Space Syntax

Space syntax was developed by Bill Hiller and his colleagues in London University in 1970. Space syntax began as a method of accessing and understanding the social phenomena that occur in the continuous of space in a city. It starts with a certain description of the spatial architecture of buildings and cities. In Space Syntax, spaces are understood as voids (streets, squares, rooms, parks, etc.) (Fig. 3). Voids are defined by obstructions that might either constrain access and/or occlude vision (such as walls, fences, furniture, partitions and other imped-iments). Buildings are composed of a series of spaces; each space has at least one link to other spaces. The structural properties that comprise these spaces and links might have an embedded social meaning that has implications on the overall behaviour of human habitat.

The same description might also apply on an urban scale. Cities are aggregates of buildings held together by a network of spaces fowing in-between the blocks. This network connects a set of street spaces that form together a discrete structure. The structure is the optimum result of shortest paths from all origins to all destinations in the spatial system. It is what holds it all together. It has an architecture, and by this we mean a certain geometry and a certain topology, that is, a certain pattern of connections. Buildings can have different structures that relate strongly to their functionality. Prisons are normally hierarchical reinforcing power and control in the form of access and visibility relationships. Prison cells appear at the very end of these hierarchies. On the contrary, museums are made up of continuous spaces that follow some sort of narratives (Fig 4). These kinds of building organisations have their recognisable spatial characteristics. To expose these spatial characteristics we use graph-based representations and measure their structural properties [4].

The integration of specific space involves the notion of asymmetry. Thus the measure of relative asymmetry generalizes this by comparing how deep the system id from a particular point, with how deep or swallow it thoretically could be, with the least depth existing when all spaces directly are connected to the original space, and the most when all space are arranged in a un-linear sequence away from the original space. The measure of control is calculated by a simpler, but perhaps more laborious procedure. Each space has a certain number n of immediate neighbors. Each space therefore give 1/n to each of its immediate neighbors, and these are then summed for each receiving space to give the control value of that space (Table 2).

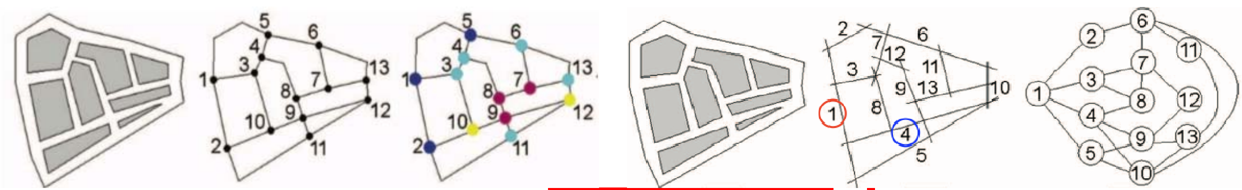


Fig. 3 Street network (left) and Axial-line map (right) (source: Crucitti et al., 2006[5].)

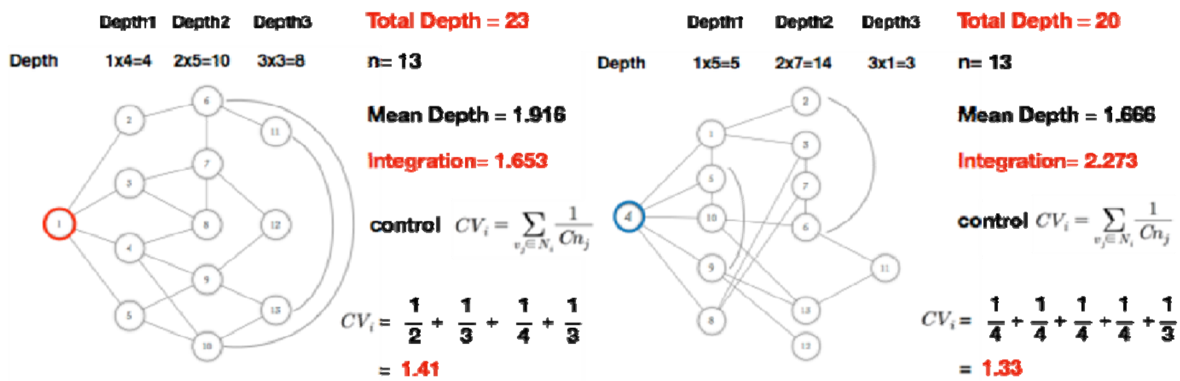


Fig. 4 Relation of spatial changes depending on depth.

Table 2 Analysis index of space syntax and social network analysis (SNA).

	Definition	SNA Centrality Indicator
Connectivity	$Cn_i = k_i = \lvert N_i \rvert \quad (N_i = \{v_j \mid e_{ij} \in E,\ e_{ji} \in E\})$	Degree Cen
Control value	$CV_i = \sum_{v_j \in N_i} \frac{1}{Cn_j}$	-
Mean Depth	$MD_i = \frac{1}{n-1} \sum_{j=1}^{n} d_{ij}$	Closeness Cen
Integration	$Intg_i = \frac{2(MD_i - 1)}{n-2} \times D_n, \quad D_n = \frac{6.644n \times \log(n+2) - 5.17n + 2}{(n-1)(n-2)}$	Closeness Cen

Control is take only into account the relationship between a relationship and immediate neighbor; where a integration is measure since it takes into account the relationship of a space to every other in the system.

3. Complexity of Spatial Networks

The definition of a power-law generally refers to the case where the relationship between a variable and frequency in a frequency distribution for a particular variable represents an integral power function. The probability density function p(x) for variable x is in the form of a power-law. If the frequency distribution of a particular variable follows the power-law, the graph of the distribution appears as a nonlinear curve. Law-related laws of the power-law generally use a “log-log plot” that converts the X-axis Y-axis to log from (Figs. 5 and 6).

In order to confirm the complexity of the urban space network, verification was conducted on an actual urban space. Xalapa city in Mexico was analyzed with natural growth. The GIS data for 2010 was extracted, an axial-line map was created, and the control value was calculated using the analysis method of space syntax. The conformity of the Rank-scale distribution of the calculated control value conforms to the power-law was checked. Then the linearity of the log-log plot was reviewed. There were 6629 axial-line maps. A rank-scale distribution was created for the control value, and the linearity was confirmed in the log-log plot. In conclusion, the characteristics of the power-law were confirmed in the distribution of the control value. Emergent behavior of a complex network can be seen in the network of the space that reproduces the urban space. The procedure of the analysis is as follows: a) To determine whether a particular phenomenon follows the law of the power law, use the rank-scale distribution method instead of the frequency distribution method. The distribution graph is basically a log-log plot. The X axis is the scale (measured value) and the Y axis is the rank. b) Check the section showing linearity in the overall distribution. c) When it is necessary to see the degree of regress to linearity or the slope of linearity, this is examined through statistical methods such as correlation analysis and nonlinear regression analysis [6].

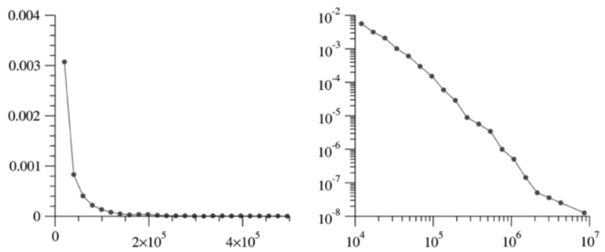


Fig. 5 Distribution of power-law.

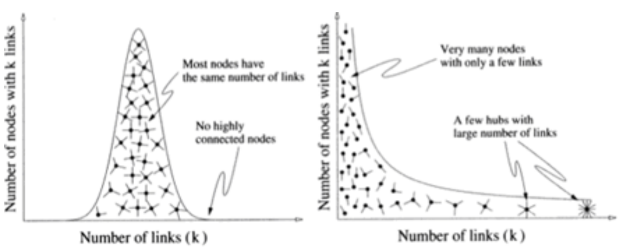


Fig. 6 Normal distribution and power-law distribution.

According to related studies, the range of effective slope, which can be regarded as following the power-law, can be defined as 0.5-2.5. And other features of the power law are observed with higher ratio of largest to smallest values. In the case of the typical normal distribution, the male mean height, it has a low ratio of largest to smallest (4.8) [7, 8].

As a result of the analysis, the urban network reproduced by the axial line map can be judged as a kind of complex system. Uneven distribution of degrre in a complex network appears as an uneven distribution of control values in an axial-line map (Figs. 7 and 8). Uneven distribution of control values means unequal location conditions. In other words, the logic of unequal space arrangement in the process of forming the city has worked, and as a result, it can be seen that unequal location conditions have emerged. The result is clearly different from the street network structure. Axial-line map is the abstraction of the longest area (space) that can be seen as line segment. Axial-line morphologically expresses human movement and walking. An Axial-line represents the maximum space visible to a person located in a specific space (Table 3).

Additional visual information is needed to move to another space. An Axial-line means a space with uniform accessibility. Axial-line maps include human behavioral meanings such as movement or visual information and accessibility. It is a dynamic network in which various aspects of mobility interact with one another. Dynamic networks evolve slowly through interaction. The process of evolution is dynamic and continuous. Evolution in spatial networks means growth.

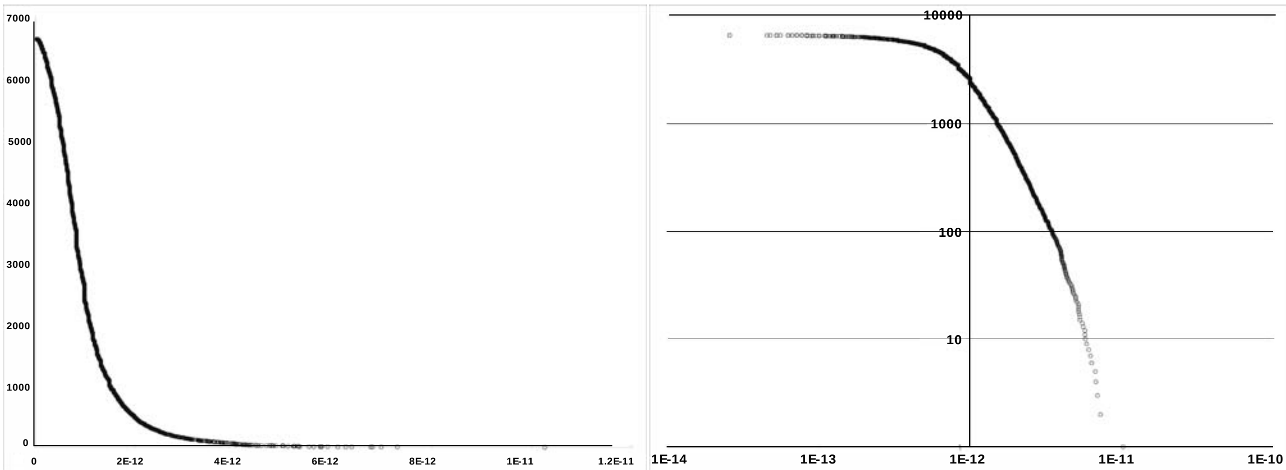


Fig. 7 Rank-scale distribution (Left) and log-log plot (right).

Table 3 Analysis index of space syntax and social network analysis (SNA).

	axial-line number	Control value (MAX)	Control value (MIN)	ratio of largest to smallest	least sum of square Slope (R^2)
2010	6629	10.26	0.025465	402.5132	0.7441

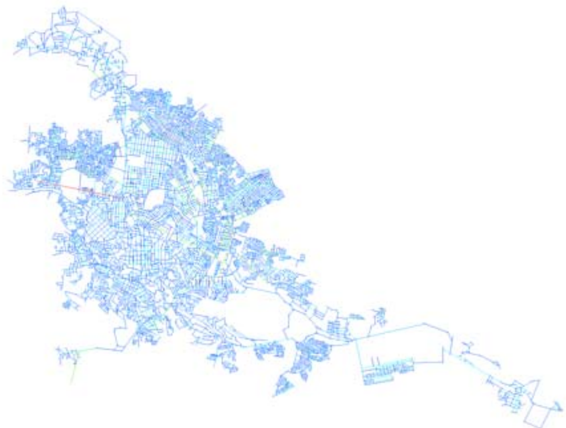


Fig. 8 Axial-line map of Xalapa.

4. The Growth of Spatial Networks

4.1 Growth Logic Verification Method

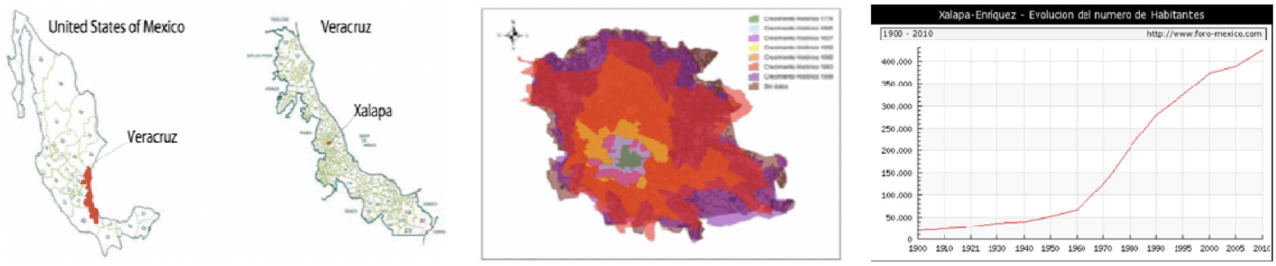
In Chapter 3, the urban space reproduced by the axial-line map showed the characteristics of a complex network. In this section, the growth logic of complex networks is applied to urban space. The analysis method uses the method applied in a previous study [9]. The procedure of the analysis is as follows: a) Literature study identifies growth periods of xalapa city; b) An axial-line map is created for each period; c) The adjacent axial-line maps are compared for each period and the changed axial line is extracted; d) The extracted axial line and the axial line of the previous period are statistically verified. The statistical analysis assumes two logic characterisics. First, the preferential attachment logic explains the evolution of complex networks. When a new node is created, it is likely that it will be connected to a node having a high influence (preference) in the existing network. Second, spatial networks have physical limitations different from other complex networks (Internet networks). When a city grows, it cannot grow indefinitely. Thus, the assumption of the minimum depth attachment logic is established by maintaining a low spatial depth in the urban center or in the suburban area.

4.2 Growth Logic Verification

Xalapa, located in the municipality of Xalapa in the centre of the state of Veracruz, covers an area of 122.33 km^2 and has 457,614 inhabitants. The city is located in a region of great historical importance, as the Spanish conquistadores passed through Xalapa on their way to Mexico City (Figs. 9 and 10). From 1521, Xalapa became the entry point for Spanish immigrants looking for a better climate and healthier conditions. In Xalapa, the capital, expansion through informal settlement is proceeding apace and exacerbating urban problems, with no sign of any reduction in pressure on natural resources and neighbouring productive areas. Growth has been chaotic, with unplanned new settlements constantly springing up on the outskirts of the city [10].

Before growth After growth Axial-line extraction

Fig. 9 Axial-line extraction process.



Location Urban space growth (INEGI 2000) Population growth curve

Fig. 10 Spatial range.

The population of Xalapa began to rise sharply in the 1960s, increasing by more than 300 per cent by 1980. Between 1950 and 1980, 100,000 people are reported to have migrated from rural areas to the city. In the following two decades, 1980-2000, the population nearly doubled with considerable further growth in the outlying settlements of makeshift dwellings inhabited by low-income groups [11]. This important time of growth of xalapa city can be distinguished based on literature study and National Institute of Statistic and Geography (INEGI) information. The times for comparison are set as 1776, 1927, 1950, 1980, 2000, and 2010. It is classified into five periods considering population growth and expansion of the city. (1) 1776-1927: Urban occurrence stage, (2) 1927-1950: slow-grown stage, (3) 1950-1980: urbanization stage, (4) 1980-2000: Urban expansion stage, (5) 2000-2010: Sub-urbanization stag (Fig. 11). To verify the preferential attachment logic, the extracted axial line and the previous time are statistically verified. Control values are used for comparison. The verification hypothesis is that the means of the control values of the extracted axis are higher than the means of the control values of the previous period. Therefore, the null hypothesis (H0) for the T-test is that "the mean of the control values of the extracted axial-line is not higher than mean of the population control value". Verification uses a one-tailed approach. The null hypothesis (H0) to verify the minimum depth attachment logic is "the mean of the integration of the extracted axial-line is not higher than mean of the population integration".

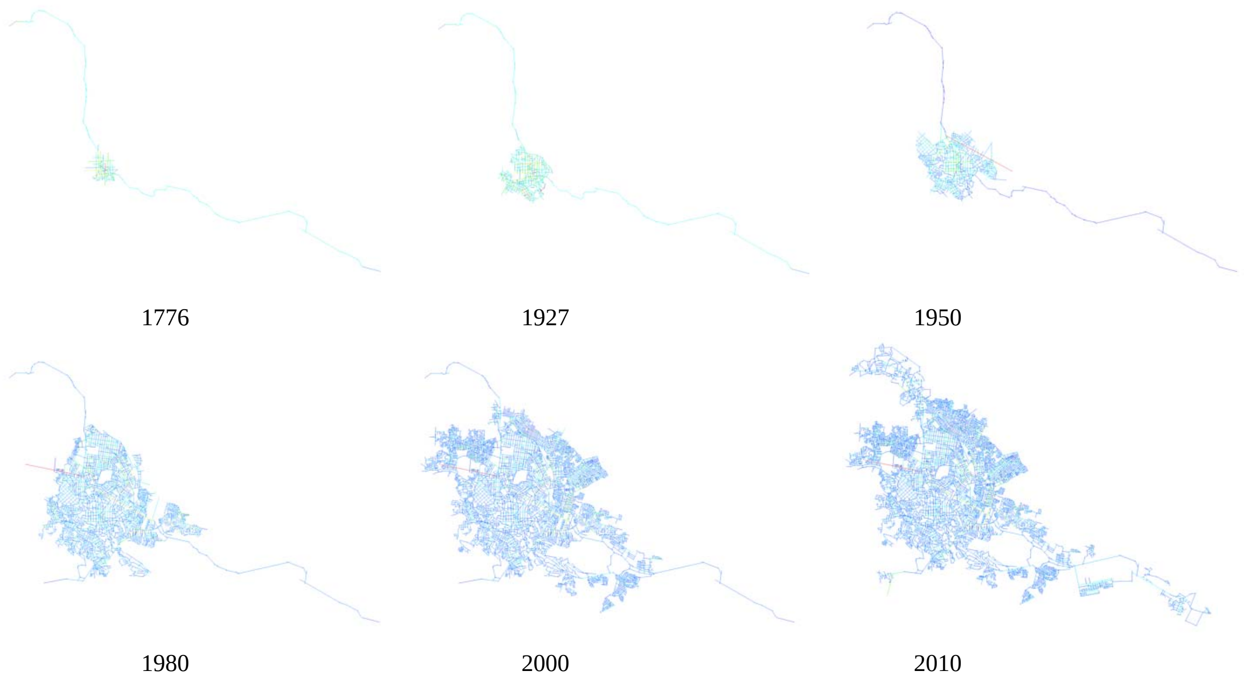


Fig. 11 Spatial Range and Axial-line map by period.

Table 4 T-test results (p < 0.05)

period	Originally axial-line number	Extracted axial-line number	Control value (P-value)	Integration (P-value)	local Integration (R3) (P-value)
1776-1927	159	42	**0.04**	3.4E-06	4.34E-09
1927-1950	415	52	**0.01**	8.25E-06	3.27E-06
1950-1980	705	92	**0.01**	0.33	0.08
1980-2000	2576	113	**0.00**	**0.00**	0.15
2000-2010	5567	46	0.45	**0.00**	0.09

5. Conclusion

The complexity of the urban space reproduced by the axial line is verified and the growth logic of the complex network is applied to a real urban space. From 1776 to 1980, the city of xalapa seems to have grown according to the preferential attachment logic. This indicates that there is a high probability that a new space will be opened in a space with better connectivity than other spaces. Between 2000 and 2010, urban space is considered to have grown with minimum depth attachment logic. Consider that the city has physicality grown, but with a certain level of internal connectivity and accessibility. A notable phenomenon is that between 1980 and 2000, urban growth follows the characteristics of both logic characteristics simultaneously. In other words, it has a combined growth characteristic combined with Introverted expansion outward expansion. These results show the complexity of the city presented in the preceding research [9]. The results of this study provide a basis for judging the complexity of urban space and explaining the urban growth process quantitatively (Table 4). However, this research is analyzed the structure of space from an ideal point of view, and it has limitations for the analysis method of complex network that analyzes the result of development.

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